# Crop Calibration – what data do you need? And why?

## 1 Introduction

We are often asked for a list of data required for crop calibration. It is quite difficult to provide such a list, because requirements differ depending on whether earlier crop calibrations have been carried out that can form a base for the work, or whether parameterization has to take place from scratch. It also depends on the purpose of the study, the level of detail required and whether you may want to introduce improved process descriptions. It is important already at planning phase of the experiment to understand how the Daisy submodules are describing plant growth in order to be able to pinpoint the right variables for a given study, and not least which assumptions are made in the model.

The Daisy crop model was developed to describe well drained Danish agricultural systems, meaning that the crops are well cared for and the yield levels are relatively high. The potential production in a given year is controlled by the genetics of the plant, the global radiation and the temperature, and the limiting factors considered by Daisy are water and nitrogen. The Daisy code does not include limitations of P or micronutrients, and it does not include pest attacks or serious weed competition (except if the weed can be handled as a separate crop in the field).

Traditionally, we have worked with “winter wheat” or “spring barley”, but there are often some significant differences between varieties, meaning that it may be preferable to work with one variety at a time or at least keep track of varieties used in the experiments to be modelled. Heidmann et al. (2008) describes a procedure for handling different varieties of potatoes tested across EU, and how to build a generic parameterization that can be used as a base for parameterizations of different varieties.

The first advice in Good Modelling Practice (Travis, 1995) is that:”The model user is responsible for understanding the model and its appropriate usage”. It is therefore important to understand why a given parameter is important and where it fits in the overall picture. This paper contains a short overview of the generic crop model, but additional features have been added for specific crops over time. As an example, a special function (nitrogen_stress_limit) was introduced for potatoes to increase the allocation of nitrogen to tubers under stress (Heidmann et al., 2008), and recently, a function was added for wheat to described dependency of assimilate partitioning on N-content (Gyldengren et al., in prep).

The structure of the paper is such that general issues, such as the plant environment, the Daisy language and the overall crop model are described in section 2-4.In the next sections, the most important processes and equations are described, followed by a description of measurements required. The steps of the calibration process are described in section 11. An example of a crop input file is attached as Annex I.

# 2 The environment of the plant

The outcome of all experimental work with plants will depend on the environment of the crop. The environment thus has to be properly described in the Daisy model before crop calibration can be done satisfactorily. Errors in the description of the environmental factors are likely to cause errors in the calibrated parameters. The environmental conditions that need to be described in the model can be divided into weather (upper boundary), groundwater/drainage conditions (lower boundary), the soil profile (growth medium), and management. If the plants are subject to optimal conditions with respect to water and nutrients all through the growing season, the detailed description of the soil conditions may be less important. If the plants are subject to water stress only, the soil moisture conditions are important, while the detailed N-dynamics are less important. However, for field experiments involving water or nitrogen stress, it will be necessary to ensure that the water and nitrogen conditions experienced by the plant are well described. This requires calibration of the system and therefore preferably good data to calibrate against. See more here.

The crop may also be subject to constraints not included in the Daisy model (P, K, Mn, other nutrients or micronutrients). The model can still be calibrated, but its general validity may be questionable. If the crop has been subject to a significant weed-pressure or pests and diseases, the data are not suited for crop calibration.

Although the general rule is that soil conditions should be calibrated before the crop calibration, it is important to remember that there is an interaction and some iteration may therefore be necessary. If the plant develops faster than expected, the water consumption may be higher and therefore influence the water content of the soil at a particular time. Faster or slower root growth or a different actual length of growing period than anticipated in the original calibration also influences the water and perhaps N-balance.

## 2.1 Weather

The minimum requirement with respect to weather data are daily values of rainfall, temperature and global radiation. For crop calibration purposes, particularly the rainfall should be measured locally. Daily min-max-temperatures are considered better than average temperature. Both temperature and global radiation should be provided from a near-by station if not available locally.

Additional access to data for wind speed and relative humidity allows the use of the Penman Monteith-equation for evapotranspiration and therefore a more precise assessment. Hourly values of weather parameters are even better and are absolutely necessary if detailed measurements (water content, soil water potential, eddy covariance etc.) are available. See more here.

## 2.2 The lower boundary condition

The moisture conditions of the soil profile are influenced by the presence/absence of groundwater and drainage conditions. It is impossible to describe occurrence of water stress or nutrient movements correctly without a correct description of the lower boundary condition. If the groundwater always is below 3-4 m's depth, "free drainage" can be selected as the boundary condition. In coarse sandy soils, the groundwater may be shallower and still not affect the root zone. If the groundwater level is within the upper meter for part of the year, the soil is typically drained. It is then necessary to know the depth and spacing of drains,

and measurement of the groundwater level is recommended. Other indirect indicators of the groundwater level would be the actual drain flow (measured as a time series) or the periods where drain flow is observed. If the field is close to a stream, the variation in water level in the stream may be a proxy for the variation in groundwater level.

