

7 Crop growth

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7.1 Introduction

SWAP contains three crop growth routines: a simple model, a detailed model (WOFOST), and the same model attuned to simulate grass growth. The simple model prescribes crop development, independent of external stress factors. The main function is to provide proper upper boundary conditions for soil water movement.

WOFOST simulates in detail photosynthesis and crop development, and takes into account the effects of water and salt stress on crop development. WOFOST (WORLD FOOD STUDIES) originated in the framework of an interdisciplinary study on the potential world food production by the Centre for World Food Studies (CWFS) in cooperation with the Wageningen Agricultural University, Department of Theoretical Production Ecology (WAU-TPE) and the DLO-Centre for Agrobiological Research (CABO-DLO, currently Plant Research International), Wageningen, the Netherlands. After cessation of the CWFS in 1988, the model was further developed at the DLO-Winand Staring Centre (SC-DLO) in cooperation with AB-DLO and WAU-TPE. Related models to WOFOST are the successive SUCROS (Simple and Universal Crop Simulator) models (Spitters et al., 1989; Van Laar et al., 1992), Arid Crop (Van Keulen, 1975; Van Keulen et al., 1981), Spring wheat (Van Keulen and Seligman, 1987), MACROS (Penning de Vries et al., 1989) and ORYZA1 (Kropff et al., 1993). All these Wageningen models follow the hierarchical distinction between potential and actual production, and share similar crop growth submodels, with light interception and CO₂ assimilation as growth driving processes, and crop phenological development as growth controlling process.

In SWAP, WOFOST 6.0 has been implemented. The description in Par. 7.3 is based on Spitters et al. (1989), Supit et al. (1994) and the program source code. A user's guide of WOFOST 6.0 was written by Hijmans et al. (1994). Boons-Prins et al. (1993) documented specific parameters for the crops winter wheat, grain maize, spring barley, rice, sugar beet, potato, field bean, soy bean, winter oilseed rape and sunflower. WOFOST input files for these crops will be provided with the SWAP program.

7.2 Simple crop module

This option is useful when crop growth doesn't need to be simulated or when crop growth input data are insufficient. The simple crop growth model represents a green canopy that intercepts precipitation, transpires and shades the ground. The user specifies leaf area index, crop height and rooting depth as function of development stage. In stead of the leaf area index also the soil cover fraction can be provided (see Par. 0). The development stage can be controlled either by the temperature sum or can be linear in time.

When the simple crop model is used in combination with the reference evapotranspiration, the crop factor should be given of the particular crop completely covering the soil and with optimal water supply.

The simple model does not calculate the crop potential or actual yield. However, the user may define yield response factors (Doorenbos and Kassam, 1979; Smith, 1992) for various growing stages as function of development stage. Each growing stage k the actual yield $Y_{a,k}$ (kg ha^{-1}) relative to the potential yield $Y_{p,k}$ (kg ha^{-1}) during this growing stage is calculated by:

$$1 - \frac{Y_{a,k}}{Y_{p,k}} = K_{y,k} \left(1 - \frac{T_{a,k}}{T_{p,k}} \right) \quad (7.1)$$

where $K_{y,k}$ (-) is the yield response factor of growing stage k , and $T_{p,k}$ (cm) and $T_{a,k}$ (cm) are the potential and actual transpiration, respectively, during growing period k .

The relative yield of the whole growing season is calculated as product of the relative yields of each growing stage:

$$\frac{Y_a}{Y_p} = \prod_{k=1}^n \left(\frac{Y_{a,k}}{Y_{p,k}} \right) \quad (7.2)$$

where Y_a is the cumulative actual yield (kg ha^{-1}) of the whole growing season, Y_p is the cumulative potential yield (kg ha^{-1}) of the whole growing season, index k is the growing stage and n is the number of defined growing stages.

In case of a linear relation between Y_a/Y_p and T_a/T_p during the whole growing period, or when no information is available of the yield response factors as function of development stage D_s for the particular crop, specify $K_{y,k} = 1$ for $0 < D_s < 2$ and specify one growing stage k . Mind that increase of the number of growing stages k , reduces the relative yield as calculated by Eq. (7.1).

<i>Model input for each crop</i>			
<i>Variable</i>	<i>Code</i>	<i>Description</i>	<i>Default</i>
	LCC	length of crop cycle (d) (optional)	
	TSUMEA	temperature sum from emergence to anthesis ($^{\circ}\text{C}$) (optional)	
	TSUMAM	temperature sum from anthesis to maturity ($^{\circ}\text{C}$) (optional)	
K_{df}	KDIF	extinction coefficient for diffuse visible light (-) (optional)	0.60
K_{dir}	KDIR	extinction coefficient for direct visible light (-) (optional)	0.72
<i>LAI</i>	LAI	leaf area index as function of development stage ($\text{m}^2 \text{m}^{-2}$) (optional)	
<i>SC</i>	SCF	soil cover fraction as function of development stage (-) (optional)	
k_c	CF	crop factor as function of development stage (-) (optional)	
h_{crop}	CH	crop height as function of development stage (cm) (optional)	
D_{root}	RD	rooting depth as function of development stage (cm)	
$K_{y,k}$	KY	yield response factor as function of development stage (-)	1.0

