The APSIM-Wheat Module (7.5 R3008)

January 8, 2015

This documentation is compiled from the source codes and internal documents of APSIM-Wheat module by Bangyou Zheng (bangyou.zheng@csiro.au), Karine Chenu (karine.chenu@uq.edu.au), Alastair Doherty (alastair.doherty@daff.qld.gov.au) and Scott Chapman (scott.chapman@csiro.au).

Contents

1 Scope of the APSIM-Wheat module

The APSIM-Wheat module simulates the wheat growth and development of a wheat crop in a daily time-step on an area basis (per square meter, not per single plant). In this module, the wheat crop Wheat growth and development responds to weather (radiation, temperature), soil water and soil nitrogen, and management practices. The wheat module returns information on its soil water and nitrogen uptake to the soil water and nitrogen modules on a daily basis for reset of these systems. Information on crop cover is also provided to the water balance module for calculation of evaporation rates and runoff. Wheat stover and root residues are 'passed' from wheat to the surface residue and soil nitrogen modules, respectively at the harvest of the wheat crop.

The approaches used in modeling crop processes balance the need for a comprehensive description of the observed variation in crop performance over diverse production environments and the need to avoid reductionist approaches of ever-greater complexity with large numbers of parameters that are difficult to measure.

A list of the module outputs is provided in the Wheat module outputs section below. Basically the module simulates phenological development, leaf area growth expansion, biomass and N concentration of different crop components (`Leaf`, `Stem`, `Root` and `Grain`) on a daily basis. It also predicts grain size and grain number.

2 APSIM-Wheat history

APSIM-Wheat has been developed from a combination of the approaches used in previous APSIM wheat modules:Asseng et al. (1998a,b); Wang et al. (2003); Meinke et al. (1997, 1998). The current version of the model is implemented within the APSIM Plant model framework which is currently used for other crops such as grain legumes and canola. Most of the model constants (species-specific) and parameters (cultivar specific) are externalized from the code (wheat.xml file).

3 Phenology

There are 11 phases in APSIM-Wheat module (Figure 1). The timing of each phase (except from sowing to germination, which is driven by sowing depth and thermal time) is determined by the accumulation of thermal time (TT) adjusted for other factors which vary with the phase considered (e.g. vernalisation, photoperiod, N). The length of each phase is determined by a fixed thermal time (thermal time target), which is specified by tt_<phase_name> in wheat.xml. Most parameters of thermal time targets are cultivar-specific.

3.1 Thermal time calculation

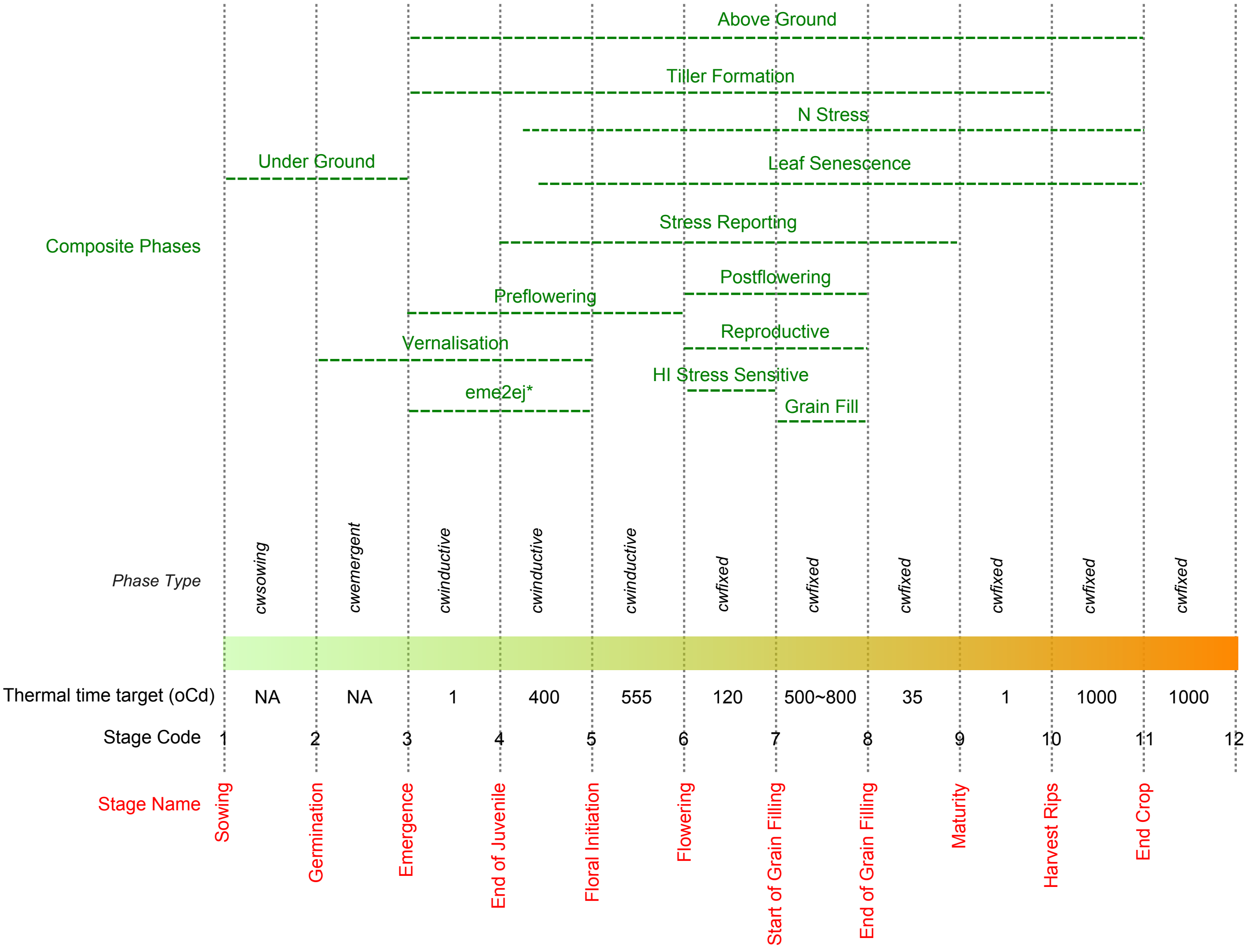
The daily thermal time (ΔTT) is calculated from the daily average of maximum and minimum crown temperatures, and is adjusted by genetic and environmental factors. Hence, the duration of phases between emergence and floral initiation is adjusted for photoperiod and vernalisation, using the cultivar-specific parameters "photoperiod factor" (f_D, Equation 8) and "vernalisation factor" (f_V, Equation 12). Other environmental factors include soil water stress ($f_{W,pheno}$, Equation 94), nitrogen stress ($f_{N,pheno}$, Equation 106) and phosphorus stress ($f_{P,pheno}$, section 13) in all phases except from Sowing to Emergence (See details below), but they are all parametrized to have to effect in the current released APSIM-Wheat. All factors are bound from 0 to 1.

Crown temperatures are simulated according to the original routines in CERES-Wheat and correspond to air temperatures for non-freezing temperatures. The maximum and minimum crown temperatures (T_{cmax} and T_{cmin}) are calculated according to the maximum and minimum air temperature (T_{max} and T_{min}), respectively.

$$T_{cmax} = \begin{cases} 2 + T_{max}(0.4 + 0.0018(H_{snow} - 15)^2) & T_{max} < 0 \\ T_{max} & T_{max} \geq 0 \end{cases} \tag{1}$$

$$T_{cmin} = \begin{cases} 2 + T_{min}(0.4 + 0.0018(H_{snow} - 15)^2) & T_{min} < 0 \\ T_{min} & T_{min} \geq 0 \end{cases} \tag{2}$$

where H_{snow} is the snow depth (cm). The default value of H_{snow} is set to zero in the source codes (Figure 2). For more detail information about Equation 1 and Equation 2, please see the function `CWVernalPhase::vernalisation` in the APSIM code.



* The photoperiod and vernalisation factor were calculated in these phases

Figure 1: Phenology in the APSIM_ Wheat module. Targets are expressed in adjusted thermal time (Equation 6) and are cultivar-specific parameters. The values given for the reference genotype Hartog.

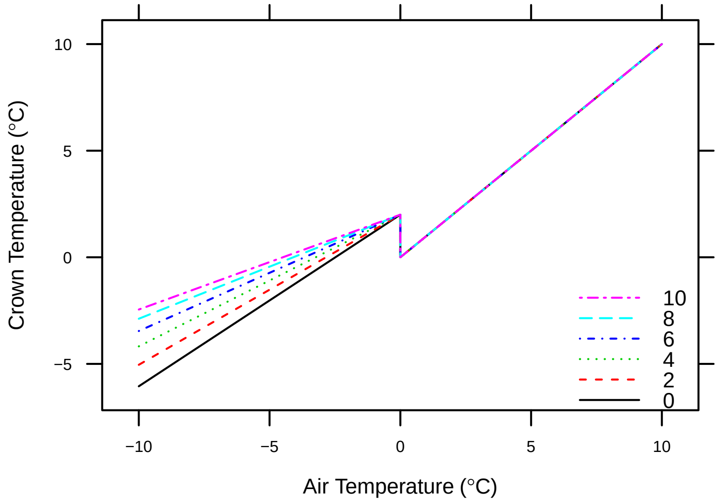


Figure 2: Crown temperature (T_c) in response to air temperature (T) for different snow depth (H_{snow}) in APSIM-Wheat. In the released APSIM version, H_{snow} equals zero cm.

The daily crown mean temperature (T_c) is calculated by the maximum (T_{cmax}) and minimum (T_{cmin}) crown temperature.

$$T_c = \frac{T_{cmax} + T_{cmin}}{2} \tag{3}$$

Daily thermal time (ΔTT) is calculated based on daily mean crown temperature, using three cardinal temperatures (Figure 3). The default values of the cardinal temperatures and relative thermal time are specified by x_temp (0, 26, 34) and y_tt (0, 26, 0), respectively, in the wheat.xml (Figure 3). Other crop modules in APSIM calculate thermal time every 3 hours.

$$\Delta TT = \begin{cases} T_c & 0 < T_c \leq 26 \\ \frac{26}{8}(34 - T_c) & 26 < T_c \leq 34 \\ 0 & T_c \leq 0 \text{ or } T_c > 34 \end{cases} \tag{4}$$

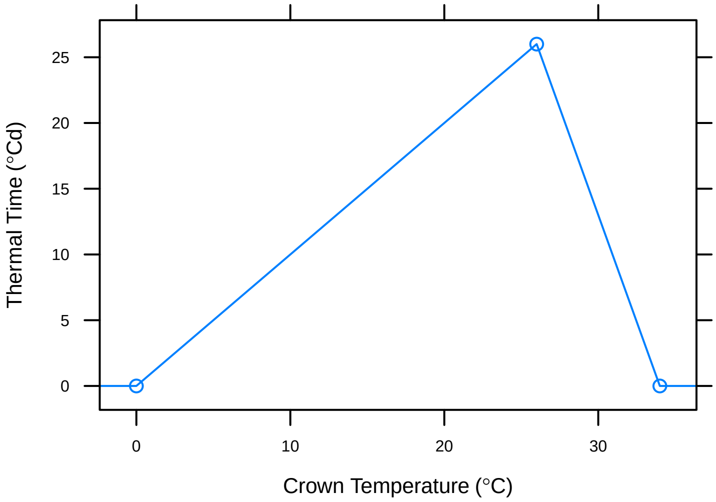


Figure 3: Daily thermal time (ΔTT) in response to daily crown temperature (T_c) in APSIM-Wheat.

For each phenological stage, the daily thermal time (TT') is summed from the start of phase and can be reduced by photoperiod (f_D, Equation 8) and vernalisation factor (f_V, Equation 12) and also dependent on environmental factors (photoperiod and temperature). The environmental factors include soil water stress ($f_{W,pheno}$, Equation 94), nitrogen stress ($f_{N,pheno}$, Equation 106) and phosphorus stress ($f_{P,pheno}$, section 13). The next phenological stage occurs when this adjusted thermal time (TT' in Equation 5) reaches the "target thermal time" for the stage considered Figure 1.

$$TT' = \sum[\Delta TT \times \min(f_D,\ f_V) \times \min(f_{W,pheno},\ f_{N,pheno},\ f_{P,pheno})] \tag{5}$$

In the current released version, soil water, nitrogen and phosphorus stresses have no effect on phenological development (i.e. parameters $f_{W,pheno} = f_{P,pheno} = 1$ Equation 94, and $f_{N,pheno}$ has values typically above 1 Equation 106). So, Equation 5 is reduced to

$$TT' = \sum[\Delta TT \times \min(f_D,\ f_V)] \tag{6}$$

In the output variables of wheat module, TT' from the start of each phase is named as "ttafter<phasename>". For example, the output variable "ttaftersowing" is not the actual thermal time after sowing, but the thermal time adjusted for genetic and environmental factors.

3.2 Sowing-germination phase

The seed germination is determined by soil water availability in the seeded layer (specified by `pesw_germ` with default value 0 mm). The crop will die if germination has not occurred before a certain period, defined by `days_germ_limit` in wheat.xml, which has a default value of 40 d.

3.3 Germination-emergence phase

The germination to emergence phase includes an effect of the depth of sowing (D_{seed}) on the thermal time target. The phase is comprised of an initial period of fixed thermal time during which shoot elongation is slow (the lag phase, T_{lag}) and a linear period, where the rate of shoot elongation (r_e, C d mm^{-1}) towards the soil surface is linearly related to air temperature. Then, the period of emergence (T_{emer}) is calculated by

$$T_{emer} = T_{lag} + r_e D_{seed} \tag{7}$$

The crop will die if emergence has not occurred before a certain period, defined by `tt_emerg_limit` in wheat.xml, which has a default value of 300°C d.

Most studies on seedling germination have simply recorded the accumulated thermal time between germination and 50% emergence from a given sowing depth. For the purposes of model parametrization the value of T_{lag} (`shoot_lag`) has been assumed to be around 40 °C d, while r_e (`shoot_rate`) has been derived from studies where thermal time to emergence was measured and where sowing depth was known and it is set to 1.5 °C d per mm. This means that at a sowing depth of 40 mm emergence occurs 100°C d after germination ($40 + 1.5 \times 40$).

There is the capability of increasing the time taken to reach emergence due to a dry soil layer in which the seed is germinating, through the relationship between `fasw_emerg` and `rel_emerg_rate`. Currently this effect is turned off in the Wheat.xml file.

3.4 Photoperiod impact on phenology

Photoperiod is calculated from day of year and latitude using standard astronomical equations accounting for civil twilight using the parameter twilight, which is assumed to be -6° (civil twilight) in wheat.xml. Twilight is defined as the interval between sunrise or sunset and the time when the true center of the sun is 6° below the horizon. Other crop modules of APSIM have used -2.2° as twilight parameters. In APSIM, the photoperiod affects phenology between emergence and floral initiation (Figure 1). During this period, thermal time is affected by a photoperiod factor (f_D in Equation 5 and Equation 6) that is calculated by

$$f_D = 1 - 0.002 R_p (20 - L_P)^2 \tag{8}$$

where L_P is the day length (h), R_P is the sensitivities to photoperiod which is cultivar-specific and is specified by `photop_sens` in wheat.xml. The default value of R_P is 3 (Figure 4).

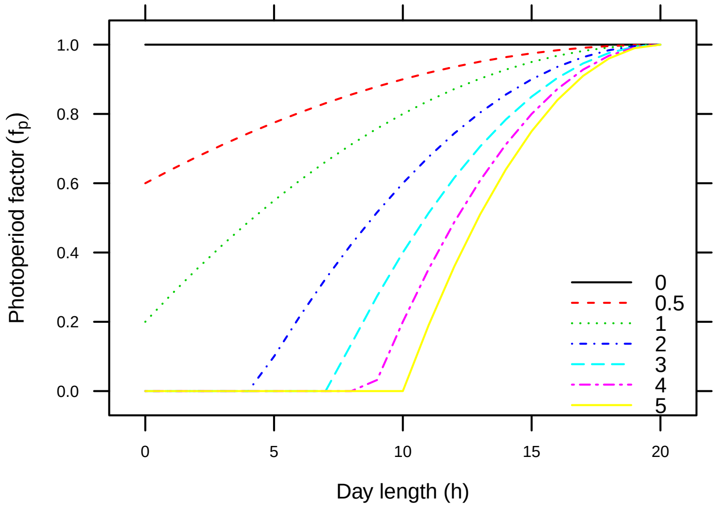


Figure 4: Relationship between photoperiod factor (f_D) and day length (L_P) with different sensitivities to photoperiod (R_p). The default value of R_P is 3.

3.5 Vernalisation impact on phenology

In APSIM, vernalisation effects phenology between emergence and floral initiation (Figure 1). During this period, thermal time is affected by a vernalisation factor (f_V in Equation 5 and Equation 6).