If groundwater is found between 1 and 3 m, measurement of the groundwater level is recommended. Measurement of moisture conditions at different depth in the profile using TDR may be an indirect way of establishing the boundary conditions.

## 2.3 Soil profile

The minimum requirement for the soil profile is a description of the soil horizons within the root zone (remember that the root zone can be well below 1 m for some crops). A description of a soil horizon consists of the soil texture (make sure you know which textural division was used in the analysis), bulk density, organic matter content and preferably C/N-ratio. Particularly if water and nutrient stress is investigated, it is preferable to measure the hydraulic parameters (moisture retention curve and hydraulic conductivity). Detailed calibration of root water and nutrient uptake, water stress etc., will benefit from measurements of water content (TDR) or water potential in the soil at different depths.

## 2.4 Management

A description of crop management includes the tillage operations carried out before sowing (date and type of operation, sowing time and seed rate, fertilization date(s), type, and amount, and irrigation dates and amounts if relevant. With respect to harvest, the harvest date is required as well as information about stubble height and which fraction of the harvested products (primary and secondary products, e.g. grain and straw) that stays on the field.

## 2.5 Initial conditions

The crop growth in a particular year is influenced by what happened on the field earlier. It is therefore necessary to know the conditions at simulation start or to generate them through modelling. A “hot start” will require information about water content in the different calculation points in the soil, the groundwater level, the content of nitrate and ammonia and the distribution of organic matter in the different organic pools in Daisy. This information is hardly ever available. Instead we set up the model with the best information available for a number of years before the year to be simulated. The water balance is usually well initialized with an initialization of one year, but particularly organic matter turn-over requires a longer period. How long also depends on the crop rotation and organic matter input in the system. If possible, do at least a 5 year warm up-period to get the organic pools properly initialized. The main issue during initialization is to get at least the relatively fast responding organic matter pools calibrated reasonably well, so the net-mineralization level is approximately right as well as the level of mineral nitrogen in the soil at the beginning of the simulation. Including a “0”-fertilizer level in the experiment can provide very useful information about the mineralization level. As mentioned earlier, these conditions are particularly important if the plant is subject to water and/or N-stress during the growth.

**Table 1. Overview of environmental parameters required for calibration of a crop. For specific crop processes additional measurements may be required.**

| Type of data | Minimum requirement | Better | Comment |
|---|---|---|---|
| Weather | Daily values of:<br>Rainfall<br>Min and Max Temp,<br>Global radiation | Wind speed<br>Relative humidity<br>Hourly values of weather parameters | All variables should be retrieved from stations nearby, but rainfall is particularly important to collect locally. |
| Lower boundary condition | Where is the groundwater?<br>Drainage depth and density if present<br>When are the drains running? | Measurement of drain flow<br>Measurement of groundwater level (piezometers)<br>The level and variation in a nearby stream. | If the calibration includes water stress and/or nutrient stress, the correct description of the lower boundary condition is paramount. |
| Soil profile | Soil horizons in the root zone,<br>For each horizon:<br>Texture, bulk density, OM and C/N-ratio. | Moisture retention curves and saturated and unsaturated hydraulic conductivity. | Continuous measurements of soil moisture (TDR) and/or water potential at different depths are useful for calibration of soil moisture conditions and provide additional information about root depth and water uptake at different depths. |
| Management | Tillage operations:<br>Date, type of operation, working depth | | The description of tillage operations are present in tillage.dai (lib). |
| | Sowing:<br>Date, crop, amount of seed applied. | It is possible to specify row width and row position (see sow_base in ref. manual), but it is mainly relevant for 2-D simulations. | Daisy does not include a depth of sowing at present<br>By default, Daisy will assume that the seed are equally spaced. |
| | Fertilization<br>Date, type and amount applied. | For organic fertilizer, DM%, C% and N% as well as $NH_4$-fraction is useful. | See tutorial.<br>Volatilization from organic manure has to be specified by the user. |
| | Irrigation:<br>On actual experiments, date and amount applied should be specified | | Daisy can irrigate according to different rules (e.g. moisture content or suction). |
| | Harvest:<br>Date, crop, stub height and fraction of the primary and secondary product harvested. | | See also section….<br>For crops with multiple cuts, see also the tutorial. In this case the DS-value is set back to a specified value when harvesting. |
| Initial conditions | What was grown on the field earlier and how was it treated?<br>Weather data for the warm-up period. | A plot with 0 fertilizers to provide a measure of background mineralization. | A good estimate of background mineralization is very important when working with N-stress. |