Other input parameters are related to water stress (Par. 2.4) and to interception (Par. 3.3)

7.3 Detailed crop module

Figure 38 shows the processes and relations incorporated in WOFOST. The radiation energy absorbed by the canopy is a function of incoming radiation and crop leaf area. Using the absorbed radiation and taking into account photosynthetic leaf characteristics the potential gross photosynthesis is calculated. The latter is reduced due to water and/or salinity stress, as quantified by the relative transpiration, and yields the actual gross photosynthesis. The actual gross photosynthesis is reduced by maintenance respiration and growth respiration to yield the dry matter increase. The dry matter increase is partitioned among roots, stems, storage organs, and leaves. The leaf area is determined by the partitioning to leaves. The dry weights of the plant organs are obtained by integrating their growth rates over time. During the development of the crop, part of living biomass dies due to senescence.

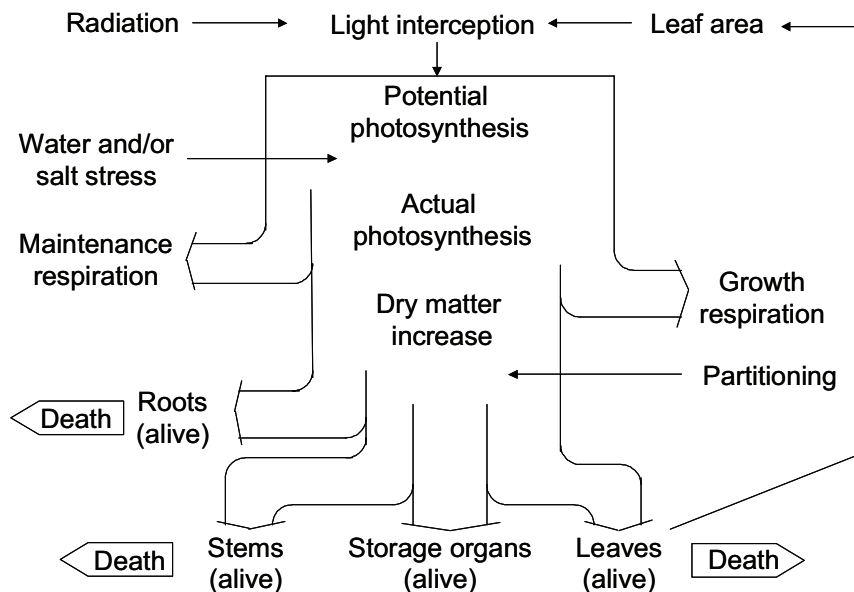


Figure 38 Schematization of the crop growth processes incorporated in WOFOST

Part of the carbohydrates (CH_2O) produced 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 dry matter produced is partitioned among 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. During the development of the crop, part of living biomass dies due to senescence.

Some simulated crop growth processes are influenced by temperature, like for example the maximum rate of photosynthesis and the maintenance respiration. Other processes, like the partitioning of assimilates or decay of crop tissue, are steered by the phenological development stage.

7.3.1 Phenological development stage

As many physiological and morphological processes change with the phenological stage of the plant, quantification of phenological development is essential in any crop growth simulation model. For many annual crops, the phenological development can conveniently be expressed in development stage D_s (-), having the value 0 at seedling emergence, 1 at flowering and 2 at maturity (Van Heemst, 1986a; 1986b). The most important phenological

change is the one from vegetative ($0 < D_s < 1$) to reproductive stage ($1 < D_s < 2$), which changes drastically the dry matter allocation to organs.

WOFOST starts crop growth simulation at emergence, which date should be specified by the user. A crop passes through successive phenological development stages from 0 to 2. The length of these stages depends on the development rate. Development rates before and after floral initiation or anthesis ($D_s = 1$) are controlled by day length and/or temperature. In the model, before anthesis both factors can be active. After anthesis only temperature will affect development rate.

Higher temperatures accelerate 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 and Seligman, 1987). WOFOST uses the temperature sum to determine the development stage. An effective temperature T_{eff} (°C) is calculated as function of daily average temperature T_{air} (°C). For species originating from temperate regions $T_{\text{eff}} = 0$ at $T_{\text{air}} = 0-3$ °C, while for species of subtropical and tropical origins $T_{\text{eff}} = 0$ at $T_{\text{air}} = 9-14$ °C (Angus et al., 1981). Within a species, cultivars may vary substantially in their temperature requirements. The temperature sum, therefore, is characteristic for each cultivar. Accordingly, the development stage, D_s (-), is calculated as:

$$D_s^{j+1} = D_s^j + \frac{T_{\text{eff}}}{T_{\text{sum},i}} \quad (7.3)$$

where superscript j is the day number and $T_{\text{sum},i}$ is the temperature sum required to complete either the vegetative or the reproductive stage.