Vernalisation is simulated from daily average crown temperature (T_c), daily maximum (T_{max}) and minimum (T_{min}) temperatures using the original CERES approach (Figure 5).

$$\Delta V = \min(1.4 - 0.0778T_c,\ 0.5 + 13.44\frac{T_c}{(T_{max} - T_{min} + 3)^2}) \quad \text{when, } T_{max} < 30\,^\circ\text{C and } T_{min} < 15\,^\circ\text{C} \tag{9}$$

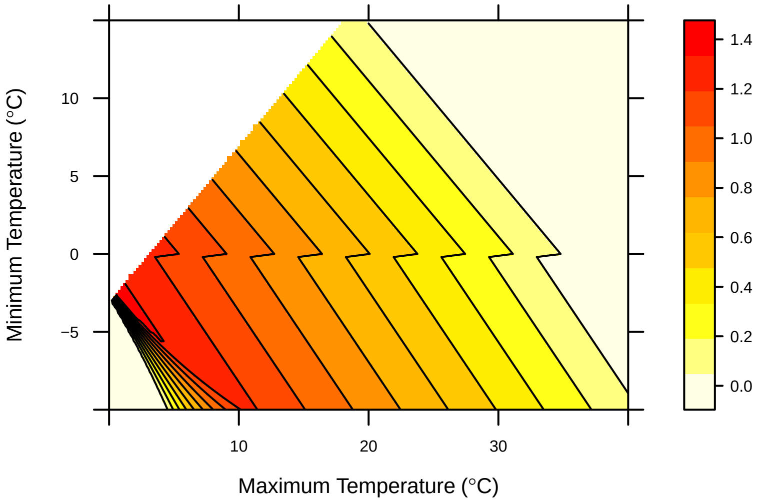


Figure 5: Relationship between vernalisation (ΔV) and maximum (T_{max}) and minimum (T_{min}) temperature.

Devernalisation can occur if daily T_{max} is above 30 °C and the total vernalisation (V) is less than 10 (Figure 6).

$$\Delta V_d = \min(0.5(T_{max} - 30),\ V) \quad \text{when, } T_{max} > 30\,^\circ\text{C and } V < 10 \tag{10}$$

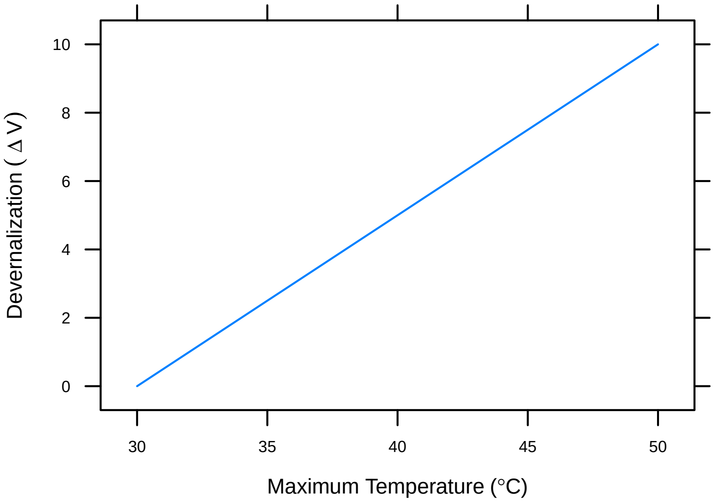


Figure 6: Relationship between devernalisation (ΔV_d) and maximum temperature (T_{max}) when the total vernalisation (V) is less than 10.

The total vernalisation (V) is calculated by summing daily vernalisation and devernalisation from Germination to Floral initiation (Composite phase `Vernalisation` in Figure 1).

$$V = \sum(\Delta V - \Delta V_d) \tag{11}$$

However, the vernalisation factor (f_v) is calculated just from Emergence to Floral initiation (Composite phases **eme2ej** in Fig. 1).

$$f_V = 1 - (0.0054545 R_V + 0.0003) \times (50 - V) \tag{12}$$

where R_V is the sensitivities to vernalisation, which is cultivar-specific and is specified by `vern_sens` in wheat.xml. The default value of R_V is 1.5 (Figure 7)

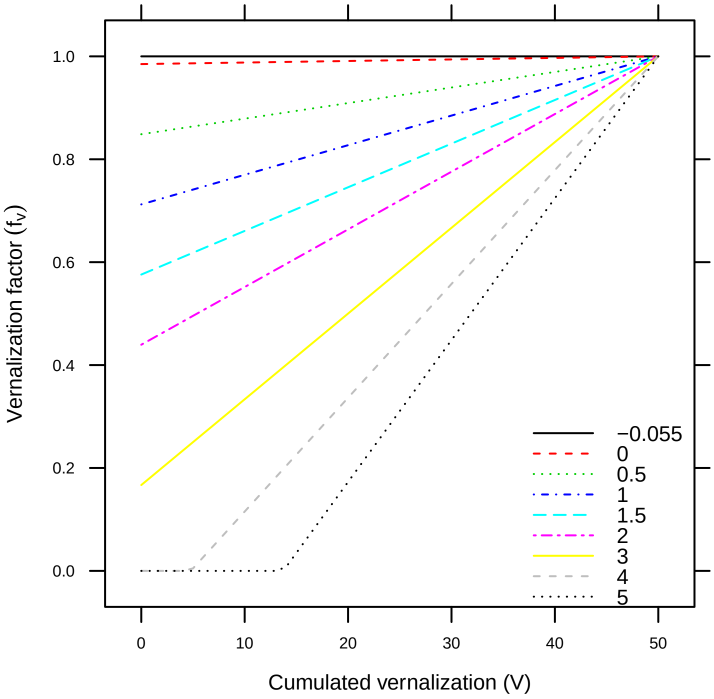


Figure 7: Relationship between cumulated vernalisation (V) and vernalisation factor (f_V) and for different sensitivities to vernalisation (R_V). The default value of R_V is 1.5.

4 Biomass accumulation (Photosynthesis)

The daily biomass accumulation (ΔQ) corresponds to dry-matter above-ground biomass, and is calculated as a potential biomass accumulation resulting from radiation interception (ΔQ_r, Equation 13) that is limited by soil water deficiency (ΔQ_w, Equation 30).

4.1 Potential biomass accumulation from radiation use efficiency

The radiation-limited dry-biomass accumulation (ΔQ_r) is calculated by the intercepted radiation (I), radiation use efficiency (RUE), diffuse factor (f_d, section 4.1.3), stress factor (f_s, Equation 18) and carbon dioxide factor (f_c, Equation 22).

$$\Delta Q_r = I \times RUE \times f_d \times f_s \times f_c \tag{13}$$

where f_d, f_s and f_c are defined in the wheat.xml file. In the current version of APSIM-Wheat, only `Leaf` produces photosynthate. Diffuse factor (f_d) equals to 1 (section 4.1.3), so that Equation 13 can be:

$$\Delta Q_r = I \times RUE \times f_s \times f_c \tag{14}$$

4.1.1 Radiation interception

Radiation interception is calculated from the leaf area index (LAI, m^2 m^{-2}) and the extinction coefficient (k) (Monsi and Saeki, 2005).

$$I = I_0(1 - \exp(-k \times LAI \times f_h)/f_h) \tag{15}$$

where I_0 is the total radiation at the top of the canopy (MJ) which is directly imported from weather records; f_h is light interception modified to give hedge-row effect with skip row. f_h could be calculated based on the canopy width, but is not used in the current version of APSIM (i.e. $f_h = 1$). So, Equation 15 is reduced to.

$$I = I_0(1 - \exp(-k \times LAI)) \tag{16}$$

Extinction coefficient (k) varies with row spacing,

$$k = h_e(W_r) \tag{17}$$

where W_r is the row spacing which is specified by the user (in the APSIM interface, the .sim or .apsim file); h_e is a function of rowing spacing which is defined for both green leaf and dead leaves by parameters `x_row_spacing`, `y_extinct_coef` in the wheat.xml file (Figure 8) and is linearly interpolated by APSIM. In the current version of APSIM-Wheat, no impact of row spacing is considered (Figure 8)

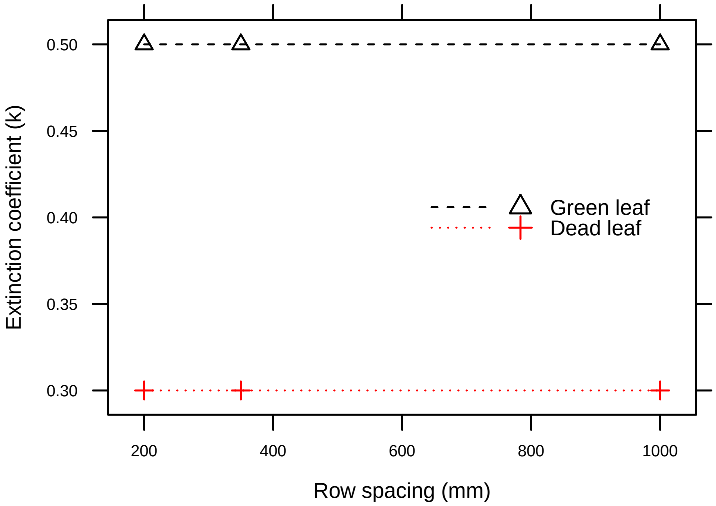


Figure 8: Values of extinction coefficient for different row spacings.

4.1.2 Radiation use efficiency

RUE (g MJ^{-1}) is a function of growth stages which is defined by parameters `x_stage_rue` and `y_rue` in wheat.xml (Figure 9) and linearly interpolated by APSIM. In the current version of APSIM-Wheat, RUE equal to 1.24 from emergence to the end of grain-filling and does not vary as a function of daily incident radiation as in the model NWHEAT.

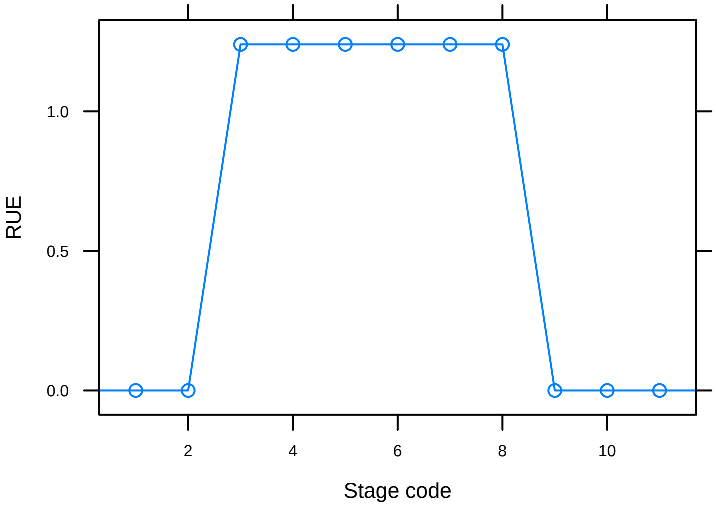


Figure 9: Radiation use efficiency (RUE) for different growth stages.

4.1.3 Stress factor (Temperature, nitrogen, phosphorus (not applied), oxygen (not applied))

Actual daily radiation-limited biomass accumulation can be reduced by a stress factor (f_s, Equation 13 and Equation 14). This stress factor is the minimum value of a temperature factor ($f_{T,\ photo}$, Equation 20), a nitrogen factor ($f_{N\ photo}$, Equation 107), a phosphorus factor ($f_{P\ photo}$) and an oxygen factor ($f_{O\ photo}$).

$$f_s = \min(f_{T,\ photo},\ f_{N,\ photo},\ f_{P,\ photo},\ f_{O,\ photo}) \tag{18}$$

No phosphorus stress $f_{P,photo}$ and oxygen stress $f_{O,photo}$ are applied in the current version of APSIM-Wheat. So, Equation 18 is reduced to

$$f_s = \min(f_{T,\ photo},\ f_{N,\ photo}) \tag{19}$$

The temperature factor $f_{T,\ photo}$ is a function of the daily mean temperature and is defined by parameters `x_ave_temp` and `y_stress_photo` in the wheat.xml (Figure 10). Values are linearly interpolated by APSIM. The temperature stress is applied from sowing to harvest.

$$f_{T,\ photo} = h_{T,\ photo}(\frac{T_{max} + T_{min}}{2}) \tag{20}$$

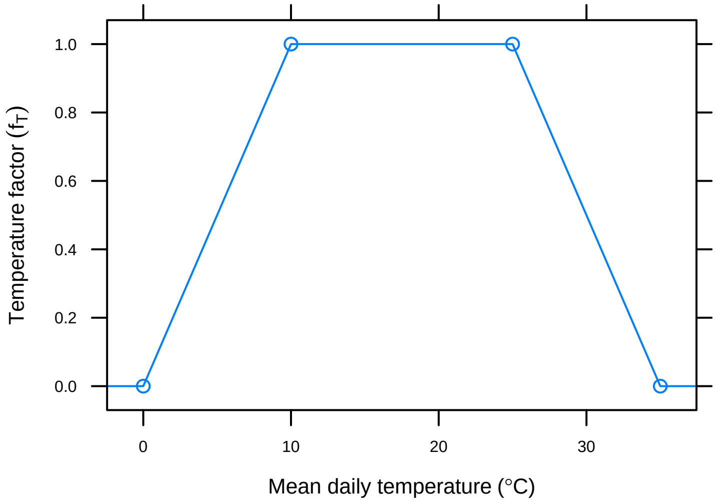


Figure 10: Temperature factor in response to mean daily temperature.

The nitrogen factor $f_{N,photo}$ is determined by the difference between leaf nitrogen concentration and leaf minimum and critical nitrogen concentration.

$$f_{N,photo} = R_{N,photo} \sum_{leaf} \frac{C_N - C_{N,\,min}}{C_{N,\,crit} - C_{N,\,min}} \tag{21}$$

where C_N is the nitrogen concentration of `Leaf` parts; $R_{N,\,expan}$ is multiplier for nitrogen deficit effect on phenology which is specified by `N_fact_photo` in the wheat.xml and default value is 1.5.

The CO_2 factor For C3 plants (like wheat), the CO_2 factor of APSIM is calculated by a function of environmental CO_2 concentration (C, ppm) and daily mean temperature (T_{mean}) as published by Reyenga et al. (1999)

$$f_c = \frac{(C - C_i)(350 + 2C_i)}{(C + 2C_i)(350 - C_i)} \tag{22}$$

where C_i is the temperature dependent CO_2 compensation point (ppm) and is derived from the following function.

$$C_i = \frac{163 - T_{mean}}{5 - 0.1T_{mean}} \tag{23}$$

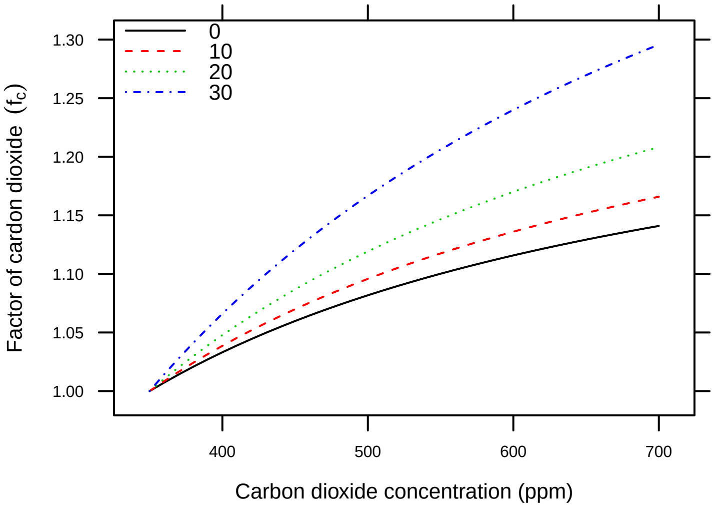


Figure 11: CO_2 factor in response to the CO_2 level (C) for different mean air temperatures.

Diffuse factor (not used in the current version) The daily diffuse fraction was calculated using the functions suggested by Roderick (1999):

$$\begin{cases} \frac{R_d}{R_s} = Y_0 & for\ \frac{R_s}{R_o} \le X_0 \\ \frac{R_d}{R_s} = A_0 + A_1\frac{R_s}{R_o} & for\ X_0 < \frac{R_s}{R_o} \le X_1 \\ \frac{R_d}{R_s} = Y_1 & for\ \frac{R_s}{R_o} > X_1 \end{cases} \tag{24}$$

where

$$\begin{gathered} A_0 = Y_1 - A_1 X_1 \\ A_1 = \frac{Y_1 - Y_0}{X_1 - X_0} \end{gathered} \tag{25}$$

where R_o is the daily extra-terrestrial solar irradiance (i.e. top of the atmosphere); R_d and R_s are the daily diffuse and global solar irradiance at the surface, respectively. X_0, X_1, Y_0 and Y_1 are four empirical parameters.

$$\begin{gathered} X_0 = 0.26, \qquad Y_0 = 0.96, \qquad Y_1 = 0.05, \ and \\ X_1 = 0.80 - 0.0017|\varphi| + 0.000044|\varphi|^2 \end{gathered} \tag{26}$$

where φ is latitude.

R_o is derived from this function

$$R_0 = \frac{86400 \times 1360 \times (\varpi \times \sin(\varphi) \times \sin(\theta) + \cos(\varphi) \times \cos(\theta) \times \sin(\varpi_0))}{1000000\pi} \tag{27}$$

where ϖ_0 is the time of sunrise and sunset, which derives from any solar declination (θ) and latitude (φ) in terms of local solar time when sunrise and sunset actually occur (`http://en.wikipedia.org/wiki/Sunrise_equation`)

$$\varpi_0 = \arccos(-\tan(\varphi)\tan(\theta)) \tag{28}$$

Solar declination (θ) can be calculated by

$$\theta = 23.45\sin(\frac{2\pi}{365.25}(N - 82.25)) \tag{29}$$

where N is day of year.

f_d is calculated by a function of the diffuse fraction which is not implemented in current wheat module, (i.e. $f_d = 1$).