# 3 Daisy setup language

Please familiarize yourself with the Daisy language through the tutorial and the initial chapter of the reference manual. However, below some examples are given using the syntax of that language. The general form is

```
(name value)
```

Where name is the *name* of a specific parameter, and *value* is the value of the parameter. Most parameters have a simple numeric value, which consist of a *number* (like `20.1`) and a *unit* (like `[dg C]`). The unit is surrounded by square brackets. For example

```
(T 20.1 [dg C])
```

Daisy knows some common units and can convert between them, so we could instead have written:

```
(T 293.25 [K])
```

and got the same result. The other kind of value used in the document is a **piecewise linear function**, which is written as a sequence of `(x y)` pairs separated by whitespace. Both *x* and *y* are numeric values like above, and the *x* values must be increasing. For example

```
(TempEff (4  [dg C] 0 []) (10 [dg C] 1 [])
         (25 [dg C] 1 []) (35 [dg C] 0 []))
```

The value will be a function that has the specified value for each `(x y)` pair, and which does linear interpolation between the points. The function will have a constant value outside the specified range, defined by the first and last point respectively. The value for `TempEff` is depicted below.

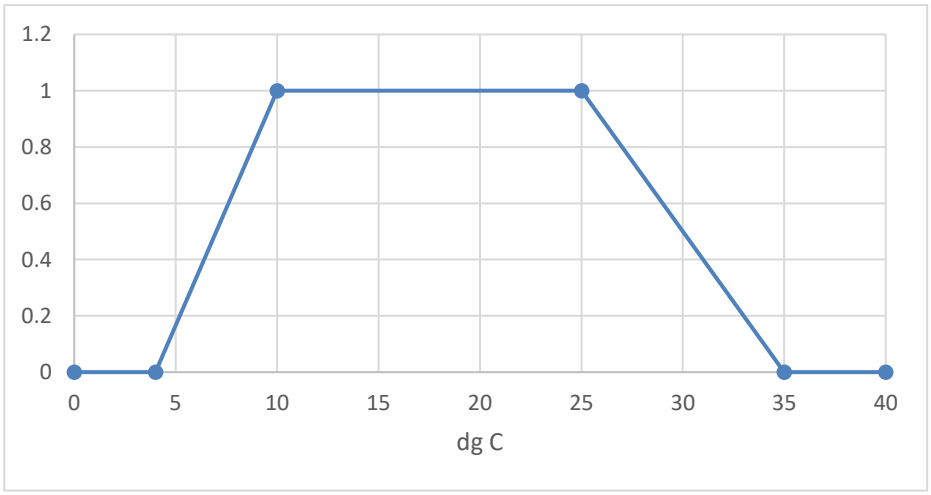


**Figure 1. Example of a piecewise linear function (plf). See text for details.**

This example could be used for a process that is most efficient between 10 and 25 dg C, and not active below 4 dg C or above 35 dg C.

# 4 The basics of the crop model

A general overview of the crop model is shown in Figure 2. Photosynthesis is driven by "photosynthetically active radiation" (PAR) and is dependent on temperature. Plant growth is driven by the assimilate (sugar molecules) generated through photosynthesis. Assimilates are allocated to different parts of the plant as a function of development stage. The growth of the different organs in turn feeds back on photosynthetic capacity and uptake of water and nitrogen. $CO_2$ is lost due to respiration and conversion of assimilate, and leafs and roots may die off during the growing season. Most of the processes are influenced by temperature. The parameterization, however, differ (sometimes considerably) for different crops, and the overall scheme may also be modified in different ways. Crop calibration focusses on determining and describing the parameters for conversion and growth as well as their dependency on environmental factors, such as temperature.