For certain species or cultivars, during the vegetative stage, the effect of day length should be taken into account. Approaches that describe such effects quantitatively are given, amongst others, by Weir et al. (1984), Hadley et al. (1984) and Reinink et al. (1986). In the model, a reduction factor for the development rate as function of day length f_{lday} (-) is introduced:

$$f_{\text{lday}} = \frac{L_{\text{day}} - L_{\text{cday}}}{L_{\text{oday}} - L_{\text{cday}}} \quad \text{with} \quad 0 < f_{\text{lday}} < 1 \quad (7.4)$$

with L_{day} the actual day length (d), L_{cday} the shortest day length for any development (d), and L_{oday} the minimum day length for optimum development (d).

The user should provide information whether the development rate depends on temperature, on day length or on both. 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 be ignored by choosing an appropriate temperature sum, which leads to an equivalent crop life cycle.

The simulation of crop growth stops when the development stage reaches the stage at which the crop will be harvested. The development stage at harvest time should be provided by the user.

Model input for each crop

<i>Variable</i>	<i>Code</i>	<i>Description</i>
T_{eff}	DTSM	effective temperature as function of daily temperature(°C) (optional)
$T_{\text{sum}, 1}$	TSUMEA	temperature sum from emergence to anthesis (°C) (optional)
$T_{\text{sum}, 2}$	TSUMAM	temperature sum from anthesis to maturity (°C) (optional)
L_{oday}	DLO	minimum day length for optimum crop development (h) (optional)
L_{cday}	DLO	shortest day length for any crop development (h) (optional)
	DVSEND	crop development stage at harvest (-)

7.3.2 Radiation fluxes above the canopy

Measured or estimated daily global solar radiation (wavelength 300-3000 nm) is input for the model. Incoming radiation is partly direct, with the angle of incidence equal to the angle of the sun, and partly diffuse, with incidence under various angles. The sine of solar elevation as a function of the day hour, can be calculated with:

$$\sin \beta_{\text{sun}} = \sin L_{\text{g}} \sin \sigma_{\text{sun}} + \cos L_{\text{g}} \cos \sigma_{\text{sun}} \cos \left(\frac{2\pi (t_{\text{h}} + 12)}{24} \right) \quad (7.5)$$

with β_{sun} the solar elevation (degrees), σ_{sun} is solar declination (degrees), L_{g} is geographic latitude (degrees) and t_{h} is hour of the day.

Only 50 percent of the global solar radiation (wavelength 300-3000 nm) is photosynthetically active (PAR, Photosynthetically Active Radiation, wavelength 400-700 nm). This fraction, is generally called 'light' or 'visible radiation'.

The instantaneous incoming photosynthetically active radiation PAR ($\text{J m}^{-2} \text{d}^{-1}$) 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, taking into account reduced atmospheric transmission at low solar elevations:

$$PAR = 0.5 R_{\text{s}} \frac{\sin \beta_{\text{sun}} (1 + 0.4 \sin \beta_{\text{sun}})}{\int \sin \beta_{\text{mod, sun}}} \quad (7.6)$$

where R_{s} is global radiation flux density ($\text{J m}^{-2} \text{d}^{-1}$) and $\int \sin \beta_{\text{mod, sun}}$ the integral of $\sin \beta_{\text{sun}}$ over the day (-) which is corrected for reduced atmospheric transmission at low solar elevations.

A diffuse radiation flux results from scattering of sun rays by clouds, gases and dust in the atmosphere. To quantify the degree of scattering, the measured daily total radiation is compared with the amount that would have reached the earth's surface in the absence of an atmosphere, S_{sun} , which can be calculated from theoretical considerations:

$$S_{\text{sun}} = 1.18 \cdot 10^8 \left(1 + 0.033 \left(\frac{2j\pi}{365} \right) \right) \quad (7.7)$$

where S_{sun} is the solar constant ($\text{J m}^{-2} \text{d}^{-1}$) and j the Julian day number. The ratio of potential and measured daily total radiation is called atmospheric transmission A_t (-). The proportion of diffuse radiation, I_{dif} (-), is derived from the atmospheric transmission by an empirical relationship (Spitter et al., 1986). Taking also into account that only 50 percent of the solar radiation is photosynthetically active, the diffuse photosynthetic active radiation PAR_{dif} ($\text{J m}^{-2} \text{d}^{-1}$) can thus be calculated by:

$$PAR_{\text{dif}} = 0.5 I_{\text{dif}} A_t S_{\text{sun}} \sin \beta_{\text{sun}} \quad (7.8)$$