4.2 Actual daily biomass accumulation

The actual daily biomass accumulation (ΔQ) results from water limitation applied on the potential radiation-driven biomass accumulation (ΔQ_r). This water-limited biomass (ΔQ_w) is a function of the ratio between the daily water uptake (W_u, Equation 92) and demand (W_d, Equation 31) capped by

$$\Delta Q_w = \Delta Q_r f_{w,photo} = \Delta Q_r \frac{W_u}{W_d} \tag{30}$$

where $f_{w,photo}$ is the water stress factor affecting photosynthesis (Equation 95); W_u is the actual daily water uptake from the root system (which corresponds to the soil water supply (W_s) capped by W_d), W_d is the soil water demand of Leaf and Head parts (section 11).

When the soil water is non-limiting ($f_{w,photo} = 1$, i.e. $W_d \geq W_s$), biomass accumulation is limited by the radiation ($\Delta Q = \Delta Q_r$, Equation 32). When the soil water is limiting, biomass accumulation is limited by water supply ($\Delta Q = \Delta Q_w$).

The water demand (W_d, in mm) corresponds to the amount of water the crop would have transpired in the absence of soil water constraint, and is calculated from the potential biomass accumulation from RUE (ΔQ_r, Equation 13). Following Sinclair (1986), transpiration demand is modeled as a function of the current day's crop growth rate, estimated by the potential biomass accumulation associated with intercepted radiation (ΔQ_r, see Equation 13), divided by the transpiration efficiency.

$$W_d = \frac{\Delta Q_r - R}{TE} \tag{31}$$

where R is respiration rate and equals to zero in the current version of APSIM-Wheat, TE is transpiration efficiency (Equation 87). See section 11 for more details about water demand and supply.

The daily biomass accumulation (ΔQ) corresponds to dry matter above ground biomass is limited by the radiation interception (ΔQ_r, Equation 13) or by soil water deficiency (ΔQ_w, Equation 96), so that daily biomass accumulation can be expressed as:

$$\Delta Q = \begin{cases} \Delta Q_r & W_u = W_d \\ \Delta Q_w & W_u < W_d \end{cases} \tag{32}$$

where W_s is water supply, W_d is the soil water demand from the shoot, limited by radiation interception (subsection 11.1). In the current APSIM-Wheat, W_d is actually only directly affected by the soil water demand of the leaf (subsection 11.1). W_u and W_d are calculated by soil module of APSIM.

5 Biomass partitioning and re-translocation

5.1 Biomass partitioning

In the wheat module, wheat is divided into four components or parts: `Root`, `Heat`, `Leaf` and `Stem` (Figure 12), and is derived from a more generic plant module (meaning that it has some parts not used or has a terminology, better adapted to other crops). `Leaf` includes only leaf blades. `Stem` is defined in a functional rather than a morphological manner and includes plant stems, leaf sheaths and stem-like petioles (not applicable for wheat). `Head` is divided into `Grain` and `Pod` (which correspond to spike without the grain). Then grain are separated into `Meal` and `Oil` (not used). The structure of wheat parts is shown in Figure 12.

On the day of emergence, biomass in plant parts (`Root`, `Head`, `Leaf`, `Stem`, `Pod`, `Meal` and `Oil`) are initialized by `root_dm_init` (set at 0.01 g plant^{-1} in the wheat.xml file), `leaf_dm_init` (0.003 g plant^{-1}), `stem_dm_init` (0.0016 g plant^{-1}), `pod_dm_init` (0 g plant^{-1}), `meal_dm_init` (0 g plant^{-1}), `oil_dm_init` (0 g plant^{-1}), respectively. Daily biomass production (Equation 32) is then partitioned to different plant parts in different ratios that vary with crop stage. Overall, Root biomass are calculated with a shoot:root ratio from the above-ground biomass (ΔQ; Figure 13). Then the above-ground biomass are partitioned into the different plant parts hierarchically, with biomass being attributed first to `Head`, then `Leaf` and finally `Stem`. This means that all parts might not have the biomass demand satisfied if the biomass production is limited.

5.2 Biomass partitioning to `Root`

Firstly, some biomass are allocated to the root as a ratio of daily available biomass (ΔQ, Equation 13). The so-called 'magic' fraction of biomass going to `Root` is calculated from a stage-dependent function, but is independent

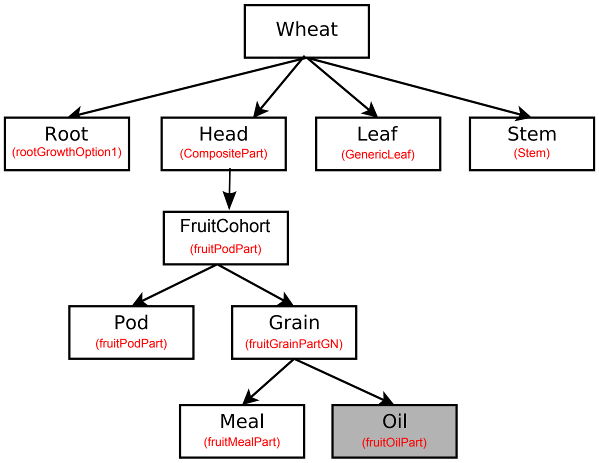


Figure 12: The hierarchical structure of wheat parts. Texts in the parentheses are classes of parts. The gray box indicates a plant part not used in wheat.

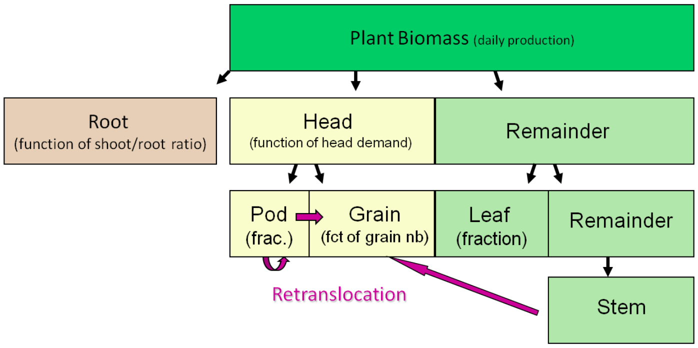


Figure 13: Biomass partition rules in the APSIM-Wheat module. Texts in the parentheses are partitioning methods of different organ types. The above-ground biomass (ΔQ) is used to calculate `Root` *biomass based on a shoot:root ratio, and is then partition to (1)* `Head` *based on the demand from* `Pod` *and* `Grain`*, and then (2)* `Leaf` *(proportion of the remaining biomass), and (3)* `Stem`*. Re-translocation occurs during grain filling, when the biomass accumulation doesn't satisfy* `Head` *demand. Biomass from* `Stem` *and* `Pod` *are then used to satisfy the* `Head` *demand (*`Pod` *and* `Grain`*).*

on pedo-climatic factors (Figure 14). All biomass in the `Root` is considered as structural fraction, meaning that it cannot be re-translocated to other parts later on.

$$\Delta Q_{root} = \Delta Q \times R_{Root:Shoot} \tag{33}$$

where ΔQ_{root} is the daily increment in `Root` biomass; and $R_{Root:Shoot}$ is the ratio root:shoot biomass, which is defined by `x_stax_stage_no_partition` and `y_ratio_root_shoot` in wheat.xml (Figure 14).

(which is specified in wheat.xml)

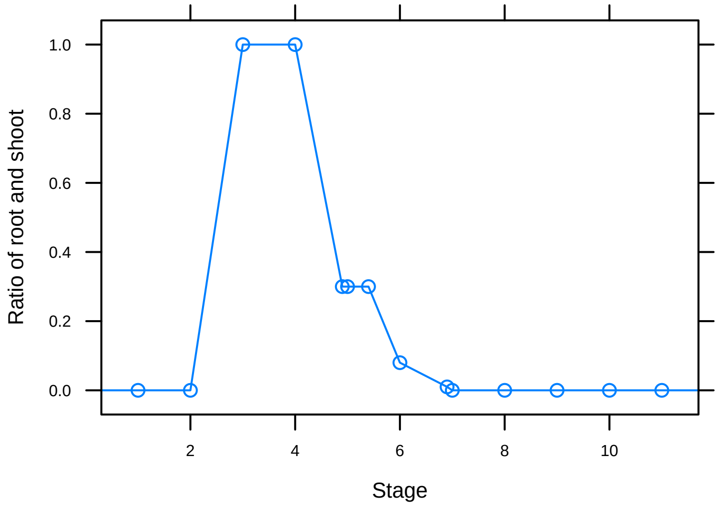


Figure 14: Relationship between ratio of root and shoot and growth stage.

5.3 Biomass partitioning to **`Head`** (**`Pod`**, **`Meal`** and **`Oil`** (not applicable in this version))

Then all or part of available biomass (ΔQ) are partitioned into `Heads` according to total demand of `Heads` (`Meal`, `Oil` and `Pod`). `Meal` and `Pod` demands are calculated by Equation 49 and Equation 52. `Oil` demand always equals to zero in the current version of the APSIM-Wheat module. Biomass directly partitioned in `Pod` or `Grain` is considered as structural and cannot be re-translocated, however the biomass providing from re-translocation is accumulated as non-structural biomass. The `Pod` non-structural biomass can then be re-translocated into `Grain` (See subsection 5.6).

$$\begin{aligned} \Delta Q_{head} &= \min(\Delta Q,\, D_{grain} + D_{pod}) \\ \Delta Q_{grain} &= \frac{D_g}{D_{head}} \Delta A_{head} \\ \Delta Q_{pod} &= \frac{D_p}{D_{head}} \Delta A_{head} \end{aligned} \tag{34}$$

where ΔQ_{head} is the daily available biomass for `Head`, D_{head}, $D_{grain}$and D_{pod} are demands for `Head`, `Grain` and `Pod`, respectively (see subsection 6.2 and subsection 6.3). ΔQ_{grain} and ΔQ_{pod} are biomass increment of `Grain` and `Pod`, respectively.

5.4 Biomass partitioning to **`Leaf`**

Then, the remaining biomass (after the partitioning to the `Heads`) are partitioned into `Leaf` based on a stage dependent function (Figure 15). `Leaf` biomass is considered as structural and thus cannot be re-mobilised.

$$\Delta Q_{leaf} = (\Delta Q - \Delta Q_{head}) \times F_{leaf} \tag{35}$$

where ΔQ_{leaf} is the daily increment in `Leaf` biomass; and F_{leaf} is the fraction of available biomass partitioned to the leaf, which is defined by `x_stage_no_partition` and `y_frac_leaf` in wheat.xml (Figure 15).

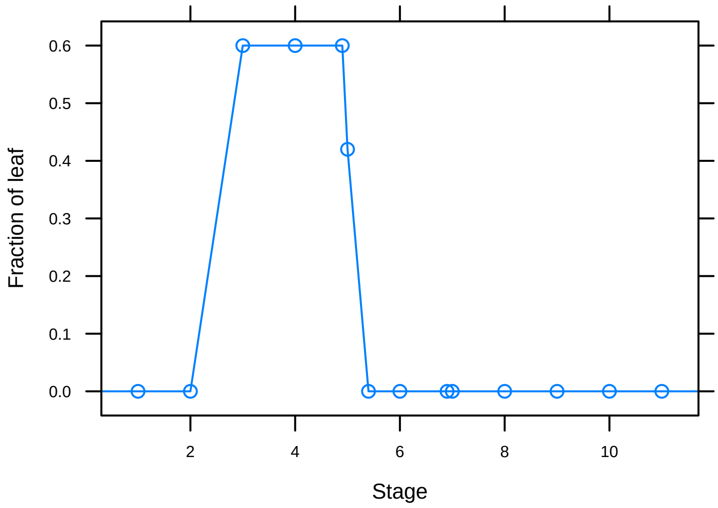


Figure 15: Relationship between fraction of leafLeaf and growth stage.

5.5 Biomass partitioning to `Stem`

Finally, the whole remaining biomass (if any) are partitioned into `Stem` (Figure 13). Until the stage "start of grain filling", 65% of this biomass is distributed to structural biomass (Figure 16), while remaining 35% is allocated in un-structural biomass. Afterwards, all new biomass allocated to `Stem` is for non-structural biomass (which can re-mobilised).

$$\Delta Q_{stem} = \Delta Q - \Delta Q_{head} - \Delta Q_{leaf} \tag{36}$$

$$\Delta Q_{stem.\,structural} = \Delta Q_{stem} \times h_{structual} \tag{37}$$

$$\Delta Q_{stem.\,non-structural} = \Delta Q_{stem} \times (1 - h_{structual}) \tag{38}$$

where ΔQ_{stem} is the daily increment in `Stem` biomass; $\Delta Q_{stem.\,structural}$ is the structural biomass of `Stem`; $\Delta Q_{stem.\,non-structural}$ is the non-structural biomass of `Stem`; and $h_{structual}$ is the fraction of `Stem` biomass distributed to structural biomass which depends on the growth stage (S). $h_{structual}$ is specified by `stemGrowthStructuralFracti` and `stemGrowthStructuralFractionStage` in wheat.xml, with a default value of 0.65 before beginning of grain filling and 0 after.

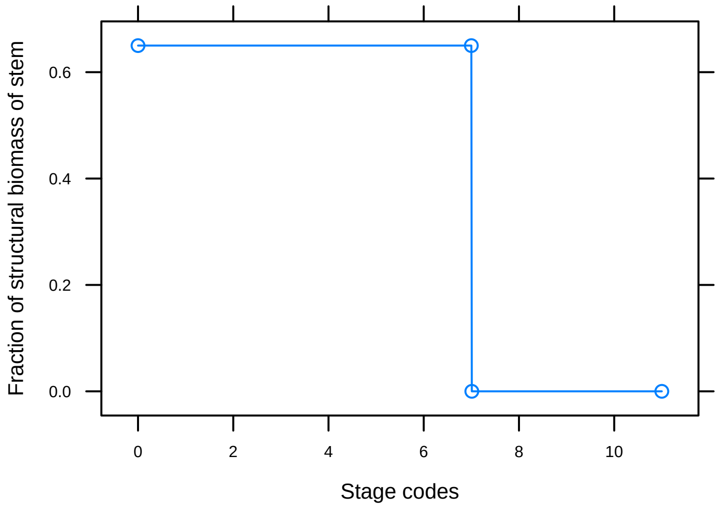


Figure 16: Relationship between fraction of structural and unstructural biomass in Stem.

5.6 Re-translocation

If the supply in assimilate (daily biomass increase) is insufficient to meet `Grain` demand, then re-translocation may occur to meet the shortfall (Figure 13). The biomass re-translocation first occurs from the `Stem` non-structural biomass. From the start of grain filling, the wheat module allows a total re-translocation of up to 20% of `Stem` biomass per day. If required, biomass can then be re-translocated from the `Pod` non-structural biomass. The re-translocated biomass is used to fulfill the `Grain` and `Pod` demands (subsection 6.2 and subsection 6.3) and is accumulated as non-structural biomass.

$$D_{diff,\, head} = (D_{grain} - \Delta Q_{grain}) + (D_{pod} - \Delta Q_{pod}) \tag{39}$$

where $D_{diff,\, head}$ is the unfulfilled demand from the plant, D_{grain} and D_{pod} are the demands from `Grain` and `Pod` (subsection 6.2 and subsection 6.3), and ΔQ_{grain} and ΔQ_{pod} are the daily increments in biomass accumulated to `Grain` and `Pod` (before re-translocation; Equation 34).

$$\Delta Q_{retrans,\, stem} = \min(D_{diff},\, Q_{stem.\, non-structural} \times 20\%) \tag{40}$$

where $\Delta Q_{retrans,\, stem}$ is the dry biomass re-translocated from `Stem`, and $Q_{stem.\, non-structural}$ is the non-structural part of the `Stem` biomass (Equation 38).

$$D_{diff,\, head} = D_{diff,\, head} - \Delta Q_{retrans} \tag{41}$$

where $D_{dff,\, head}$ is updated value of the unfulfilled demand from the head.

$$\Delta Q_{retrans,\, pod} = \min(D_{diff,\, head},\, Q_{pod,\, non-structural}) \tag{42}$$

where $\Delta Q_{retrans,\, pod}$ from pod is the dry biomass re-translocated from `Pod`, and $Q_{pod,\, non-structural}$ is the non-structural part of the `Pod` biomass.

$$D_{dff,\, head} = D_{diff,\, head} - \Delta Q_{retrans,\, pod} \tag{43}$$

where $D_{dff,\, head}$ is updated value of the unfulfilled demand from the head.

$$\Delta Q_{retrans} = \Delta Q_{retrans,\, stem} + \Delta Q_{retrans,\, pod} \tag{44}$$

where $\Delta Q_{retrans}$ is re-translocated biomass within the plant.

$$\Delta Q_{grain.\, non-structural=}\Delta Q_{retrans\, to\, grain} = \frac{D_{diff,\, grain}}{D_{diff,\, head}} \Delta Q_{retrans} \tag{45}$$

$$\Delta Q_{retrans\,to\,pod} = \frac{D_{diff,\,pod}}{D_{diff,\,head}} \Delta Q_{retrans} \tag{46}$$

$$\Delta Q_{pod.\,non-structural{=}} \Delta Q_{retrans\,to\,pod} - \Delta Q_{retrans,\,pod} \tag{47}$$

where $\Delta Q_{grain.\,non-structural}$ and $\Delta Q_{pod.\,non-structural}$ are the daily increment in the non-structural part of `Grain` and `Pod` biomass; $\Delta Q_{retrans\,to\,grain}$ and $\Delta Q_{retrans\,to\,pod}$ to pod are the daily biomass re-translocated to `Grain` and `Pod`; $D_{diff,\,grain}$ and $D_{diff,\,pod}$ are the unfulfilled demand of `Grain` and `Pod`, which are calculated as $(D_{grain} - \Delta Q_{grain})$ and $(D_{pod} - \Delta Q_{pod})$, respectively.