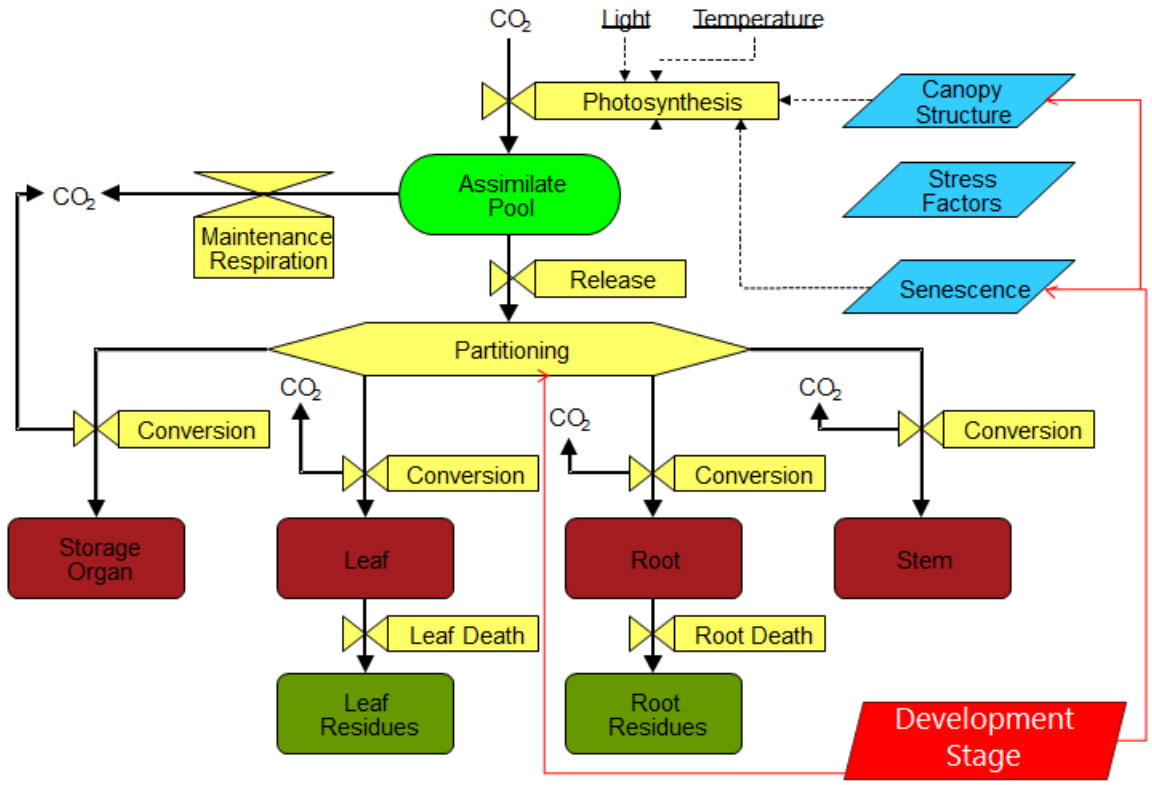


Figure 2. The overall principles of the Daisy crop models.

# 5 Crop Phenology

## 5.1 What does the model do?

In the Daisy model, the crop stage is described by the development stage (DS), which acts as a counter in the model. This counter only has the physical/biological meaning we assign to it and is the only variable which can be calibrated independently of other crop parameters, as it is mainly governed by external factors such as temperature and photoperiod. Unfortunately there is no direct conversion between DS and established plant stage classifications, as this was not prioritized in the past. It would be very beneficial to establish a relationship, as much research on plant physiology and growth available in international literature link specific processes to specific crop stages. Keeping a record of dates and crop stages throughout your experiment is therefore useful information. The Daisy growth stage is -1 at sowing, 0.01 at emergence, 1 at flowering (or earing in grain crops) and 2 for a mature crop.

### 5.1.1 Emergence

Emergence is governed by the soil temperature sum at emergence, calculated from the date of sowing and the moisture conditions during the period. DS at emergence (DS_Emr) is given a value, which by default is 0.01. The process is described as:

$$T_{sum} = \sum_{sow.date}^{present} \left( T_{soil} * \Delta t * f(h_p) \right) \qquad (5.1.1)$$

where

- $T_{sum}$ = the soil temperature sum at emergence [deg C d], calculated from the date of sowing. In Daisy: EMrTSum,
- $T_{soil}$ = The average soil temperature at sowing depth [deg C]
- $\Delta t$ = the time step of the model (1 for daily values)
- $f(h_p)$ = a function describing the influence of soil moisture levels, expressed as tension . In Daisy: EmrSMF. The default values are *(EmrSMF (-1000 [cm] 1[]) (-150 [cm] 1[]) (-50 [cm] 1[]) (-30 [cm] 1[]))*, equal to no effect.

The moisture relationship is a piecewise linear function that can be used to modify emergence. As shown above, the default value is equal to no effect of moisture on emergence, but emergence can be reduced by the user by specifying a value less than 1 when the soil is particularly dry or wet. Both the temperature sum and the modifier-function may be calibrated.

It is possible to specify a lower temperature limit (EmrThrs [dg C]), which is the minimum soil temperature for emergence. The default value is 0 [dg C]. Temperatures below this value will not count in the sum.

### 5.1.2 Vegetative stage

During the vegetative stage, the DS-value usually increases from 0.01 to 1, which represents flowering in most crops and earing in at least winter wheat and spring barley. The rate of increase for the vegetative stage (DSRate1) can be modified by temperature and photoperiod. A number of other functions in the growth description are closely tied to the DS-value (e.g the partitioning of assimilate, see section 7.3.2) because processes differ depending on the growth stage of the plant.