The direct radiation flux, PAR_{dir} ($\text{J m}^{-2} \text{d}^{-1}$), is obtained by subtracting the diffuse part from the photosynthetically active radiation flux:

$$PAR_{\text{dir}} = PAR - PAR_{\text{dif}} \quad (7.9)$$

7.3.3 Radiation profiles within the canopy

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, ρ_{rad} (-), equals:

$$\rho_{\text{rad}} = \left(\frac{1 - \sqrt{1 - \sigma_{\text{leaf}}}}{1 + \sqrt{1 - \sigma_{\text{leaf}}}} \right) \left(\frac{2}{1 + 1.6 \sin \beta_{\text{sun}}} \right) \quad (7.10)$$

with σ_{leaf} the scattering coefficient of single leaves for visible radiation (-), which is taken to be 0.2. The first term of Eq. (7.10) denotes the reflection of a canopy of horizontal leaves and the second term is the approximate correction factor for a spherical leaf angle distribution. The fraction $(1 - \rho_{\text{rad}})$ of the incoming visible radiation is potentially available for absorption by the canopy.

Light intensity, adjusted for crop reflection, decreases approximately exponentially with leaf area index when going deeper into the canopy:

$$PAR_L = (1 - \rho_{\text{rad}}) PAR e^{-\kappa L} \quad (7.11)$$

where PAR_L is the net light intensity ($\text{J m}^{-2} \text{d}^{-1}$) at depth L , κ is the radiation extinction coefficient (-) and L is the cumulative leaf area index, ΣLAI ($\text{m}^2 \text{ leaf m}^{-2} \text{ ground}$), counted from the top of the canopy downwards.

The profiles of the net diffuse flux and the net flux caused by direct irradiance can be characterized analogously (Goudriaan, 1982). Diffuse and direct fluxes each attenuate at a different rate. For a spherical leaf angle distribution with leaves distributed randomly within the canopy volume, the extinction coefficients of the direct component of the direct flux, κ_{dir} (-), is approximated by (Goudriaan, 1977, 1982):

$$\kappa_{\text{dir}} = \frac{0.5}{\sin \beta_{\text{sun}}} \quad (7.12)$$

and the extinction coefficient of the diffuse flux, κ_{df} (-), is calculated as:

$$\kappa_{df} = \kappa_{dir} \sqrt{1 - \sigma_{leaf}} \quad (7.13)$$

In Eq. (7.12), the factor 0.5 represents the average projection on the ground surface of leaves showing a spherical angle distribution. Averaging $0.5/\sin\beta$ during a day with an overcast sky, gives a value of $\kappa_{dir} = 0.8$ (-). In SWAP, κ_{df} should be given as an input by the user. It's value can be measured directly under diffuse sky conditions. The average value is about 0.72 (-) (Goudriaan, 1977).

In many situations, the leaf angle distribution is not spherical. In the model, therefore, the actual 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.

On its way through the canopy, part of the direct flux is intercepted and scattered by the leaves; hence, the direct flux segregates into a diffused, scattered component and another component which remains direct. Attenuation of the direct component of the direct flux proceeds equally to the attenuation of light in a hypothetical canopy of black, non scattering leaves. The diffused component is obtained as the difference between the total direct flux and its direct component.

The decline of the radiation flux reflects the amount of absorption. The rate of absorption at a depth L in the canopy, $PAR_{L,a}$ ($J\ m^{-2}\ leaf\ d^{-1}$), is obtained by taking the derivative of Eq. (7.11) with respect to L :

$$PAR_{L,a} = \kappa(1 - \rho_{rad}) PAR e^{-\kappa L} \quad (7.14)$$

Similar expressions can be derived for the separate light components: the diffuse flux, the total direct radiation flux and the direct component of the direct radiation flux. The absorbed diffused component of the direct flux is obtained by subtracting the direct component from the total direct flux.

Two leaf area classes are distinguished: shaded leaf area and sunlit leaf area. The shaded leaf area absorbs the diffuse flux and the diffused component of the direct flux. The sunlit leaf area receives diffuse and direct radiation. At every horizon within the canopy, the intensity of the unobstructed direct beam equals its intensity above the crop.

<i>Model input for each crop</i>			
<i>Variable</i>	<i>Code</i>	<i>Description</i>	<i>Default</i>
κ_{df}	KDIF	extinction coefficient for diffuse visible light (-) (optional)	0.60
κ_{dir}	KDIR	extinction coefficient for direct visible light (-) (optional)	0.72

7.3.4 Instantaneous assimilation rates per leaf layer

The CO_2 assimilation rate of a canopy layer is obtained by substituting the absorbed amount of light energy into the assimilation-light response of single leaves. Of the two-parameter response functions, the asymptotic exponential function appears to be the most satisfactory (Peat, 1970):

$$A_L = A_{\max} \left(1 - e^{-\frac{\varepsilon_{\text{PAR}} \text{PAR}_{L,a}}{A_{\max}}} \right) \quad (7.15)$$

where A_L is the gross assimilation rate ($\text{kg CO}_2 \text{ m}^{-2} \text{ leaf d}^{-1}$), A_{\max} the gross assimilation rate at light saturation ($\text{kg CO}_2 \text{ m}^{-2} \text{ leaf d}^{-1}$), and ε_{PAR} the initial slope or light use efficiency ($\text{kg CO}_2 \text{ J}^{-1}$ absorbed).