6 Head development

6.1 Grain number

The number of grains per plant (N_g) is determined by the stem weight at anthesis.

$$N_g = R_g W_s \tag{48}$$

where W_s is the stem dry weight at anthesis, R_g is the grain number per gram stem which is specified by `grain_per_gram_stem` in wheat.xml, with default value at 25 grain g^{-1}.

6.2 `Grain` (`Meal`) demand

The `Grain` demand (or `Meal` demand, D_g) is calculated in the growth phase `postflowering` (from flowering to end of grain filling Figure 1). D_g equals to 0 before flowering.

$$D_g = N_g R_p h_g(T_{mean}) f_{N,\,grain} \tag{49}$$

where N_g is the grain number, R_p is the potential rate of grain filling (0.0010 grain^{-1} d^{-1} from flowering to start of grain filling (Figure 1); 0.0020 grain^{-1} d^{-1} during grain filling (Figure 1)), $h_g(T_{mean})$ is a function of daily mean temperature which affects the rate of grain filling (0-1) and is defined by parameters `x_temp_grainfill` and `y_rel_grainfill` in wheat.xml and linearly interpolated by APSIM (Figure 17).

$f_{N,\,grain}$ is a nitrogen factor to grain filling.

$$f_{N,\,grain} = \frac{h_{N,\;poten}}{h_{N,\;min}} h_{N,\,grain} \sum_{stem,\,leaf} \frac{C_N - C_{N,\,min}}{C_{N,\,crit} \times f_{c,\,N} - C_{N,\,min}} \qquad (0 \leq f_{N,\,fill} \leq 1) \tag{50}$$

where $h_{N,\;poten}$ is the potential rate of grain filling which is specified by `potential_grain_n_filling_rate` in wheat.xml and has a default value of 0.000055 g grain^{-1} d^{-1}; $h_{N,\;min}$ is the minimum rate of grain filling which is specified by `minimum_grain_n_filling_rate` in wheat.xml and has a default value of 0.000015 g grain^{-1} d^{-1}; $h_{N,\,grain}$ is a multiplier for nitrogen deficit effect on grain, which is specified by `n_fact_grain` in wheat.xml and has a default value of 1; C_N is the nitrogen concentration of `Stem` or `Leaf` parts; $C_{N,\,crit}$ and $C_{N,\,min}$ are critical and minimum nitrogen concentration, respectively, for `Stem` and `Leaf` parts. $C_{N,\,crit}$ and $C_{N,\,min}$ are functions of growth stage and nitrogen concentration which is defined by parameters `x_stage_code`, `y_n_conc_min_leaf`, `y_n_conc_crit_leaf`, `y_n_conc_min_stem`, `y_n_conc_crit_stem` in wheat.xml and linearly interpolated by APSIM (Figure 36); and $f_{c,\,N}$ is a factor with a value of 1 (i.e. no impact) for Stem, and is depending on CO$_2$ for `Leaf` (Figure 18).

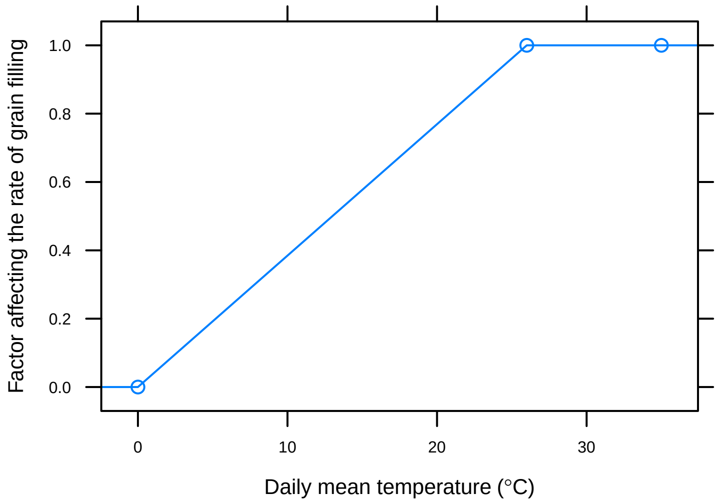


Figure 17: Response of the factor affecting the rate of grain filling in regards to daily mean temperature.

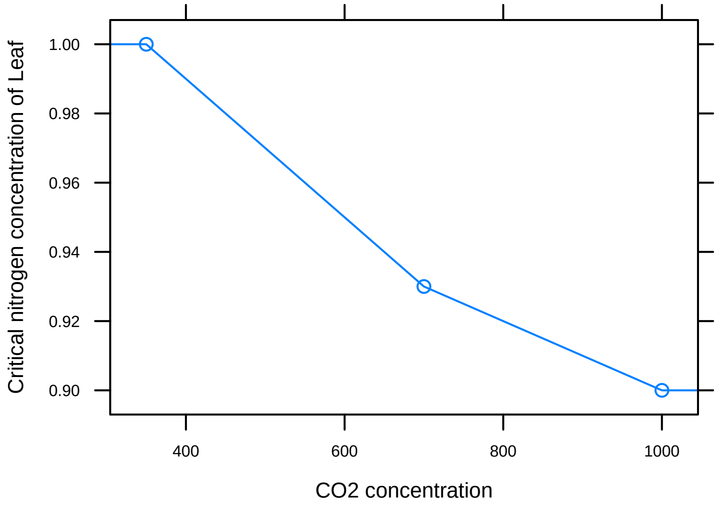


Figure 18: The CO2 modifier for critical nitrogen concentration of Leaf.

Finally, `Grain` demand is limited by the maximum grain size (corresponding to D_{gm})

$$\begin{aligned} D_g &= \min(D_g,\, D_{gm}) \\ D_{gm} &= N_g S_{gm} - Q_{meal} \qquad (D_{gm} \geq 0) \end{aligned} \tag{51}$$

where N_g is the grain number; Q_{meal} is the dry weight of `Meal` part (i.e. the `Grains`); S_{gm} is the maximum grain size which is specified by max_grain_size in wheat.xml and is a cultivar-specific parameter with 0.04 g for default value.

6.3 `Pod` demand

`Pod` demand (D_p) is calculated by `Grain` demand (D_g, Equation 49) or daily biomass accumulation (ΔQ, Equation 32)

$$D_p = \begin{array}{ll} D_g h_p(S) & D_g{>}0 \\ \Delta Q h_p(S) & D_g{=}0 \end{array} \tag{52}$$

where $h_p(S)$ is a function of the growth stage (S) and of the `Pod` demand fraction of D_g or ΔQ. $h_p(S)$ is defined by parameters `x_stage_no_partition` and `y_frac_pod` in wheat.xml and linearly interpolated by APSIM (Figure 19).

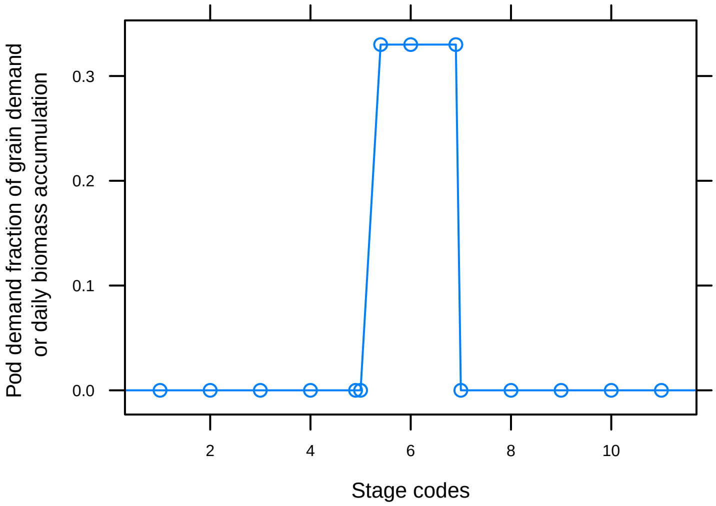


Figure 19: Pod demand over the stages (fraction of Grain demand or of daily biomass accumulation).

7 Leaf and node appearance and crop leaf area

In the current version of APSIM-Wheat, wheat plants are assumed to be uniclum (i.e. with a single stem), meaning that tillering is not simulated *per se*. While a node corresponds to a phytomer on the main stem, it actually represents all the phytomers that appear simultaneously on different tillers (i.e. cohort of leaves) in the real world.

7.1 Node number

7.1.1 Potential node appearance rate

At emergence (Figure 1), a number of initial leaves are specified by `leaf_no_at_emerg`, with a default value of 2. The initial number of nodes is the same as the initial number of leaves.

During the tiller formation phase (i.e. up to 'Harvest rips', Figure 1), nodes appear at a thermal time interval (the equivalent of a phyllochron for leaf appearance, P_n) that depends on the node number of the main stem (n_d, i.e. total number of nodes of the plant) at days after sowing (d, days).

$$P_n = h_P(n_d) \tag{53}$$

where the function $h_P(n_d)$ is defined by parameters `x_node_no_app` and `y_node_app_rate` in wheat.xml and is linearly interpolated by APSIM. In the current version of APSIM-Wheat, P_n is set to 95 °C d, meaning that the 'node phyllochron' is supposed to be constant (Figure 20). No effect from water and N stress on leaf appearance is accounted for.

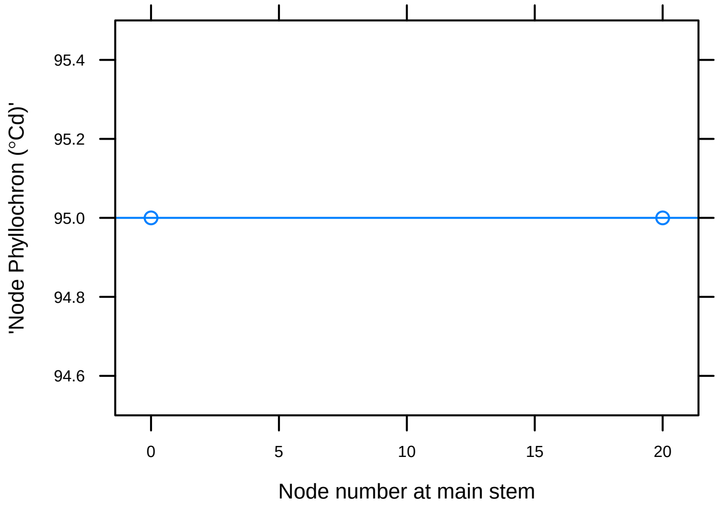


Figure 20: Relationship function ($h_p(n_d)$) between 'node phyllochron' (P_n) and the node number at main stem (n_d).

7.1.2 Potential node number (daily increase)

The potential daily increase in the node number of this unique stem ($\Delta n_{d,\,p}$) is calculated by the daily thermal time (Figure 3) and the 'node phyllochron', and occurs during the tiller formation phase (Figure 1).

$$\Delta n_{d,\,p} = \frac{\Delta TT_d}{P_n} \tag{54}$$

where ΔTT_d is the thermal time (°Cd) at day d (Figure 3 and Equation 4).

7.2 Leaf number

7.2.1 Potential leaf number (daily increase)

In the current version of APSIM-Wheat, all leaves appeared from a main and unique stem. The potential leaf number of each node is defined by a function ($h_l(n_d)$) of node (n_d) number of day d (or 'node position'; n_d) (Figure 21 and Equation 56). $h_l(n_d)$ is specified by parameters `x_node_no_leaf` and `y_leaves_per_node` in wheat.xml and linearly interpolated by APSIM.

At day d, the leaf number of the current node n_d nodes ($N_{n,\,d,\,p}$) is determined by the potential leaf number $d-1$ for the past n_{d-1} nodes ($N_{n,\,d-1}$) and environmental stresses.

$$N_{d,\,p} = \min[N_{n,\,d-1},\ h_l(n_{d-1})] + [h_l(n_{d-1} + \Delta n_{d,\,p}) - h_l(n_{d-1})] \times f_{S,\,expan} \tag{55}$$

where n_{d-1} is the node number at $d-1$ days after sowing, $\Delta n_{d,\,p}$ is the potential daily increase of node number (Equation 54), $f_{S,\,expan}$ is the environmental stresses for canopy expansion.

$$f_{S,\,expan} = \min\{[\min(f_{N,\,expan},\ f_{p,\,expan})]^2,\ f_{w,\,expan}\} \tag{56}$$

where $f_{N,\,expan}$, $f_{p,\,expan}$ and $f_{w,\,expan}$ are the nitrogen, phosphorus and soil water stress for canopy expansion, respectively, which is explained in section 13 and Equation 97, respectively.

The potential daily increase in leaf number for the whole plant is calculated based on the potential increase for the current node and the potential increase in node number ($\Delta n_{d,\,p}$, Equation 54) as follows.

$$\Delta N_{d,\,p} = N_{n,\,d} \times \Delta n_{d,\,p} \tag{57}$$

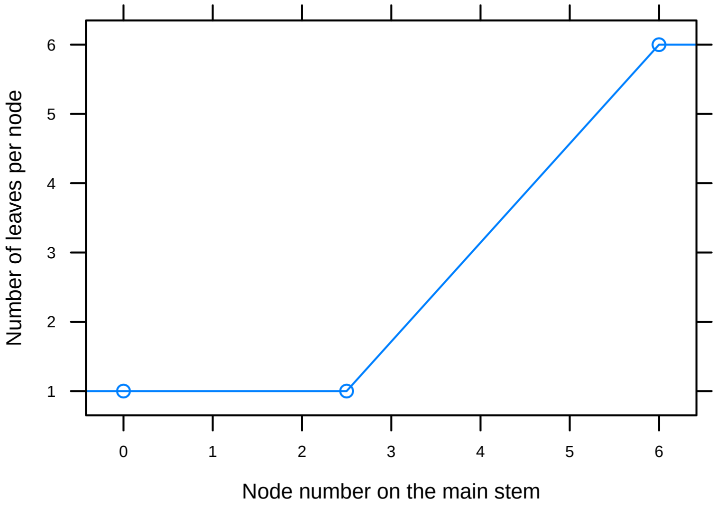


Figure 21: Number of leaves per node as a function of the number of nodes on the main stem and unique stem considered in APSIM-Wheat (n_d). This relation corresponds the function $h_l(n_d)$.

7.2.2 Actual leaf number (daily increase)

The increase in actual leaf number ($\Delta N_{d,\ LAI}$) is calculated in relation to the fraction between the actual and stressed increase of leaf area index, as follow:

$$\Delta N_{d,\,LAI} = \Delta N_{d,\,p} \times h_{LAI}(\frac{\Delta \mathrm{LAI}_d}{\Delta \mathrm{LAI}_{d,\,s}}) \tag{58}$$

where h_{LAI} is a function between the fraction of leaf area index and the fraction of leaf number which is defined by parameters x_lai_ratio and y_leaf_no_frac in the wheat.xml and linearly interpolated by APSIM (Figure 22).

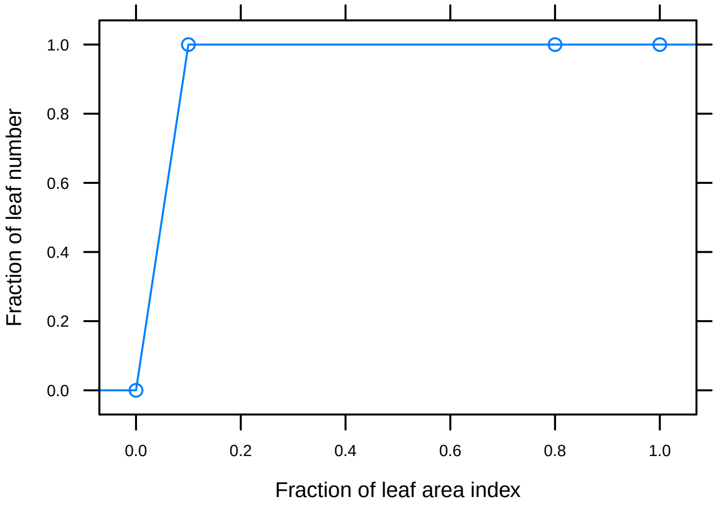


Figure 22: Relationship between fraction of leaf area index and fraction of leaf number.

8 Leaf area expansion

8.1 Actual leaf area (daily increase)

At emergence (Figure 1), an initial leaf area is specified for each plant by `initial_tpla`, with a default value of 200 mm^2 plant^{-1}.