Daily increments of the development stage, $\Delta D$, are calculated as:

$$\Delta D = d \; f_t(T_a) \; f_d(D_l) \tag{5.1.2}$$

where

- $d$ = the development rate at reference temperature and reference day length [DS/d], in Daisy DSRate1 for the vegetative stage.
- $T_a$ = The average daily temperature [deg C]
- $f_t(T_a)$ = modifying plf-function accounting for air temperature []. In Daisy TempEff1 for the vegetative stage.
- $f_d(D_l)$ = modifying plf-function accounting for day length []. In Daisy PhotEff1 for the vegetative stage.

Examples are shown below:

*(TempEff1 (0. [deg C] 0.30 []) (10. [deg C] 0.30 []) (15. [deg C] 0.75 []) (25. [deg C] 1.00 []) (35. [deg C] 1.20 []))*

*(PhotEff1 (0. [h] 0.90 []) (12. [h] 1.00 []) (14. [h] 0.95 []) (16. [h] 0.90 []) (24. [h] 0.90 []))*

In this case, the growth rate is reduced to 30 % at temperatures below 10 $^{o}$C and the growth rate also reduced if the day length is below or above 12 hours. The day length is defined as the number of hours[1] where the top of the canopy receives more than 12.5 W/m$^2$ in average. This will usually be close to the astronomically defined day length, e.g. http://ptaff.ca/soleil/?lang=en_CA, but may differ especially for undersown crops.

The development rate and the modifying functions can be calibrated.

### 5.1.3 Vernalization

Some crops require vernalization during the vegetative phase. This means that it requires a cold period to proceed in its development.To following parameters are used to describe this in Daisy:

i. DSLim [DS]: DS-value when the vernalization requirement sets in,
ii. TaLim [dg C]: Required temperature threshold.
iii. TaSum [dg C d]: Temperature sum required for the plant to develop further. The temperature sum is calculated as the difference between the actual temperature and TaLim, so it needs to be negative.

If DS = DSLim and $T_a < T_{a,Lim}$

$$\begin{aligned} DS &= DS \\ T_{sum}^{vern} &= \sum \left( T_a - T_{a,\lim} \right) \end{aligned} \tag{5.1.3}$$

Until the required temperature sum is reached.

[1] More precisely, the sum of the length of the time steps during which the average radiation is above the specified threshold. This means the day length depends on the temporal discretization used.

All three parameters may be calibrated, but it is recommended to build on available studies for the crop in question. It is, however, likely that some variation exists between crop varieties.

### 5.1.4 Other modifiers of DS

The crop module includes other ways to modify DS for particular events, such as Harvest actions/cuts (e.g. grass). DSnew is the value off DS after harvest, and DSmax, which is the maximum DS-value for which the crop survives a harvest or cutting action. The progress of the DS-value stops if respiration becomes higher than the photosynthesis on a daily basis.

### 5.1.5 Reproductive stage

During the reproductive stage, the DS-value usually increases from 1 to 2. The equation is similar to equation (1.1.2), but there is no dependency on daylength. The rate of increase for the vegetative stage (DSRate2) can be modified by temperature (TempEff2), similarly to the modification in the vegetative phase. Both DSRate2 and the temperature modification can be calibrated.

In reality, the actual growth stages may be influenced by other stressors than included here, but a basic assumption in the model is that the plants are not severely stressed, particularly not by factors other than water and nitrogen.

## 5.2 Measurements

### 5.2.1 Emergence

Data requirements for calibration of emergence are summed up in Table 2. There may be information in literature concerning minimum temperature for germination which can be used for the estimating the required temperature sum. As described in section 2, weather and soil data are required to, as a minimum, allow calculation of soil temperature and soil moisture conditions.

**Table 2. Information required for calibration of emergence.**

| | Minimum req. | Better | Comment |
|---|---|---|---|
| Sowing date | measured | More than one year | |
| Date of emergence | measured | More than one year | |
| Weather and soil data | Soil temperature and moisture conditions may be simulated by Daisy based on the adopted setup and calibration of the soil column | Local measurements of soil temperature and moisture conditions. | See section 2 |

In many cases information about sowing date and date of emergence may be available, but the temperature at sowing depth is not. Instead, the temperature estimated by the model is the base of the calibration. Generally, the soil temperature is estimated using air temperature as the upper boundary condition. This has a tendency of underestimating the actual temperature when the soil is bare (which is the typical situation at germination), but the calibration compensates for this.