Substitution into Eq. (7.15) the absorbed amount of radiation by shaded leaves and by sunlit leaves, yields the assimilation rates of sunlit and shaded leaves. The shaded leaf area receives the diffuse flux and the scattered component of the direct flux. The sunlit leaf area receives both diffuse and direct flux. Illumination intensity of sunlit leaves varies strongly with leaf angle. In the model, the assimilation rate of the sunlit leaf area is therefore integrated over the leaf angle distribution.

The assimilation rate per unit leaf area in a canopy, is the sum of the assimilation rates of sunlit and shaded leaves, taking into account their proportion in each layer. The proportion of sunlit leaf area at depth L in the canopy equals the proportion of the direct component of the direct flux reaching that depth. This proportion is calculated in analogy to Eq. (7.14), using the extinction coefficient of the direct radiation component.

Model input for each crop

<i>Variable Code</i>	<i>Description</i>
A_{\max} AMAX	maximum CO_2 assimilation rate as function of development stage (-)
ε_{PAR} EFF	light use efficiency ($\text{kg CO}_2 \text{ J}^{-1}$ adsorbed)

7.3.5 Daily gross assimilation rate of the canopy

The instantaneous rates per leaf layer need to be integrated over the canopy leaf area index and over the day. This is efficiently achieved with the Gaussian integration method (Press et al., 1989). This method specifies the discrete points at which function values have to be calculated, and the weighting factors with which the function values have to be multiplied in order to attain minimum deviation from analytical integration. A three-point algorithm evaluates the function at $0.1127a$, $0.5a$ and $0.8873a$ of the interval $(0,a)$, with weighting coefficients 1.0, 1.6 and 1.0, respectively. The Gaussian integration method is remarkable accurate in case of trigonometric (radiation) and exponential (light absorption) functions. WOFOST computes at three selected moments of the day incoming PAR just above the canopy. Using this radiation, assimilation is computed at three selected depths in the canopy (Spitters et al., 1989). Gaussian integration of these values results in the daily rate of potential gross CO_2 assimilation, A_{pgross} ($\text{kg CO}_2 \text{ ha}^{-1} \text{ d}^{-1}$).

Until now the assimilation has been 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. Other factors that may reduce the daily assimilation rate are typical crop characteristics, unfavourable temperatures and water stress.

Crop characteristics depend on the phenological crop stage. This is taken into account by specifying the maximum assimilation rate, A_{\max} ($\text{kg CO}_2 \text{ ha}^{-1} \text{ d}^{-1}$), as function of development stage.

A reduction factor f_{tday} (-), which is a function of the average daytime temperature T_{day} ($^{\circ}\text{C}$), accounts for sub-optimum temperatures. T_{day} is calculated by:

$$T_{\text{day}} = 0.75 T_{\max} + 0.25 T_{\min} \quad (7.16)$$

where T_{\max} and T_{\min} ($^{\circ}\text{C}$) are the daily maximum and minimum temperature, respectively.

The crop characteristics and the day temperature result in a reduction of A_{pgross} to A_{pgross}^1 ($\text{kg CO}_2 \text{ ha}^{-1} \text{ d}^{-1}$):

$$A_{\text{pgross}}^1 = \max(A_{\text{pgross}}, f_{\text{tday}}, A_{\max}) \quad (7.17)$$

In addition, low nighttime temperatures affect assimilation. At night, 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 assimilates accumulate in the plant and the assimilation rate diminishes and ultimately halts. In the model, this temperature effect is accounted for by a reduction factor $f_{7\min}$, which is a function of the minimum temperature during the last seven days.

Another important factors that may reduce assimilation, is water and/or salinity stress. WOFOST uses the ratio of actual transpiration and potential transpiration, T_a/T_p , as reduction coefficient.

Reduction due to low minimum temperatures, water stress, and salinity stress, and taking into account that for each kg CO_2 30/44 kg biomass (CH_2O) is formed, results in the following equation for the daily gross assimilation rate A_{gross} ($\text{kg ha}^{-1} \text{ d}^{-1}$):

$$A_{\text{gross}} = \frac{30}{40} f_{7\min} \frac{T_a}{T_p} A_{\text{pgross}}^1 \quad (7.18)$$

Model input for each crop

<i>Variable</i>	<i>Code</i>	<i>Description</i>
f_{tday}	TMPF	reduction factor of AMAX as function of average day temperature (-)
$f_{7\min}$	TMNF	reduction factor of AMAX as function of minimum day temperature (-)

7.3.6 Maintenance respiration

Some of the carbohydrates formed are respired to provide energy for maintaining the existing bio structures. 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.