During the tiller formation phase (Figure 1), the daily increase in leaf area index ($\Delta\mathrm{LAI}_d$) is the minimum between stressed leaf area index ($\Delta\mathrm{LAI}_{d,\,s}$) and the carbon-limited leaf area index ($\Delta\mathrm{LAI}_{d,\,c}$).

$$\Delta\mathrm{LAI}_d = \min(\Delta\mathrm{LAI}_{d,\,s},\ \Delta\mathrm{LAI}_{d,\,c}) \tag{59}$$

8.2 "Stressed" leaf area

During the tiller formation phase, the "stressed" daily increase in leaf area ($\Delta LAI_{d,s}$) is calculated as the potential increase in LAI reduced by environmental factors.

$$\Delta\mathrm{LAI}_{d,\,s} = \Delta\mathrm{LAI}_{d,\,p} \times \min(f_{w,\,expan},\ f_{N,\,expan},\ f_{P,\,expan}) \tag{60}$$

where $f_{N,\,expan}$, $f_{p,\,expan}$ and $f_{w,\,expan}$ are the nitrogen, phosphorus and soil water stress factors concerning canopy expansion, respectively (Equation 108, section 13 and Equation 97).

The potential daily increase of leaf area ($\Delta\mathrm{LAI}_{d,\,p}$) is calculated by the potential daily increase in leaf number and leaf size.

$$\Delta\mathrm{LAI}_{d,\,p} = \Delta N_{d,\,p} \times L_n \times D_p \tag{61}$$

where $\Delta N_{d,\,p}$ is the potential increase in leaf number (for the whole plant), D_p is the plant population, and L_n is the potential leaf area for leaves of the "current" node (this corresponds to the new potential leaf area produced by the different tillers in the real world) and depends on the node number on the main and unique stem considered by APSIM-Wheat.

$$L_n = h_{ls}(n_d + n_0) \tag{62}$$

where n_0 is the growing leaf number in the sheath (`node_no_correction` in wheat.xml) and equals to 2 as default value. The function $h_{ls}(n_d)$ is defined by parameters `x_node_no` and `y_leaf_size` in wheat.xml and linearly interpolated by APSIM (Figure 23).

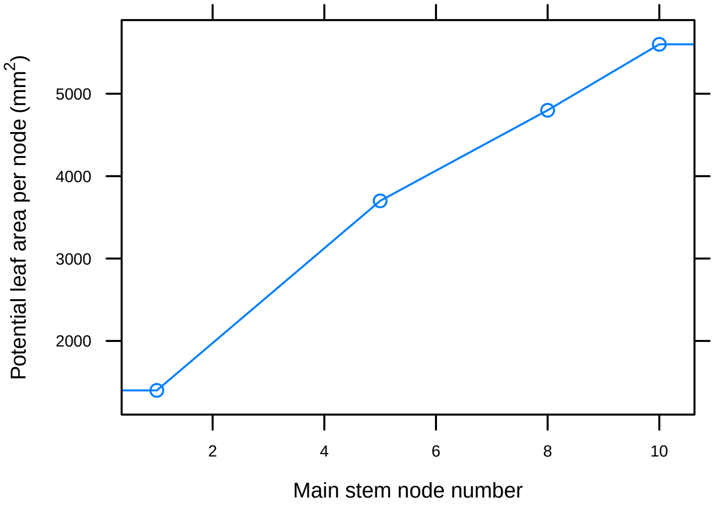


Figure 23: Leaf area per node (L_n) in regards to the main stem node number $n_0 + n_d$.

8.3 Carbon-limited leaf area

Leaf area related to carbon production is calculated by the increase in leaf dry weight (ΔQ_{leaf} Equation 32) and the maximum specific leaf area (SLA_{max}), which is related to leaf area index (LAI).

$$\Delta\mathrm{LAI}_{d,\,c} = \Delta Q_{leaf} \times \mathrm{SLA}_{max} \tag{63}$$

$$\mathrm{SLA}_{max} = h_{SLA}(\mathrm{LAI}) \tag{64}$$

This function is defined by parameters `x_lai` and `y_sla_max` in wheat.xml and linearly interpolated by APSIM (Figure 24).

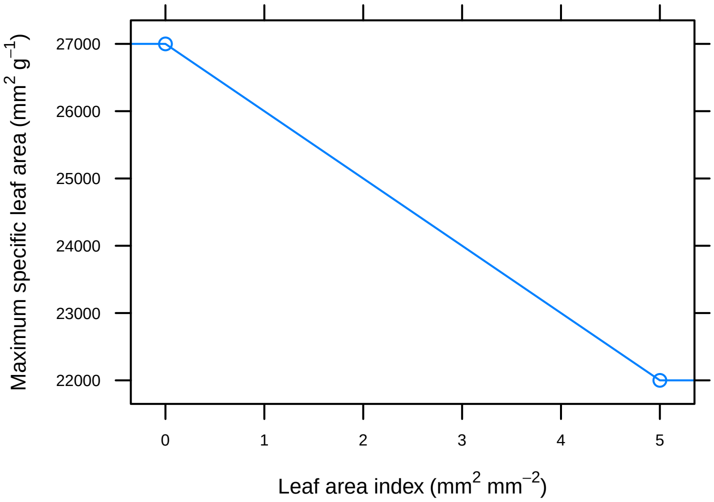


Figure 24: Relationship between maximum specific leaf area and leaf area index.

9 Root growth and distribution

9.1 Root depth growth

Between germination and start of grain filling (Figure 1), the increase in root depth (ΔD_r) is a daily rate multiplied by a number of factors. Daily root depth growth (ΔD_r) is calculated by root depth growth rate (R_r), temperature factor (f_{rt}), soil water factor (f_{rw}), and soil water available factor (f_{rwa}) and root exploration factor ($\mathrm{XF}(i)$).

$$\Delta D_r = R_r \times f_{rt} \times \min(f_{rw},\ f_{rwa}) \times \mathrm{XF}(i) \tag{65}$$

where i is the soil layer number in which root tips are growing. Root depth growth rate is a function of growth stage, which is defined by parameters `stage_code_list` and `root_depth_rate` in the wheat.xml and is linearly interpolated by APSIM (Figure 25).

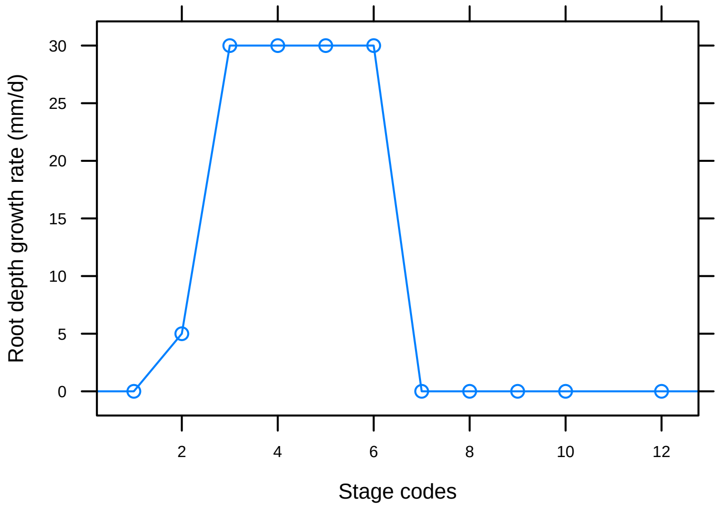


Figure 25: Relationship between root depth growth rate (R_r) and growth stages.

The temperature factor (f_{rt}) is calculated by daily mean temperature.

$$f_{rt} = h_{rt}(\frac{T_{max} + T_{min}}{2}) \tag{66}$$

where h_{rt} is a function of factor of temperature on root length and daily mean temperature and is defined by parameters `x_temp_root_advance` and `y_rel_root_advance` in the wheat.xml which is linearly interpolated by APSIM (Figure 26).

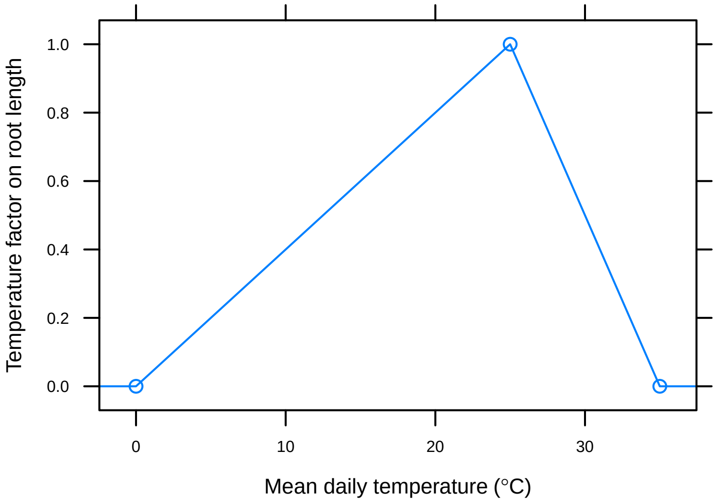


Figure 26: Relationship (h_{rt}) between temperature factor on root length and daily mean temperature.

The soil water factor (f_{rw}) is calculated by soil water stresses of photosynthesis ($f_{w,photo}$, Equation 95).

$$f_{rw} = h_{rw}(f_{w,photo}) \tag{67}$$

where h_{rw} is a function of soil-water factor affecting root depth growth in response to soil water stress for photosynthesis. This function is defined by parameters `x_ws_root` and `y_ws_root_fac`, which are linearly interpolated by APSIM. The default value of f_{rw} is 1, i.e. there is no soil water stress on root depth growth in current APSIM-Wheat.

The soil water available factor (f_{rwa}) is calculated by fraction of available soil water.

$$f_{rwa} = h_{rwa}(\text{FASW}) \tag{68}$$

where h_{rwa} is a function of the fraction of available soil water (FASW) is defined in wheat.xml by parameters `x_sw_ratio` and `y_sw_fac_root` which is linearly interpolated by APSIM (Figure 27).

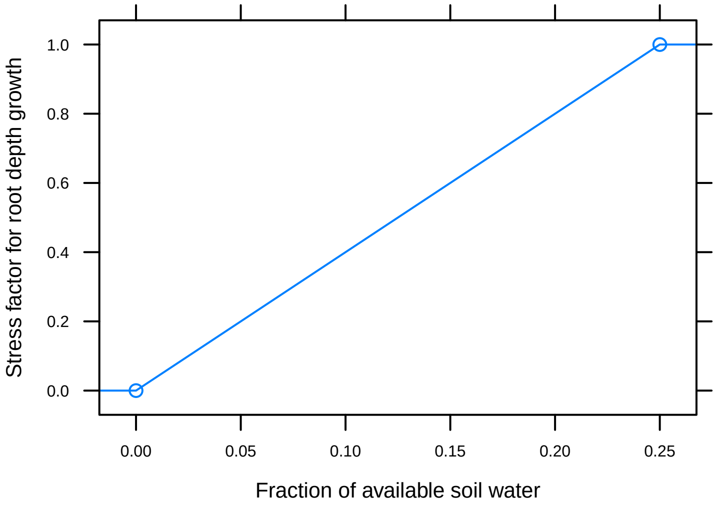


Figure 27: Available soil water fraction (f_{rwa}) in response to the fraction of available soil water (FASW).

The fraction of available soil water (FASW) is calculated by a fraction of root dpeth in soil layer i ($D_r(i)$) and depth of soil layer i ($D_s(i)$), and FASW at layer $i+1$ and i.

$$\text{FASW} = \frac{D_r(i)}{D_s(i)}\text{FASW}(i+1) + (1 - \frac{D_r(i)}{D_s(i)})\text{FASW}(i) \tag{69}$$

where $\text{FASW}(i)$ is the fraction of available soil water in soil layer i. $D_r(i)$ is the root depth within the deepest soil layer (i) where roots are present , $D_s(i)$ is the thickness of this layer i, and

$$\text{FASW}(i) = \frac{\text{SW}(i) - \text{LL}(i)}{\text{DUL}(i) - \text{LL}(i)} \tag{70}$$

where $\text{SW}(i)$ is the soil water content at layer i (mm), $\text{LL}(i)$ is the lower limit of plant-extractable soil water in layer i (mm), $\text{DUL}(i)$ is drained upper limit soil water content in soil layer i (mm). $\text{XF}(i)$, $\text{SW}(i)$, $\text{LL}(i)$ and $\text{DUL}(i)$ are specified at the soil module of APSIM simulation files.

Finally, Equation 65 is reduced to this function.

$$\Delta D_r = R_r \times f_{rt} \times f_{rwa} \times \text{XF}(i) \tag{71}$$

Overall, root depth is constrained by the soil profile depth. The optimum root expansion rate is 30 mm d^{-1} (Figure 25). This can be limited by supra- or sub-optimal mean air temperatures (Figure 26). Dry soil can slow root depth progression if the soil water content is less than 25% of the extractable soil water (drained upper limit - lower limit) in the layers they are about to reach (Figure 27). The increase of root depth through a layer can also be reduced by knowing soil constraints (soil compression) through the use of the 0-1 parameter XF, which is input for each soil layer. Root depth is used by APSIM to calculate soil available water (e.g section 11).

9.2 Root length

Daily root length growth is calculated by daily growth of `Root` biomass (ΔQ_{root}, Equation 33) and specific root length (SRL, defined by `specific_root_length` in wheat.xml with a default value of 105000 mm g^{-1}).

$$\Delta L_r = \Delta Q_{root} \times \text{SRL} \tag{72}$$

The daily root length growth (ΔL_r) is distributed to each soil layer i according to root depth and soil water availability in soil layer i.

$$\Delta D_r(i) = \frac{f_{rl}(i)}{\sum_{j=1}^{N} f_{rl}(j)} \tag{73}$$

where $f_{rl}(i)$ is a factor of root length growth in soil layer i.

$$f_{rl}(i) = f_{rwa} \times f_b(i) \times \text{XF}(i) \times \frac{D_s(i)}{D_r} \tag{74}$$

where $\Delta L_r(i)$ is the daily root length growth for soil layer i, $D_s(i)$ is the depth of the soil layer i, D_r is total root depth from the previous day, $\text{XF}(i)$ is root exploration factor in soil layer i, f_{rwa} is soil water available factor (Equation 68), $f_b(i)$ is branch factor at layer i.

$$f_b(i) = h_b(\frac{L_r(i)}{D_p D_s(i)}) \tag{75}$$

where $L_r(i)$ is the root length in soil layer i, D_p is plant population, h_b is a function for branch factor that is defined by parameters `x_plant_rld` and `y_rel_root_rate` in the wheat.xml and linearly interpolated by APSIM (Figure 28).

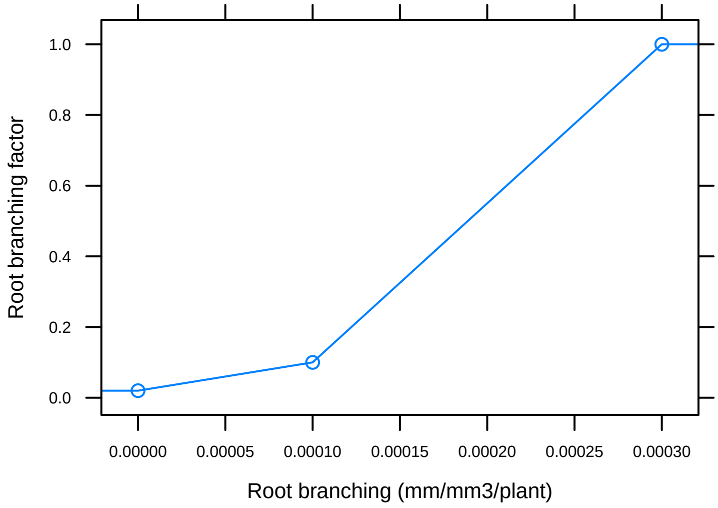


Figure 28: Root branching factor in response to root branching.

Root length has no effect on other traits in the current version of APSIM-Wheat. It is just used by the root senescence routine.

10 Senescence

10.1 Leaf number senescence

The leaf senescence phase begins 40% between floral initiation and end of juvenile, and ends at harvest ripe (Figure 1), at which stage, all green leaves are dead. During leaf senescence phase (Figure 1), leaf number senescence is calculated by daily thermal time (ΔTT, Equation 4) as follows:

$$\Delta N_{d,\,sen} = \Delta TT \times \frac{f_{sen,\,l} \times N_d}{r_{sen,\,l}} \tag{76}$$

where N_d is the total leaf number; $f_{sen,\,l}$ is the fraction of the total leaf number senescing per main stem node and specified by `fr_lf_sen_rate` in wheat.xml (default value 0.035); $r_{sen,\,l}$ is the rate of node senescence on main stem and specified by `node_sen_rate` in wheat.xml (default value 60.0 °Cd node^{-1}).

10.2 Leaf area senescence

There are five causes of leaf senescence: age ($\Delta \text{LAI}_{sen,\,age}$), water stress ($\Delta \text{LAI}_{sen,\,sw}$), light intensity ($\Delta \text{LAI}_{sen,\,light}$), frost ($\Delta \text{LAI}_{sen,\,frost}$) and heat ($\Delta \text{LAI}_{sen,\,heat}$). The maximum of these causes is the day's total leaf area index senescence.

$$\Delta \text{LAI}_{sen} = \max(\Delta \text{LAI}_{sen,\,age},\ \Delta \text{LAI}_{sen,\,sw},\ \Delta \text{LAI}_{sen,\,light},\ \Delta \text{LAI}_{sen,\,frost},\ \Delta \text{LAI}_{sen,\,heat}) \tag{77}$$

Leaf area senescence caused by age corresponds to the leaf area of the number of leaves senesced ($\Delta N_{d,\,sen}$) from the lowest leaf position.