The more advanced "Sun Shade Open Canopy" (SSOC)-SVAT model (Plauborg et al., 2010) allows calculation of soil temperature based on energy balances and may, if well calibrated, provide a better estimate of the soil temperature at the time of emergence. The temperature sum for a given crop should most probably be higher, if this module is used. This model can only be used with detailed weather data and the Farquhar photosynthesis model (section 10), and the full model is not described in this document.

If data for several years are present, it may be possible to calibrate the moisture relationship ($f(h_p)$ in equation (5.1.1) or EMrSMF). It is possible to slow down emergency during particularly wet or dry conditions.

### 5.2.2 Vegetative stage

Data requirements for the vegetative phase are summed up in Table 3. As mentioned earlier, it would be beneficial to tie DS to well-known growth stage measures (e.g. BBCH-stages), which may also help define the points in time where allocation of assimilate to different organs change or where the governing N-concentrations in different organs changes. A Daisy crop requires, of course, a medium to grow in, but the calculation of DS in the vegetative stage is not influenced by this, particularly not if stresses are deactivated.

Vernalisation requirements may be described in literature.

**Table 3. Information required for calibration of phenology in the vegetative phase.**

| | Minimum req. | Better | Comment |
|---|---|---|---|
| Date of emergence | Measured | More than one year | |
| Date of flowering/earing | Measured | More than one year | |
| Date of important growth stages between the two. | | Measured, More than one year | This may be particularly relevant in connection with vernalisation in order to match the dormant period. |
| Dates of any management interventions | Recorded | | e.g. harvests, cuts. |
| Weather data | Must be available | More than one year | See section 2 |
| Photoperiod | | | Calculated by Daisy |
| Temperature close to the soil surface | Simulated by Daisy sub-modules based on air temperature or radiation balances based on adopted setup and calibration of the soil column. | Measurements close to the soil surface. | Generally we have relied on air temperature, but recent research indicates that this may be improved. This, however, requires more detailed weather data, the SSOC module and Farquhar photosynthesis. |

### 5.2.3 Reproductive stage

As for the vegetative phase, registration of important growth stages may help defining changes in allocation patterns in the plant at a later calibration stage.

**Table 4. Information required for calibration of phenology in the reproductive phase.**

| | Minimum req. | Better | Comment |
|---|---|---|---|
| Date of flowering/earing | Measured | More than one year | |
| Date of maturity | Measured | More than one year | Based on judgement of when the crop is ready for harvest. |
| Date of harvest | Recorded | More than one year | |
| Date of important growth stages between the two. | | Measured, More than one year | |
| Weather data | Must be available | More than one year | See section 2 |

# 6 Conditions at emergence

## 6.1 What does the model do?

When the Daisy plant emerges, the initial growth is governed by carbon release from the seeds. The amount of seed sown has to be specified together with the dry matter fraction as well as the C and N-fractions. A carbon release rate determines the allocation of seed carbon to the assimilate pool, which can then be moved to leaves and root.

$$\frac{dC}{dt} = r_{C-release} * W_{seed} * f_{DM} * f_C \qquad (6.1.1)$$

Where

- $r_{C\text{-}release}$ = the rate of carbon release from the seed [$h^{-1}$]. In Daisy: rate.
- $W_{seed}$ = the seed weight [kg $ha^{-1}$]. The initial weight of seed is generally specified at sowing.
- $f_{DM}$ = dry matter fraction of the seed[]. In Daisy DM_fraction.
- $f_C$ = the fraction of carbon in the dry matter []. In Daisy: C_fraction.

Photosynthesis takes over, as the leaves form, and the relationship between leaf dry matter and $L_{ai}$ is determined by the specific leaf area as described below:

$$L_{ai} = S_{ai} W_t \qquad (6.1.2)$$

where

- $L_{ai}$ = Leaf area index[2] [$m^2 m^{-2}$]
- $S_{ai}$= Specific leaf area [$m^2 g^{-1}$]
- $W_t$= weight of leaf dry matter [g]

The full nitrogen content of the seeds is available for the crop right away (no release rate).

The plant is assigned an initial rooting depth (DptEmr), which by default is 10 cm. Assuming a sowing depth of 5 cm, a root depth of 10 cm corresponds to twice the sowing depth. Thus, in this case the seed sends roots down with the same rate as it growth up towards the surface.

Some older parameterizations use a different model where the leaf area used for photosynthesis in initially not directly dependent on the amount of dry matter in the leaves, and the seeds are ignored. This model is complex, fragile, and should not be used for new parameterizations.

[2] Daisy uses an effective leaf area index (or green crop area index), which at emergence are equal to the leaf area index. However, at later stages, other plant organs may contribute to photosynthesis and this has to be accounted for, see later.