The maintenance costs may be estimated from the quantities of proteins and minerals present in the biomass and from crop metabolic activity, as presented by De Wit et al. (1978). This method, however, requires information on the vegetation nitrogen and mineral

contents. Based on De Wit et al. (1978), typical values for the maintenance coefficients of various plant organs have been derived by Penning de Vries and Van Laar (1982). These coefficients should be specified by the user in WOFOST. According to this approach, the reference maintenance requirements R_{mref} ($\text{kg ha}^{-1} \text{d}^{-1}$) are proportional to the dry weights of the plant organs to be maintained:

$$R_{mref} = c_{m,leaf} W_{leaf} + c_{m,stem} W_{stem} + c_{m,stor} W_{stor} + c_{m,root} W_{root} \quad (7.19)$$

where $c_{m,i}$ denotes the maintenance coefficient of organ i ($\text{kg kg}^{-1} \text{d}^{-1}$) and W_i the organ dry weight (kg ha^{-1}).

The maintenance respiration rate still has to be corrected for senescence and temperature. The reduction factor for senescence f_{senes} (-) is crop specific and is defined as a function of development stage. 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 and Catsky, 1984; Penning de Vries and Van Laar, 1982). To be more flexible, the user may specify the increase factor of the respiration rate per 10°C temperature increase, Q_{10} (-):

$$R_m = f_{senes} R_{mref} Q_{10}^{\frac{T_{avg}-25}{10}} \quad (7.20)$$

where R_m is the actual maintenance respiration rate ($\text{kg ha}^{-1} \text{d}^{-1}$).

Thus, the maintenance respiration rate depends on the amount of dry matter in the various organs, the relative maintenance rate per organ and the temperature. We may assume that the vegetation will not be 'self-consuming' in terms of carbohydrates. Therefore the maintenance respiration rate cannot exceed the gross assimilation rate.

Gross assimilation rate A_{gross} minus maintenance respiration rate R_m results in the net assimilation rate A_{net} ($\text{kg ha}^{-1} \text{d}^{-1}$), the amount of carbohydrates available for conversion into structural material:

$$A_{net} = A_{gross} - R_m \quad \text{with} \quad A_{net} \geq 0 \quad (7.21)$$

Model input for each crop

<i>Variable</i>	<i>Code</i>	<i>Description</i>
$c_{m,leaf}$	RML	relative maintenance respiration rate of leaves ($\text{kg H}_2\text{O kg}^{-1} \text{d}^{-1}$)
$c_{m,stor}$	RMO	relative maintenance respiration rate of storage organs ($\text{kg H}_2\text{O kg}^{-1} \text{d}^{-1}$)
$c_{m,root}$	RMR	relative maintenance respiration rate of roots ($\text{kg H}_2\text{O kg}^{-1} \text{d}^{-1}$)
$c_{m,stem}$	RMS	relative maintenance respiration rate of stems ($\text{kg H}_2\text{O kg}^{-1} \text{d}^{-1}$)
f_{senes}	RFSE	reduction factor of senescence as function of development stage (-)
Q_{10}	Q10	relative increase in respiration rate with temperature (10°C^{-1})

7.3.7 Dry matter partitioning and growth respiration

The primary assimilates in excess of the maintenance costs, are available for conversion into structural plant material. 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 as a process of cut and paste, the scraps representing the weight lost in growth respiration.

The magnitude of growth respiration is determined by the composition of the end product formed (Penning de Vries et al., 1974). Thus the weight efficiency of conversion of primary photosynthates into structural plant material varies with the composition of that material. Fats and lignin are produced at high costs; structural carbohydrates and organic acids are relatively cheap. Proteins and nucleic acids form an intermediate group.

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 increase in total dry weight of the crop is partitioned over the plant organs: roots, leaves, stems and storage organs. This is correct simulation of what occurs during the vegetative phase. Storage organs, however, may not only be formed from current photosynthates but also from carbohydrates and proteins that have been stored temporarily in vegetative parts and that are redistributed during the reproductive stage. In the model, the latter process is not incorporated: the total growth of the crop is partitioned among the plant organs according to partitioning factors that are introduced as forcing functions; their values only change with the development stage of the crop.

In the model, average (crop specific) conversion factors $C_{e,i}$ (kg kg^{-1}) are used for leaf, storage organ, stem and root biomass. A weighted average, C_e (kg kg^{-1}), of these organ specific conversion factors is calculated by multiplying the organ specific values with the partitioning factors :

$$C_e = \frac{1}{\left(\frac{\xi_{\text{leaf}}}{C_{e,\text{leaf}}} + \frac{\xi_{\text{stor}}}{C_{e,\text{stor}}} + \frac{\xi_{\text{stem}}}{C_{e,\text{stem}}} \right) (1 - \xi_{\text{root}}) + \frac{\xi_{\text{root}}}{C_{e,\text{root}}}} \quad (7.22)$$

where ξ_i is the partitioning factor for organ i .