Leaf area senescence caused by soil water ($\Delta \text{LAI}_{sen,\,sw}$) is calculated as follows.

$$\Delta \text{LAI}_{sen,\,sw} = k_{sen,\,sw} \times (1 - f_{sw,\,photo}) \times \text{LAI} \tag{78}$$

where $k_{sen,\,sw}$ is the slope of the linear equation relating to soil water stress to leaf senescence rate and is specified by `sen_rate_water` in wheat.xml (default value 0.10); $f_{sw,\,photo}$ is soil water stress for photosynthesis (Equation 95); LAI is the leaf area index.

Leaf area senescence caused by light intensity ($\Delta \text{LAI}_{sen,\,light}$) is calculated as follows:

$$\Delta \text{LAI}_{sen,\,light} = k_{sen,\,light} \times (\text{LAI} - \text{LAI}_{c,\,light}) \times \text{LAI} \quad \text{LAI} > \text{LAI}_{c,\,light} \tag{79}$$

where $k_{sen,\,light}$ is sensitivity of leaf area senescence to shading and is specified by `sen_light_slope` in wheat.xml (default value 0.002); $\text{LAI}_{c,\,light}$ is the critical LAI when shading is starting to cause leaf area senescence and is specified by `lai_sen_light` in wheat.xml (default value 7).

The leaf area senescence caused by frost is a ratio of LAI.

$$\Delta \text{LAI}_{sen,\,frost} = k_{sen,\,frost} \times \text{LAI} \tag{80}$$

where $k_{sen,\,frost}$ is a function of daily minimum temperature and is defined by parameters `x_temp_senescence` and `y_senescence_fac` in wheat.xml, which are linearly interpolated by APSIM. The default value of $k_{sen,\,frost}$ is zero, i.e. there is no frost stress in leaf area in the current APSIM-Wheat module.

Senescence by heat calculation has been added in APSIM 7.5. The leaf area senescence by heat is a ratio of LAI (Asseng et al., 2011).

$$\Delta \text{LAI}_{sen,\,heat} = k_{sen,\,heat} \times \text{LAI} \tag{81}$$

where $k_{sen,\,heat}$ is a function of daily maximum temperature which is defined by parameters `x_maxt_senescence` and `y_heatsenescence_fac` in wheat.xml which are linearly interpolated by APSIM.

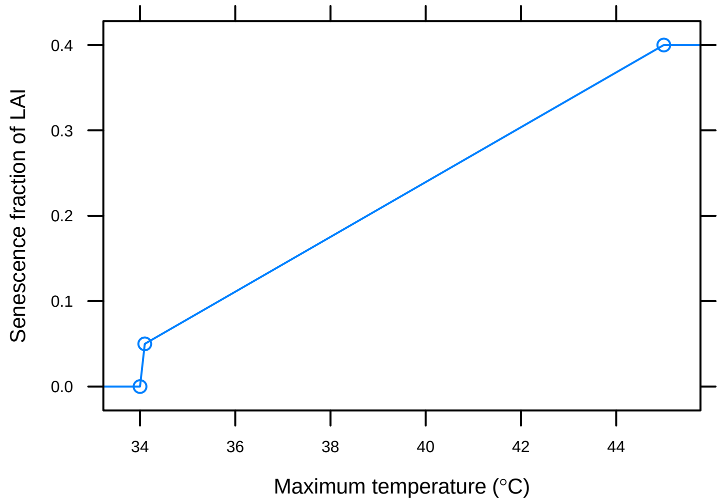


Figure 29: Fraction of senescence of leaf area index ($k_{sen,\,heat}$) in response to maximum temperature.

The total leaf area of plant must be more than the minimum plant area (`min_tpla`), which has default value 5 mm^2 plant^{-1}. When some leaves are senesced, only a small amount of nitrogen is retained in the senesced leaf, the rest is made available for re-translocation included into the `Stem` N pool (subsection 12.3). The concentration of nitrogen in senesced material is specified in wheat.xml.

10.3 Biomass senescence

Leaf biomass senescence ΔQ_{sl} is the ratio of leaf area senescence (ΔLAI_{sen}) with total the green LAI at the time considered (LAI).

$$\Delta Q_{sl} = \Delta Q_l \frac{\Delta \text{LAI}_{sen}}{\text{LAI}} \tag{82}$$

where ΔQ_l is the daily increase of leaf biomass.

10.4 Root senescence

A rate of 0.5% of root biomass and root length is senesced each day and detaches immediately being sent to the soil nitrogen module and distributed as fresh organic matter in the profile.

$$\Delta Q_{sen,\,root} = \Delta Q_{root} \times f_{sen,\,root} \tag{83}$$

where $\Delta Q_{sen,\,root}$ is the daily `Root` senesced biomass, and $f_{sen,\,root}$ is the fraction of senesced root biomass, which is defined in `x_dm_sen_frac_root` and `y_dm_sen_frac_root` in wheat.xml (Figure 30)

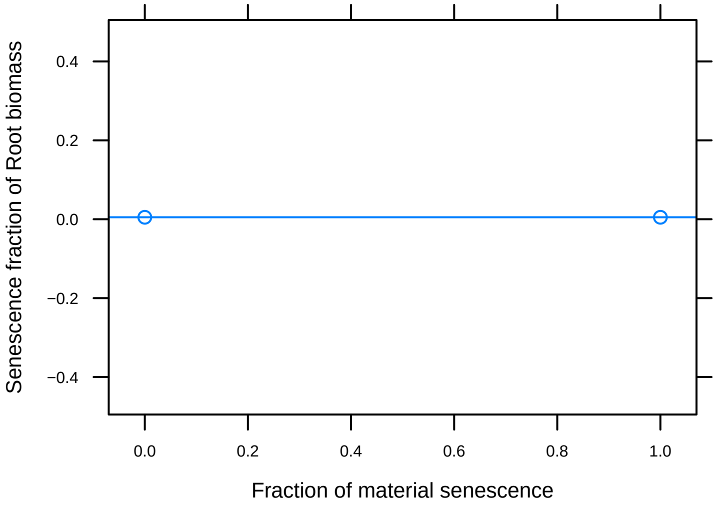


Figure 30: Fraction of senescence of root biomass.

$$\Delta L_{sen,\,root} = \Delta Q_{sen,\,root} \times \text{SRL} \tag{84}$$

where $\Delta L_{sen,\,root}$ is the daily root length senescence, and SRL is the specific root length.

Root senescence occurs in each of the soil layers where roots are present, as a proportion of the total root length.

$$\Delta L_{sen,\,root}(i) = \Delta L_{sen,\,root} \times \frac{L_r(i)}{\sum_{j=1}^{i} L_r(j)} \tag{85}$$

where $L_{sen,\,root}(i)$ is the root length senescence in soil layer i, $L_r(i)$ is root length in layer i, and $\sum_{j=1}^{i} L_r(j)$is the total root length for all the layers where root are present.

11 Crop Water Relations

11.1 Crop water demand

Following Sinclair (1986), transpiration demand is modeled as a function of the current day's potential crop growth rate, estimated by the potential biomass accumulation associated with intercepted radiation (ΔQ_r, see Equation 13), divided by the transpiration efficiency.

$$W_d = \frac{\Delta Q_r - R}{TE} \tag{86}$$

where R is respiration rate and equal to zero in the current version of APSIM-Wheat, TE is transpiration efficiency. TE is related to the daylight averaged vapour pressure deficit (VPD, Equation 88) and a multiple of CO_2 factor (Reyenga et al., 1999).

$$TE = f_{c,TE}\frac{f_{TE}}{VPD} \tag{87}$$

where $f_{c,TE}$ is the CO_2 factor for transpiration efficiency, which is a function of carbon dioxide concentration and is defined by parameters `x_co2_te_modifier` and `y_co2_te_modifier` in wheat.xml and linearly interpolated by APSIM (Figure 31). $f_{c,TE}$ linearly increases from 1 to 1.37 when CO_2 concentration increases from 350 ppm to 700 ppm (Reyenga et al., 1999). f_{TE} is the coefficient of transpiration efficiency, which values are defined in wheat.xml by parameters `transp_eff_cf` in wheat.xml for the different growth stages and are linearly interpolated by APSIM (Figure 32).

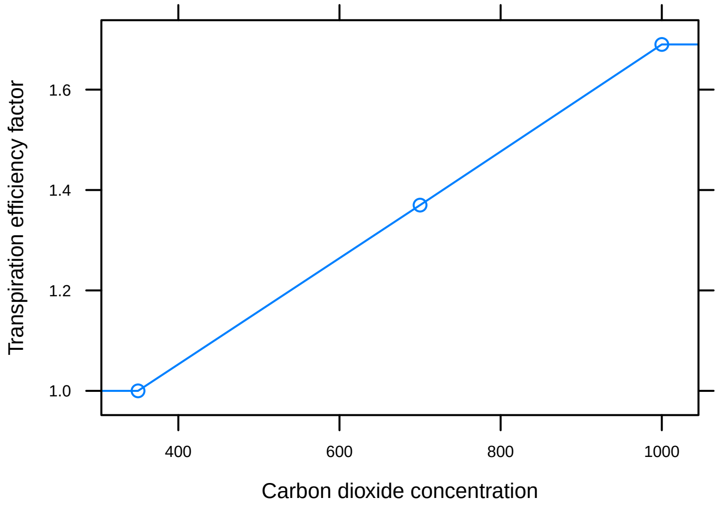


Figure 31: Relationship between factor of carbon dioxide for transpiration efficiency ($f_{c,TE}$) and CO2 concentration.

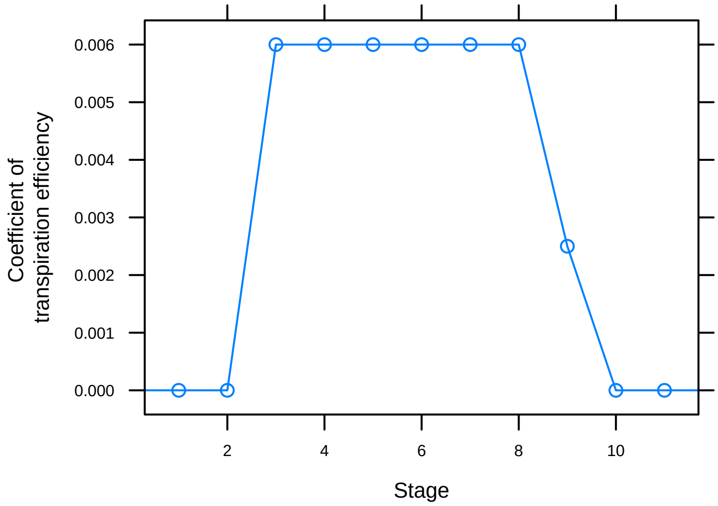


Figure 32: Change in the coefficient of transpiration efficiency with growth stages.

VPD is the vapour pressure deficit, which is estimated using the method proposed by Tanner and Sinclair (1983) and only requires daily maximum and minimum temperatures.

$$VPD = f_v[6.1078 \times \exp(\frac{17.269 \times T_{max}}{237.3 + T_{max}}) - 6.1078 \times \exp(\frac{17.269 \times T_{min}}{237.3 + T_{min}})] \tag{88}$$

In this method, it is assumed that the air is saturated at the minimum temperature. The saturated vapour pressure is calculated at both the maximum and minimum temperatures, and the default vapour pressure deficit for the day is taken as 75% (f_v, defined by `svp_fract` in wheat.xml) of the difference between these two vapour pressures.

Crop water demand is capped to below a given multiple of potential ET (taken as Priestly-Taylor Eo from the water balance module) as specified by eo_crop_factor_default in the wheat.xml file (default value 1.5). This limits water use to reasonable values on days with high VPD or in more arid environments.

11.2 Potential and actual extractable soil water

Potential and actual extractable soil water is the sum of root water contents available to the crop from each profile layer occupied by roots. If roots are only partially through a layer available soil water is scaled to the portion that contains roots. Potential extractable soil water (ESW$_p$) is the difference between drained upper limit soil water content (DUL) and lower limit of plant-extractable soil water (LL) for each soil layer. The actual extractable soil water (esw_a) is the difference between the soil water content (SW) and lower limit of plant-extractable soil water (LL) for each soil layer.

$$\begin{gathered}\text{ESW}_p(i) = \text{DUL}(i) - \text{LL}(i)\\ \text{ESW}a(i) = \text{SW}(i) - \text{LL}(i)\\ \text{ESW}_p = \sum_{i=1}^{I}[\text{DUL}(i) - \text{LL}(i)]\\ \text{ESW}_a = \sum_{i=1}^{I}[\text{SW}(i) - \text{LL}(i)]\end{gathered} \tag{89}$$

where i indicates soil layers (where roots are present), and I indicates the deepest soil water of root presented. Similar variables are calculated for the entire soil profile (i.e. roots may not occupy all the layers).

$$\begin{gathered}\text{PAWC} = \sum_{i}^{N_s}[\text{DUL}(i) - \text{LL}(i)]\\ \text{ESW} = \sum_{i}^{N_s}[\text{SW}(i) - \text{LL}(i)]\end{gathered} \tag{90}$$

where i indicates soil layers, N_s indicates the number of soil layers, and PAWC is the plant available water capacity.

11.3 Crop water supply, i.e. potential soil water uptake

The APSIM-Wheat module can be coupled to either the SWIM2 module (see module documentation) or the SOILWAT2 module (default). When the APSIM-Wheat module is coupled to APSIM-SOILWAT2, potential soil water uptake (or water supply, W_s) is calculated using the approach first advocated by Monteith (1986). Crop water supply is considered as the sum of potential root water uptake from each profile layer occupied by root. If roots are only partially through a layer available soil water is scaled to the portion that contains roots. The potential rate of extraction in a layer is calculated using a rate constant (KL) as actual extractable soil water. The KL defines the fraction of available water able to be extracted per day. The KL factor is empirically derived, incorporating both plant and soil factors which limit rate of water uptake. Root water extraction values (KL) must be defined for each combination of crop species and soil type.

$$\begin{aligned} W_s(i) &= \mathrm{KL}(i)[\mathrm{SW}(i) - \mathrm{LL}(i)] && if\, i \leq I-1 \\ &= \tfrac{D_r(i)}{D_s(i)}\mathrm{KL}(i)[\mathrm{SW}(i) - \mathrm{LL}(i)] && if\, i = I \\ W_s &= \textstyle\sum_{i=1}^{I} W_s(i) \end{aligned} \tag{91}$$

where i is the soil layer, I is the deepest soil layer where roots are present, $W_s(i)$ is the water supply available from layer i, W_s is the crop water supply, $\mathrm{SW}(i)$ is the soil water content in layer i, $\mathrm{LL}(i)$ is the lower limit of plant-extractable soil water in layer i, $\mathrm{KL}(i)$ is the root water extraction values in layer i, $D_r(i)$ is the root depth within the soil layer (i) where roots are present, and $D_s(i)$ is the thickness of this layer i.

11.4 Actual soil water uptake

The actual rate of water uptake is the lesser of the potential soil water supply (W_s, Equation 91) and the soil water demand (W_d, Equation 86), which is determining whether biomass production is limited by radiation or water uptake (Equation 32)

$$W_u = \min(W_d, W_s) \tag{92}$$

If the potential soil water supply (accessible by the roots) exceeds the crop water demand, then the actual soil water uptake (W_u) is removed from the occupied layers in proportion to the values of potential root water uptake in each layer. If the computed soil water supply from the profile is less than the demand then, and the actual root water uptake from a layer is equal to the computed potential uptake. If there are not soil water supply and demand, soil water update equals to zero.

$$\begin{aligned} \Delta W_s(i) &= -W_s(i) \times \tfrac{W_d}{W_s} \qquad if\ W_s < W_d \\ \Delta W_s(i) &= -W_s(i) \qquad if\ W_s > W_d \\ \Delta W_s(i) &= 0 \qquad if\ W_s = W_d = 0 \end{aligned} \tag{93}$$

where $\Delta W_s(i)$ is the daily change in soil water content at layer i (where roots are present), and $W_s(i)$ is the water supply available from layer i (Equation 91) .

11.5 Soil water stresses affecting plant growth

Soil water deficit factors are calculated to simulate the effects of water stress on different plant growth-and-development processes. Three water deficit factors are calculated which correspond to four plant processes, each having different sensitivity to water stress i.e. photosynthesis, leaf expansion, and phenology.

Each of these factors is capped between 0 and 1, where the value of 0 corresponds to a complete stress, while 1 corresponds to no stress.

Leaf expansion is considered more sensitive to stress than photosynthesis, while soil water has no impact on crop phenology in the current APSIM-Wheat version.