## 6.2 Measurements

The amount of seed sown should be recorded, and for comparison with other varieties, 1000-grain weight may be of interest. This can be interpreted as an indicator of energy in the seed. If the "release" module is used, the dry matter percentage as well as the fractions of carbon and nitrogen in dry matter are required.

Good calibration of the initial growth require early measurements of LAI and specific leaf area and some indications of early root growth may be beneficial.

**Table 5 .Measurements of relevance for describing the emergence.**

| | Minimum req. | Better | Comment |
|---|---|---|---|
| Amount of seed sown | To calibrate the "release module", kg seed/ha | | If comparison of varieties, 1000-grain weight may be of interest |
| Sowing date and Date of emergence | See phenology | | |
| LAI | Early recordings | Additional photos of coverage | |
| Specific leaf area | From literature | Measured | The parameter typically varies over the growth season. |
| Early root growth | From literature | If known, the initial root penetration and rate of root growth can be evaluated. | |

# 7 During the growing season

During the growing season, the carbon stocks are built up through photosynthesis, and the assimilated carbon may be used to build the different organs or be lost as maintenance- and growth respiration. The processes will be described separately below. Some of the required parameters can be measured under laboratory conditions, but in many cases, the parameters can only be indirectly established. This is particularly the case if we only have measurements from the field. This means that we have to combine data from different sources, and it is necessary to question whether they are valid for the conditions we would like to represent.

In general, the basic crop calibration should be carried out under conditions where the plants are not stressed by lack of water or nutrients, so the responses to temperature and light can be determined. When calibrating responses to lack of water or N, stresses should, of course, be included.

## 7.1 Distribution of the canopy

### 7.1.1 What does the model do?

In the model the canopy structure is defined by the Leaf Area Distribution (LAD) as function of plant height. The leaf area index ($L_{ai}$) is the integral of LAD over height. If we have more than one crop, the distributions can be added to a composite canopy, and this is important with respect to competition for light.

The LAD is described by a row of three numbers (*Z1*, *Z2 and Z3*). *Z1* is the fraction of the height where the lowest leaves are present. *Z2* and *Z3* are the fraction of the height between which the highest leaf density is found. The highest point in the distribution always equals the plant height. The LAD is described at emergence (LAIDist0) and at DS=1 (LAIDist1). Between the two growth stages, a linear development is assumed.

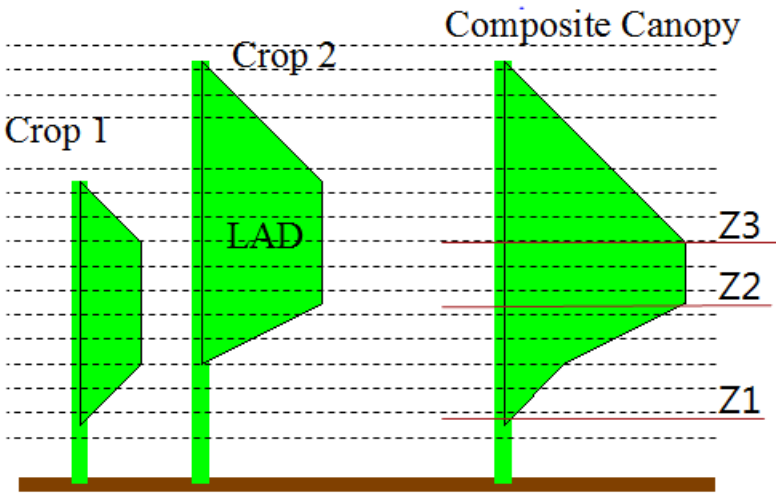


**Figure 3. Two crops with different Leaf Area distributions, combined to a composite canopy. The fractions of plant height, Z1, Z2 and Z3, used to describe the crop canopy are indicated.**

Example:

(0,0,1) describes a system where Z1 and Z2 are both located at ground level and Z3 at the top of the plant. In this case the leaves are evenly distributed along the whole height of the plant.

(0.1, 0.8, 1) describes a system where there are no leaves on the lower 10 % of the stem and the between 0.1 and 0.8, there is a linear increase in leaf density and the maximum leaf density is present in the upper 20 % of the crop height.

(0.1, 0.6, 0.9) describes a system where there are no leaves on the lower 10 % of the stem and between 0.1 and 0.6 there is a linear increase in leaf density. The maximum leaf density is present between 60 and 90% of the crop height. Between 90 and 100 % of the height the leaf density decreases from max to 0.

As mentioned earlier, the LAD and crop height is particularly important if crops are grown together, as it will govern the light distribution between the crops. However, together with the specified stubble height, it also influences the amount of leaves harvested.