The gross dry matter growth rate w_{gross} ($\text{kg ha}^{-1} \text{d}^{-1}$) is related to the net assimilation rate A_{net} by:

$$w_{\text{gross}} = C_e A_{\text{net}} \quad (7.23)$$

Gross dry matter growth is first partitioned between shoots (leaves, stems and storage organs together) and roots:

$$w_{\text{gross,root}} = \xi_{\text{root}} w_{\text{gross}} \quad \text{and} \quad w_{\text{gross,sh}} = (1 - \xi_{\text{root}}) w_{\text{gross}} \quad (7.24)$$

where ξ_{root} is the partitioning factor for roots (-) and $w_{\text{gross,root}}$ and $w_{\text{gross,sh}}$ are the gross growing rates ($\text{kg ha}^{-1} \text{d}^{-1}$) of the roots and the shoots, respectively. The gross growth rate of leaves, stems and storage organs is simply the product of the gross dry matter growth rate of the shoots and the fraction allocated to these organs. The partitioning factors are a function of development stage and are crop specific. Mind that the sum of ξ_{leaf} , ξ_{stem} and ξ_{stor} at any development stage should be one!

Model input for each crop

<i>Variable</i>	<i>Code</i>	<i>Description</i>
ζ_{root}	FR	fraction of total dry matter increase partitioned to roots (-)
ζ_{leaf}	FL	fraction of total above ground dry matter increase part. to leaves (-)
ζ_{stem}	FS	fraction of total above ground dry matter increase part. to stems (-)
ζ_{stor}	FO	fraction of total above ground dry matter incr. part. to st. organs (-)
$C_{e,\text{leaf}}$	CVL	efficiency of conversion into leaves (kg kg ⁻¹)
$C_{e,\text{stor}}$	CVO	efficiency of conversion into storage organs (kg kg ⁻¹)
$C_{e,\text{root}}$	CVR	efficiency of conversion into roots (kg kg ⁻¹)
$C_{e,\text{stem}}$	CVS	efficiency of conversion into stems (kg kg ⁻¹)

7.3.8 Senescence

The death rate of storage organs is considered to be zero. The death rate of stem and roots 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 as specified by the user.

The death rate of leaves is more complicated. Leaf senescence occurs due to water stress, shading (high LAI), and also due to exceedance of the life span.

The potential death rate of leaves due to water stress $\zeta_{\text{leaf,water}}$ (kg ha⁻¹ d⁻¹) is calculated as:

$$\zeta_{\text{leaf,w}} = W_{\text{leaf}} \left(1 - \frac{T_a}{T_p} \right) \zeta_{\text{leaf,p}} \quad (7.25)$$

where W_{leaf} is the leaf dry matter weight (kg ha⁻¹), T_a and T_p are the actual and potential transpiration rates (cm d⁻¹), respectively, and $\zeta_{\text{leaf,p}}$ is the maximum relative death rate of leaves due to water stress (kg kg⁻¹ d⁻¹). The latter is crop specific and should be provided by the user.

A potential death rate due to self-shading, $\zeta_{\text{leaf,shade}}$ (kg ha⁻¹ d⁻¹), 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:

$$\zeta_{\text{leaf,shade}} = 0.03 W_{\text{leaf}} \left(\frac{\text{LAI} - \text{LAI}_c}{\text{LAI}_c} \right) \quad \text{with} \quad 0 < \left(\frac{\text{LAI} - \text{LAI}_c}{\text{LAI}_c} \right) < 1 \quad (7.26)$$

where LAI_c is the critical leaf area index (-).

LAI_c is set equal to $3.2/\kappa_{\text{df}}$, with κ_{df} the extinction coefficient (-) for diffuse radiation (Par. 7.4). Typical values for $\zeta_{\text{leaf,p}}$ and LAI_c are 0.03 d⁻¹ and 4 ha ha⁻¹, respectively (Spitters et al., 1989).

WOFOST uses the highest value of $\zeta_{\text{leaf,w}}$ and $\zeta_{\text{leaf,shade}}$ for the combined effect of water stress and mutual shading.

Leaves that have escaped from premature death due to water stress or mutual shading, inevitably die due to exceedance of the life span for leaves (i.e. physiologic ageing). Life span is defined as the maximum time a leaf can live at a constant temperature of 35°C. Life span is crop specific. A physiologic ageing factor, f_{age} (-), is calculated each day:

$$f_{\text{age}} = \frac{T - T_{\text{b,age}}}{35 - T_{\text{b,age}}} \quad \text{with} \quad f_{\text{age}} \geq 0 \quad (7.27)$$

with $T_{\text{b,age}}$ the lower threshold temperature for physiologic ageing (°C), which 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} (d):

$$P_{\text{age}}^{j+1} = P_{\text{age}}^j + f_{\text{age}} \Delta t \quad (7.28)$$

In order to correct for leaf senescence, the specific leaf area of each day, S_{la}^j (ha kg⁻¹), the growth of the dry matter weight of leaves per day, w_{leaf} , and the physiological age, P_{age} , are stored in three different arrays. The first element of the arrays represents the most recent day and the last element of the arrays represents the oldest day.