11.5.1 Phenology

Soil water stress of phenology is determined by the soil water deficiency.

$$f_{W,\,pheno} = h_{w,\,pheno}(\frac{esw_a}{esw_p}) \tag{94}$$

where esw_a is the actual extractable soil water in root layers, esw_p is the potential extractable soil water in root layers. $h_{w,\,pheno}$ is a function of soil water available ratio and soil water stress, which is defined by parameters `x_sw_avail_ratio` and `y_swdef_pheno` (default value 1) in wheat.xml and linearly interpolated by APSIM. In the current version of APSIM-Wheat module, no soil water stress for phenology is applied (Figure 33). The soil water stress of phenology for flowering (`x_sw_avail_ratio_flowering` and `y_swdef_pheno_flowering`) and grain filling (`x_sw_avail_ratio_start_grain_fill` and `y_swdef_pheno_start_grain_fill`) phases are calculated in the source code, but don't have influence on the phenology of wheat in the current APSIM-Wheat version (default value of 1).

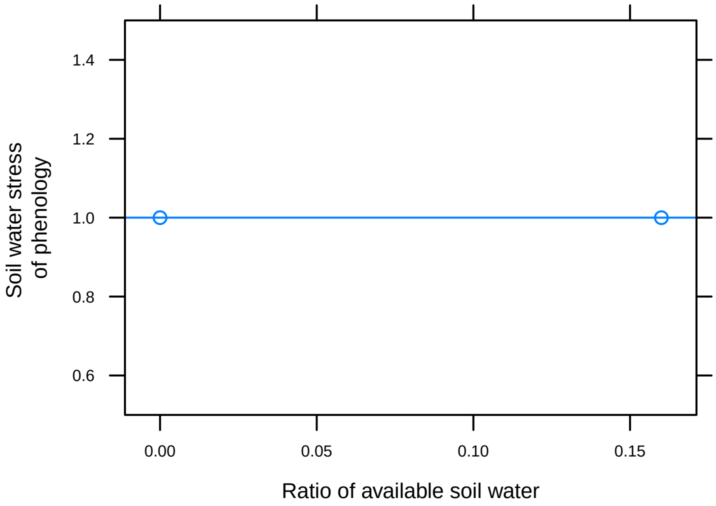


Figure 33: Relationship between soil water stress factor affecting phenology ($f_{W,\,pheno}$) and the ratio of available soil water ($\frac{esw_a}{esw_p}$).

11.5.2 Photosynthesis

Soil water stress of biomass accumulation ($f_{w,\,photo}$) is calculated as follows.

$$f_{w,\,photo} = \frac{W_u}{W_d} \tag{95}$$

where W_u is the total daily water uptake from root system (Equation 92), W_d is the soil water demand of `Leaf` and `Head` parts (Equation 86).

Finally, the potential biomass production (radiation-limitedΔQ) can limit by water uptake ($f_{w,\,photo} < 1$, i.e. when $W_u < W_d$), or not (when $f_{w,\,photo} = 1$, i.e. when $W_u = W_d$)

$$\Delta Q_w = \Delta Q_r f_{w,\,photo} = \Delta Q_r \frac{W_u}{W_d} \tag{96}$$

$f_{w,photo}$ also affect the senescence of the leaves.

11.5.3 Leaf expansion

Soil water stress of leaf expansion is determined by the deficit of soil water.

$$f_{W,\,expan} = h_{w,\,expan}(\frac{W_u}{W_d}) \tag{97}$$

where W_u is the crop water uptake (Equation 92), W_d is the crop water demand (Equation 86). $h_{w,\,expan}$ is a function of soil water content and stress, and is defined by parameters `x_sw_demand_ratio` and `y_swdef_leaf` in the wheat.xml, which is linearly interpolated by APSIM (Figure 34).

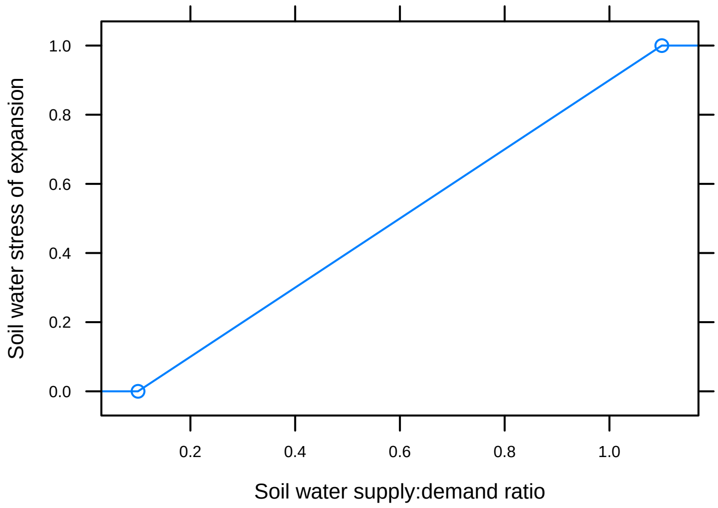


Figure 34: Relationship between the soil water stress factor affecting expansion ($f_{W,\,expan}$) and supply:demand ratio ($\frac{W_e}{W_d}$).

11.6 KL factor

APSIM 7.5 introduces a modifying factor on KL (rate of maximum daily water uptake per day) where there is an excess of chloride concentration (Cl), exchangeable sodium percentage (ESP), or electrical conductivity (EC) properties in the soil (Hochman et al., 2007). The KL modifier is optional and triggered by setting the ModifyKL parameter to yes.

When the KL modifier is activated, KL values are modified for each layer, by factors (concerning Cl, ESP, EC; Figure 35) applied to default KL values. The modifiers are calculated using one of the limiting factors in order of preference (Cl, ESP, EC), i.e. KL is modified only if there are no soil parameters for Cl. The parameters in the wheat.xml that control this mechanism are ClA, CLB, ESPA, ESPB, ECA, ECB (slope and intercept of linear relationship for Cl, ESP and EC).

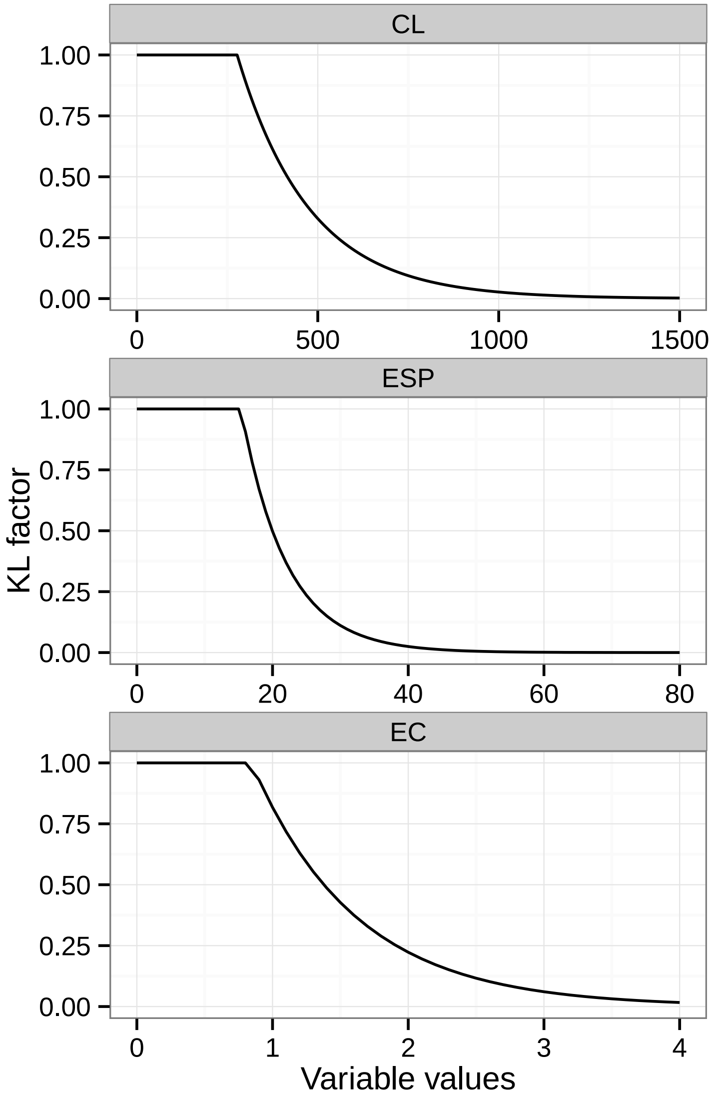


Figure 35: The KL factor in response to chloride concentration (Cl mg kg^{-1}, Exchangeable sodium percentage (ESP, %) and soil electrical conductivity (EC, dS m^{-1}.

12 Nitrogen

The nitrogen stress phase begins before 30% floral initiation to finish at the 'harvest ripe' phase (Figure 1), which are defined by `n_stress` in wheat.xml.

12.1 Nitrogen supply

Ammonium (NH_4^+) is not taken up in wheat as wheat.xml parameter knh4 (constant for NH_4 extraction) is equal to 0.

The model uses a simplified formulation for nitrate NO_3^- uptake somewhat similar in structure to that employed in water uptake. During the nitrogen stress phase (Figure 1), nitrogen supply for soil layer i ($N_s(i)$, g m^{-2}) is calculated as follows:

$$N_s(i) = K_{NO3}N(i)[N(i)\frac{1000}{\mathrm{BD}(i)D_s(i)}]\frac{\mathrm{ESW}_a(i)}{\mathrm{ESW}_p(i)} \tag{98}$$

where K_{NO3} is a constant of extractable soil nitrogen, which is defined by `kno3` with default value 0.02; $N(i)$ is the $\mathrm{NO_3^-}$ concentration in soil layer i (g m^{-2}); $\mathrm{BD}(i)$ is the bulk density of soil layer i (g cm^{-3}); $D_s(i)$ is the depth of soil layer i (cm); $\mathrm{ESW}_a(i)$ is the actual extractable soil water in soil layer i (Equation 89); $\mathrm{ESW}_p(i)$ is the potential extractable soil water in soil layer i (Equation 89).

During non-nitrogen stress phase (Figure 1), wheat could access to all available nitrogen.

$$N_s(i) = N(i)\frac{1000}{\mathrm{BD}(i)D_s(i)} \tag{99}$$

The values of $N_s(i)$ for each layer of root presented are summed to get a total potential nitrogen uptake (or crop N supply, N_s) and then each layer $N_s(i)$ is scaled by maximum total nitrogen uptake ($N_{s,\,max}$), which is defined by `total_n_uptake_max` with default value 0.6 g m^{-2}.

$$N_s'(i) = N_s(i)\frac{N_{s,\,max}}{N_s} \tag{100}$$

where $N_s'(i)$ is the actual nitrogen uptake in the layer i.

12.2 Nitrogen demand

Total wheat nitrogen demand is the sum of the N demand in all parts (i.e. `Leaf`, `Stem`, and `Pod`). Wheat has a defined minimum ($C_{N,\,min}$), critical ($C_{N,\,crit}$) and maximum ($C_{N,\,max}$) nitrogen concentration for all plant parts (Figure 36). These concentration limits change with phenological stages (Figure 36). And they are defined by parameters `x_stage_code`, `y_n_conc_min_leaf`, `y_n_conc_crit_leaf`, `y_n_conc_max_leaf`, `y_n_conc_min_stem`, `y_n_conc_crit_stem`, `y_n_conc_max_stem`, `y_n_conc_min_pod`, `y_n_conc_crit_pod`, `y_n_conc_max_pod` in wheat.xml and linearly interpolated by APSIM .

Physiologically, minimum nitrogen concentration ($C_{N,\,min}$) corresponds to the structural N required for the plant structure, and which cannot be re-translocated. Critical nitrogen concentration ($C_{N,\,crit}$) corresponds to the minimum concentration of N that plant parts will attempt to maintain (it drives the N demand of the part), and maximum nitrogen concentration ($C_{N,\,max}$) reflects to the capacity of the part to accumulate the extra available N (i.e. fulfilling more than its demand) up to a this maximum threshold N.

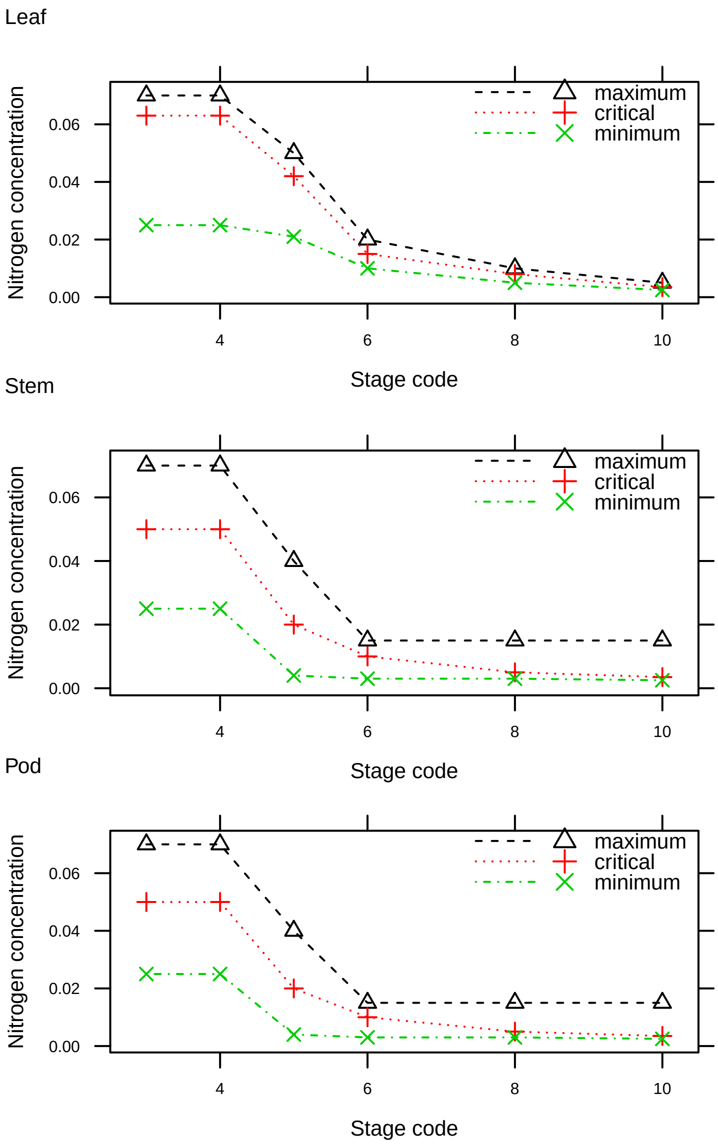


Figure 36: Relationship between maximum, critical, minimum nitrogen concentration and growth stages for the different plant parts (Leaf, Stem and Pod). Parameters are defined by defined by parameters x_stage_code, y_n_conc_min_leaf, y_n_critonc_crit_leaf, y_n_conc_max_leaf, y_n_conc_min_stem, y_n_critonc_crit_stem, y_n_critonc_max_stem in wheat.xml.

12.2.1 Nitrogen demand of `Grain`

`Grain` nitrogen demand starts at anthesis and is calculated from grain number, thermal time and a potential grain nitrogen filling rate (g grain^{-1} °Cd^{-1}).

$$N_{D,\,grain} = N_g \, R_{N,poten,} \, f_{N,\,grain} \, h_{grain}(T) \tag{101}$$

where N_g is the grain number, $R_{N,poten,}$ is the potential nitrogen filling rate, which is defined by parameter `potential_grain_n_filling_rate` in wheat.xml with default value 0.000055 g grain^{-1} d^{-1}. $f_{N,\,grain}$ is the nitrogen factor of grain filling (Equation 109). $h_{grain}(T)$ is a function of daily mean temperature (T) to influence of grain filling (Figure 37).

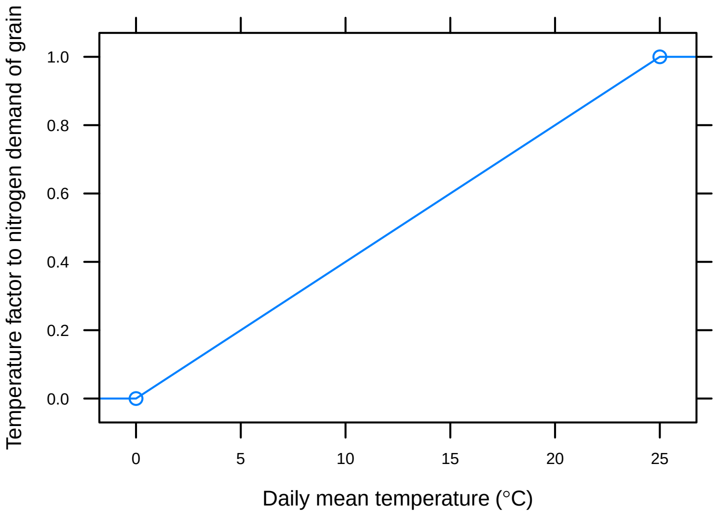


Figure 37: Relationship between nitrogen demand of Grain and daily mean temperature.

12.2.2 Nitrogen demand of other parts

Demand of nitrogen in each part (except Grain) attempts to maintain nitrogen at the critical (non-stressed) level. Nitrogen demand on any day is the sum of the demands from the pre-existing biomass of each part required to reach critical nitrogen content, plus the nitrogen required to maintain critical nitrogen concentrations in that day's produced biomass. For each plant part (`Leaf`, `Stem`, and `Pod`) the nitrogen demand is given by:

$$N_{D,\,crit} = \frac{\Delta Q_{part} C_{N,\,crit}}{f_{w,\,photo}} + f_n(C_{N,\,crit} - C_{N,\,part}) \qquad if\; C_{N,\,crit} > C_{N,\,part}\;\&\; Q_{part} > 0 \tag{102}$$

$$N_{D,\,max} = \frac{\Delta Q_{part} C_{N,\,max}}{f_{w,\,photo}} + f_n(C_{N,\,max} - C_{N,\,part}) \qquad if\; C_{N,\,max} > C_{N,\,part}\;\&\; Q_{part} > 0 \tag{103}$$

where ΔQ_{part} is the growth dry weight of parts, Q_{part} is the green (i.e. not senesced) dry weight of parts, $f_{w,\,photo}$ is soil water stress of biomass accumulation (Equation 95); $C_{N,\,part}$ is the nitrogen concentration of parts; f_n is defined by parameter `n_deficit_uptake_fraction` in wheat.xml with default value 0.0001. $C_{N,\,crit}$ and $C_{N,\,max}$ are the N concentration critic and maximal of the parts, respectively (Figure 36). $N_{D,\,crit}$ and $N_{D,\,max}$ equal to 0, if $Q_{part} = 0$.

12.3 Nitrogen uptake, partitioning and re-translocation

12.3.1 Nitrogen concentrations in wheat parts

The N concentration in Leaf is calculated as follows:

$$C_{N,leaf} = N_{leaf}/Q_{leaf} \tag{104}$$

12.3.2 Nitrogen uptake

Daily total nitrogen uptake (N_u) is the lesser of N demand (N_d, Equation 101) and N supply N_s, Equation 99).

$$N_u = \min(N_d,\; N_s) \tag{105}$$

12.3.3 Nitrogen translocation

Daily total nitrogen uptake is distributed to the plant parts in proportion to their individual demands.

12.3.4 Nitrogen re-translocation

If there is insufficient nitrogen supplied from senescing material and soil nitrogen uptake, Grain nitrogen demand is met by re-translocating nitrogen from other plant parts. Nitrogen is available for re-translocation from un-senesced leaves and stems until they reach their defined minimum nitrogen concentration. No N re-translocation is attributed to other parts than `Grain`.

12.4 Nitrogen stresses

12.4.1 Phenology

Nitrogen stress on phenology (via $f_{N,\,pheno}$ in Equation 5) is determined by the difference between organ nitrogen concentration and organ minimum and critical nitrogen concentration.

$$f_{N,\,pheno} = h_{N,\,pheno} \sum_{stem,\,leaf} \frac{C_N - C_{N,\,min}}{C_{N,\,crit} \times f_{c,\,N} - C_{N,\,min}} \tag{106}$$

where C_N is the nitrogen concentration of `Stem` or `Leaf` parts; $h_{N,\,pheno}$ is multiple for nitrogen deficit effect on phenology which is specified by `N_fact_pheno` in the wheat.xml and default value is 100; $C_{N,\,crit}$ and $C_{N,\,min}$ are the N concentration critic and minimal of the parts, respectively (Figure 36); and $f_{c,\,N}$ is a factor with a value of 1 (i.e. no impact) for Stem, and is depending on CO_2 for `Leaf` (Figure 18).

The nitrogen stress on phenology is used in the calculation of the adjusted thermal time (Equation 5). However, In the current version of APSIM-Wheat module, the default parameters are applied for no nitrogen water stress for phenology.

12.4.2 Biomass accumulation

Nitrogen stress on biomass accumulation (via $f_{N,\,photo}$ in Equation 18) is determined by the difference between leaf nitrogen concentration and leaf minimum and critical nitrogen concentration.

$$f_{N,\,photo} = h_{N,\,photo} \sum_{leaf} \frac{C_N - C_{N,\,min}}{C_{N,\,crit} \times f_{c,\,N} - C_{N,\,min}} \tag{107}$$

where C_N is the nitrogen concentration of `Leaf` parts; $h_{N,\,photo}$ is multiplier for nitrogen deficit effect on photosynthesis which is specified by `N_fact_photo` in the wheat.xml and default value is 1.5; $C_{N,\,crit}$ and $C_{N,\,min}$ are the N concentration critic and minimal of the parts, respectively (Figure 36); and $f_{c,\,N}$ is a factor with a value of 1 (i.e. no impact) for Stem, and is depending on CO_2 for `Leaf` (Figure 18).

The nitrogen stress on biomass accumulation affects the radiation-limited biomass accumulation (ΔQ_r, Equation 32).

12.4.3 Leaf appearance and expansion (i.e. leaf number and LAI)

Nitrogen stress on leaf appearance and expansion (via $f_{N,\,expan}$ in Equation 56) is determined by the difference between leaf nitrogen concentration and leaf minimum and critical nitrogen concentration.

$$f_{N,\,expan} = h_{N,\,expan} \sum_{leaf} \frac{C_N - C_{N,\,min}}{C_{N,\,crit} \times f_{c,\,N} - C_{N,\,min}} \tag{108}$$

where C_N is the nitrogen concentration of `Leaf` parts; $h_{N,\,expan}$ is multiplier for nitrogen deficit effect on expansion which is specified by `N_fact_expansion` in the wheat.xml (default value 1); $C_{N,\,crit}$ and $C_{N,\,min}$ are the N concentration critic and minimal of the parts, respectively (Figure 36); and $f_{c,\,N}$ is a factor with a value of 1 (i.e. no impact) for Stem, and is depending on CO_2 for `Leaf` (Figure 18).

The nitrogen stress on leaf appearance and expansion affects the potential leaf number ($N_{d,\,pot}$; Equation 55) and the stressed leaf area index ($\Delta \mathrm{LAI}_{d,\,s}$, Equation 60).

12.4.4 Grain filling (biomass and nitrogen demand of grain)

Nitrogen stress on grain filling affects the biomass demand of `Grain` (via $f_{N,\,grain}$ in Equation 49) and the N demand of `Grain` (Equation 101).

The nitrogen factor $f_{N,\,grain}$ (that impacts N demand of grain) is determined by the difference between organ nitrogen concentration and organ minimum and critical nitrogen concentration as follows:.

$$f_{N,\,grain} = \frac{h_{N,\ poten}}{h_{N,\ min}} h_{N,\,grain} \sum_{stem,\,leaf} \frac{C_N - C_{N,\,min}}{C_{N,\,crit} \times f_{c,\,N} - C_{N,\,min}} \qquad (0 \leq f_{N,\,fill} \leq 1) \tag{109}$$

where $h_{N,\ poten}$ is the potential rate of grain filling which is specified by `potential_grain_n_filling_rate` in wheat.xml and has a default value of 0.000055 g grain^{-1} d^{-1}; $h_{N,\ min}$ is the minimum rate of grain filling which is specified by `minimum_grain_n_filling_rate` in wheat.xml and has a default value of 0.000015 g grain^{-1} d^{-1}; $h_{N,\,grain}$ is a multiplier for nitrogen deficit effect on grain, which is specified by `n_fact_grain` in wheat.xml and has a default value of 1; C_N is the nitrogen concentration of `Stem` or `Leaf` parts; $C_{N,\,crit}$ and $C_{N,\,min}$ are critical and minimum nitrogen concentration, respectively, for `Stem` and `Leaf` parts. $C_{N,\,crit}$ and $C_{N,\,min}$ are functions of growth stage and nitrogen concentration which is defined by parameters `x_stage_code`, `y_n_conc_min_leaf`, `y_n_conc_crit_leaf`, `y_n_conc_min_stem`, `y_n_conc_crit_stem` in wheat.xml and linearly interpolated by APSIM (Figure 36); and $f_{c,\,N}$ is a factor with a value of 1 (i.e. no impact) for Stem, and is depending on CO$_2$ for `Leaf` (Figure 18).

13 Phosphorus

In the current version of APSIM-Wheat module, no phosphorus stress $f_{P,\,pheno} = 1$ is applied in the soil system through parameter labile_p in the source codes.

14 Temperature

As mentioned in previous sections, the temperature affects:

- crop phenology via the thermal time (ΔTT; Equation 4) and crop vernalisation (f_V; Equation 12), and via crop emergence (Equation 7),
- root depth growth (f_{rt}; Equation 66; Figure 26),
- radiation-limited biomass accumulation (ΔQ_r; Equation 13) via a stress factor (f_s), which depends on a temperature factor ($f_{T,photo}$; Equation 20),
- CO$_2$ effect on biomass accumulation via a temperature effect on the CO$_2$ compensation point (C_i; Equation 22; Figure 11),
- LAI senescence under minimum and maximum temperature ($\Delta LAI_{sen,\,frost}$, $\Delta LAI_{sen,\,heat}$; Equation 80 and Equation 81),
- biomass demand of `Grain` (D_g) and the rate of grain filling (Equation 49; Figure 1),
- N demand of `Grain` (Equation 101; Figure 37),
- VPD calculation (Equation 88).

15 Light

Light photoperiod is calculated as detailed in subsection 3.4. Photoperiod affects wheat phenology.

Light intensity and photoperiod also have an effect on diffuse light fraction (section 4.1.3), so that it could impact the diffuse factor (f_d; Equation 13; subsection 4.1) and reduce the radiation-limited biomass accumulation (ΔQ_r; subsection 4.1). However, in the current APSIM-Wheat, the diffuse factor equals to 1 (i.e. no impact of diffuse light on biomass production).

Light intensity affects

- radiation-limited biomass accumulation (ΔQ_r; subsection 4.1) via the radiation interception (I; Equation 15), which depends on the incoming radiation (I_0) and on a light-interception factor (f_h) based on the canopy width. However, this canopy factor has no impact in the current version of APSIM-Wheat ($f_h = 1$),
- LAI senescence under low light condition ($\Delta LAI_{sen,\,light}$; Equation 79).

16 CO_2

As mentioned in previous sections, CO_2 concentration affects:

- radiation-limited biomass accumulation (ΔQ_r; subsection 4.1) via a CO_2 factor affecting the RUE (f_c; Equation 22),
- transpiration efficiency (TE, Equation 87) via another CO_2 factor ($f_{c,\,TE}$; Figure 31),
- N critic concentration of the leaves (Equation 106, Equation 107, Equation 108, Equation 109 and Figure 18).

17 Vapour pressure deficit (VPD)

The vapour pressure deficit (VPD) is calculated as presented in Equation 88. VPD affects the transpiration efficiency (Equation 87) and thus the crop water demand (Equation 86).

References

Asseng, S., Fillery, I. R. P., Anderson, G. C., Dolling, P. J., Dunin, F. X., Keating, B. A., Jan. 1998a. Use of the APSIM wheat model to predict yield, drainage, and NO_3^- leaching for a deep sand. Australian Journal of Experimental Agriculture 49 (3), 363–378.

Asseng, S., Foster, I., Turner, N. C., 2011. The impact of temperature variability on wheat yields. Global Change Biology 17 (2), 997–1012.

Asseng, S., Keating, B. A., Fillery, I. R. P., Gregory, P. J., Bowden, J. W., Turner, N. C., Palta, J. A., Abrecht, D. G., May 1998b. Performance of the APSIM-wheat model in western australia. Field Crops Research 57 (2), 163–179.

Hochman, Z., Dang, Y. P., Schwenke, G. D., Dalgliesh, N. P., Routley, R., McDonald, M., Daniells, I. G., Manning, W., Poulton, P. L., 2007. Simulating the effects of saline and sodic subsoils on wheat crops growing on vertosols. Australian Journal of Agricultural Research 58 (8), 802–810.

Meinke, H., Hammer, G. L., van Keulen, H., Rabbinge, R., Keating, B. A., 1997. Improving wheat simulation capabilities in australia from a cropping systems perspective: water and nitrogen effects on spring wheat in a semi-arid environment. European Journal of Agronomy 7 (1-3), 75–88.

Meinke, H., Rabbinge, R., Hammer, G. L., van Vankeulen, H., Jamieson, P., 1998. Improving wheat simulation capabilities in australia from a cropping systems perspective II. testing simulation capabilities of wheat growth. European Journal of Agronomy 8 (1-2), 83–99.

Monsi, M., Saeki, T., 2005. On the factor light in plant communities and its importance for matter production. Annals of Botany 95 (3), 549–567.

Reyenga, P. J., Howden, S. M., Meinke, H., McKeon, G. M., 1999. Modelling global change impacts on wheat cropping in south-east queensland, australia. Environmental Modelling & Software 14 (4), 297–306.

Roderick, M. L., 1999. Estimating the diffuse component from daily and monthly measurements of global radiation. Agricultural and Forest Meteorology 95 (3), 169–185.

Sinclair, T. R., Nov. 1986. Water and nitrogen limitations in soybean grain production i. model development. Field Crops Research 15 (2), 125–141.

Tanner, C. B., Sinclair. T. R.,1983 . Efficient water use in crop production: research or re-search. In: Taylor, H. M., Jordan, W. R., Sinclair, T. R. (Eds.), Limitations to efficient water use in crop production. American Society of Agronomy, Madison, WI, pp. 1–27.

Wang, E., van Oosterom, E. J., Meinke, H., Asseng, S., Robertson, M. J., Huth, N. I., Keating, B. A., Probert, M., 2003. The new APSIM-Wheat model: Performance and future improvements. In: Unkovich, M., O'Leary, G. (Eds.), Proceedings of the 11th Australian Agronomy Conference. Australian Society of Agronomy, Geelong Victoria.

A Parameter list of wheat module

Variables	Units	Default Value	Description
Phenology			
tt_<phase_name>, (tt_emergence, tt_end_of_juvenile,tt_floral_initiation, tt_flowering, tt_start_grain_fill, tt_end_grain_fill, tt_maturity, tt_end_crop, tt_harvest_ripe)	°C	Figure 1	The thermal time target for all phases
x_temp, y_tt	°C, °Cd	Figure 3	The function between cardinal temperature and effective thermal time.
pesw_germ	mm mm^{-1}	0	Plant extractable soil water in seedling layer inadequate for germination
x_node_no_leaf, y_leaves_per_node	node rank in main stem	Figure 21	The function to define the potential new tiller number
shoot_lag	°Cd	40	Time lag before linear coleoptile growth starts
shoot_rate	°Cd mm^{-1}	1.5	Growing deg day increase with depth for coleoptile
fasw_emerg	[]	0.0 1.0	Fraction of available soil water
rel_emerg_rate	[]	1.0 1.0	Stress factor for thermal time calculation between germination and emergence
tt_emergence	°Cd	1	The thermal time for seed emergence
tt_end_of_juvenile	°Cd	400	The potential period from end of juvenile stage to terminal spikelet stage
twilight	°	-6.0	Twilight is defined as the interval between sunrise or sunset and the time when the true
photop_sens	[]	3	Sensitivities to photoperiod
vern_sens	[]	1.5	Sensitivities to vernalisation
N_fact_pheno	[]	100	Multiplier for N deficit effect on phenology
Biomass production			
x_stage_rue	[]	1 2 3 4 5 6 7 8 9 10 11	Numeric code for phenological stages
y_rue	g MJ^{-1}	0 0 1.24 1.24 1.24 1.24 1.24 1.24 0.00 0.00 0	The radiation use efficiency for each phenological stage
sen_rate_water	[]	0.10	slope in linear equation relating soil water stress during photosynthesis to leaf senescence rate
sen_light_slope	[]	0.002	sensitivity of leaf area senescence to shading
lai_sen_light	m^2 m^{-2}	7.0	induced senescence occurs by shading
x_sw_avail_ratio, y_swdef_pheno	[], []	Figure 33	The function between available soil water ratio and soil water stress of phenology.

Variables	Units	Default Value	Description
x_sw_avail_ratio_flowering, y_swdef_pheno_flowering	[], []	Figure 33	The function between available soil water ratio and soil water stress of phenology for flowering phase.
x_sw_avail_ratio_start_grain_fill, y_swdef_pheno_start_grain_fill	[], []	Figure 33	The function between available soil water ratio and soil water stress of phenology for grain filling phase.
x_stage_code, y_n_conc_min_leaf, y_n_conc_crit_leaf y_n_conc_min_stem, y_n_conc_crit_stem			The function between growth stage and minimum can critical nitrogen concentration.
x_row_spacing	mm	200 350 1000	
y_extinct_coef	[]	0.50 0.50 0.50	
Leaf growth			
leaf_no_at_emerg	[]	2	Leaf number at emergence
initial_tpla	mm^2 plant^{-1}	200	Initial leaf area per plant
node_no_correction	[]	2	The node number correction
min_tpla	mm^2 plant^{-1}	5.0	Lower limit of total leaf area per plant
x_lai, y_sla_max	mm^2 mm^{-2}, mm^2 g^{-1}	Figure 24	The function between leaf area index and specific leaf area.
x_lai_ratio, y_leaf_no_frac	[], []	Figure 22	The function between fraction of leaf area index and fraction of node number.
fr_lf_sen_rate	[]	0.035	Fraction of total leaf number senescing per main stem node
node_sen_rate	°Cd node^{-1}	60.0	Rate of node senescence on main stem
x_node_no, y_leaf_size	node rank in main stem, mm^2		The leaf size as a function of leaf number
leaf_no_pot_option	[]	2	The option to calculate the potential leaf number. The option 2 is for wheat.
x_sw_demand_ratio, y_swdef_leaf	[], []		The function between supply of soil water and water stress for leaf expansion.
N_fact_expansion	[],	1	Multiplier for N deficit effect on leaf expansion