The weight of the leaves that have died during a day due to water stress or mutual shading 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, and the remainder is subtracted from the next leaf class. Emptying the oldest leaf class continues, until the original amount is dissipated completely or the remaining amount of leaves becomes zero.

Leaves may attain the age defined by the crop specific life span. However, they can not exceed this age. The model checks the leaf classes ages. The first class younger than the defined life span becomes the oldest class.

Model input for each crop

<i>Variable</i>	<i>Code</i>	<i>Description</i>
	RDRR	relative death rate of roots as function of development stage (kg kg ⁻¹ d ⁻¹)
	RDRR	relative death rate of stems as function of development stage (kg kg ⁻¹ d ⁻¹)
$\zeta_{\text{leaf,p}}$	PERDL	maximum relative death rate of leaves due to water stress (d ⁻¹)
$T_{\text{b,age}}$	TBASE	lower threshold temperature for ageing of leaves (°C)
	SPAN	life span of leaves at optimum growth conditions (d)

7.3.9 Net growth

The initial amount of total dry crop weight should be provided by the user. This amount is multiplied by the partitioning factors, ξ_i , to yield the dry weight values at emergence.

The net growth rates of the plant organs, $w_{\text{net},i}$ (kg ha⁻¹ d⁻¹) result from the gross growth rates (Par. 7.8) and the senescence rates, ζ_i (kg kg⁻¹ d⁻¹):

$$w_{\text{net},i} = w_{\text{gross},i} - \zeta_i W_i \quad (7.29)$$

By integrating $w_{\text{net},i}$ over time, the dry matter weight of organ i , W_i (kg ha^{-1}), is calculated.

An exception has to be made for the growth of leaves. In the initial stage, 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. For a relative wide range of temperatures the growth rate responds more or less linearly to temperature (Hunt et al., 1985; Causton and Venus, 1981; Van Dobben, 1962). The growth rate of the leaf area index, w_{LAI} ($\text{ha ha}^{-1} \text{d}^{-1}$), in this so-called exponential stage, is described by:

$$w_{\text{LAI}} = \text{LAI} w_{\text{LAI,max}} T_{\text{eff}} \quad (7.30)$$

where $w_{\text{LAI,max}}$ is the maximum relative increase of leaf area index ($^{\circ}\text{C}^{-1} \text{d}^{-1}$).

WOFOST assumes that the exponential growth rate of leaf area index will continue until it equals the assimilation limited growth rate of the leaf area index. During this second, source limited growth stage, w_{LAI} is described by:

$$w_{\text{LAI}} = w_{\text{net,leaf}} S_{\text{la}} \quad (7.31)$$

where S_{la} is the specific leaf area (ha kg^{-1}).

The green parts of stems and storage organs, may absorb a substantial amount of radiation. Therefore the so-called green area index GAI_i (ha ha^{-1}) should be added to the leaf area index. The green area index of the stems and storage organs, are calculated from the dry matter weights of the organs:

$$GAI_i = S_{\text{ga},i} W_i \quad (7.32)$$

with $S_{\text{ga},i}$ the specific green area (ha kg^{-1}) of either stems or storage organ. $S_{\text{ga},i}$ are crop specific and should be provided by the user.

Model input for each crop

<i>Variable</i>	<i>Code</i>	<i>Description</i>
$w_{\text{LAI,max}}$	RGRLAI	maximum relative increase of leaf area index ($^{\circ}\text{C}^{-1} \text{d}^{-1}$)
S_{la}	SLA	specific leaf area as function of development stage (ha kg^{-1})
$S_{\text{ga, stor}}$	SPA	specific pod area (ha kg^{-1})
$S_{\text{ga, stem}}$	SSA	specific stem area (ha kg^{-1})
	TDWI	initial total crop dry weight (kg ha^{-1})
	LAIEM	leaf area index at emergence ($\text{m}^2 \text{m}^{-2}$)

7.3.10 Root growth

Root extension is computed in a straightforward way. The user needs to specify the initial rooting depth, the maximum rooting depth as determined by the crop and by the soil, and the maximum daily increase in rooting depth, $d_{\text{root,max}}$ (cm). Daily increase in rooting depth is equal to the maximum daily increase, unless maximum rooting depth is reached or no assimilates are available for root growth:

$$D_{\text{root}}^{j+1} = D_{\text{root}}^j + d_{\text{root,max}} \quad \text{if} \quad D_{\text{root}}^{j+1} \leq D_{\text{root,max}} \quad \text{and} \quad w_{\text{net,root}} \geq 0 \quad (7.33)$$

where D_{root}^j is the rooting depth (cm) at day j .

Model input for each crop

<i>Variable</i>	<i>Code</i>	<i>Description</i>
	RDI	initial rooting depth (cm)
$D_{\text{root, max}}$	RDC	maximum rooting depth of particular crop (cm)
$d_{\text{root, max}}$	RRI	maximum daily increase in rooting depth (cm d ⁻¹)