These values are usually specified based on field data and not calibrated.

The actual leaf area index (LAI) at a specific time is calculated as

$$L_{ai} = S_{la} W_{leaf} \tag{7.1.1}$$

where

- $L_{ai}$ is LAI [$m^2$ $m^{-2}$],
- $S_{la}$ is specific leaf area, which is assumed to be a function of DS [[($m^2$ $m^{-2}$)/(g DM $m^{-2}$)]. The parameter is called SpLAI in Daisy, and the modifying function LeafAIMod.
- $W_{leaf}$ is leaf weight, which is updated hourly based on photosynthesis [g DM $m^{-2}$].

Stem and storage organs may also contribute to an efficient LAI. Their contribution is calculated analogous to the contribution from the real leaves using specific area and weight for stem and storage organs, respectively. In addition, weight factors accounting for the different photosynthetic efficiencies of stem and, storage organs are used in the calculation of the efficient LAI. The weight factor is calculated as the ratio between the photosynthetic rates at saturated light intensity for the stem or storage organ to the corresponding value for the leaf. SOrgPhotE and StemPhotE []are the relative photosynthetic efficiency of the storage organ and stem, respectively. If necessary parameters are missing, then the contribution from stem or storage organs is neglected. LAD is calculated from efficient LAI and a predefined relative LAD distribution, which is a function of DS.

### 7.1.2 Measurements

As Daisy describes field conditions, the parameters should illustrate the conditions in a field, which usually means a relatively dense stand (in comparison to single plants in pots).

Table 6. Plant height and Leaf Area Distribution descriptors.

| | Minimum req. | Better | Comment |
|---|---|---|---|
| Plant height | From literature | From experiments with your specific variety | For many crops, plant breeding has led to shorter varieties |
| *Z1, Z2 and Z3* | Visual inspection of fields | | |
| Specific Leaf area | From literature | The parameter can be estimated from measurements of leaf area and weighing at different growth stages. | |

## 7.2 Photosynthesis

Daisy is equipped with a standard description of photosynthesis and a more advanced version using a Farquar-description. The standard description is found below, while the advanced version is described in section 10.

### 7.2.1 Photosynthesis – the standard model

#### *7.2.1.1 What does Daisy do?*

The driver of the photosynthesis is photosynthetic active light (PAR). The photosynthesis model is based on the calculation of light distribution within the canopy (or composite canopy) and single light response curves. The light distribution within the canopy is calculated on basis of Beer's law. The extinction coefficient is assumed to be a characteristic for a given crop, and so is the reflection coefficient. In the calculation of the light distribution, the canopy is divided into *n* distinct layers each containing 1/*n* of the total efficient LAI. By applying Beer's law the adsorption of light within layer *i*, counted from the top of the canopy, can be calculated as:

$$S_{a,i} = (1 - \rho_c) S_{v,0} \left( e^{-k_c (i-1) \Delta L_{ai}} - e^{-k_c i \Delta L_{ai}} \right) \qquad (7.2.1)$$

where

- $S_{a,i}$ is the absorbed light in layer *i* [W m$^{-2}$],
- $\rho_c$ is the reflection coefficient of the canopy [], in Daisy PARref,
- $S_{v,0}$ is the incident light above the canopy [W m$^{-2}$],
- $k_c$ is the extinction coefficient [], in Daisy PARext, and
- $\Delta L_{ai} = L_{ai}/n$ is the effective leaf area index [m$^2$ m$^{-2}$] within each canopy layer.

Gross photosynthesis is calculated for each individual crop, layer by layer, by applying a light response curve:

$$\Delta F_i = x\,\Delta L_{ai} F_m \left(1 - \exp\left(-\frac{\varepsilon}{F_m}\frac{S_{a,i}}{\Delta L_{ai}}\right)\right) \qquad (7.2.2)$$

where

- $\Delta F_i$ is the gross photosynthesis for layer $i$ for the considered crop, [g $CO_2$ $m^{-2}$ $h^{-1}$]
- $x$ is the LAI fraction of the considered crop []. x=1 if only one crop is grown.
- $F_m$ is a crop specific photosynthetic rate at saturated light intensity, (Fm) [g $CO_2$ $m^{-2}$ $h^{-1}$] and
- $\varepsilon$ is a corresponding initial light use efficiency at low intensity (Qeff) [g $CO_2$ $m^{-2}$ $h^{-1}$/(W $m^{-2}$)].

The shape of the curve is shown in Figure 4. $F_m$ is not a constant, but is assumed to be a function of temperature, which is taken into account indirectly, see below. The gross photosynthesis is calculated by accumulating the contribution from the individual layers. The time-step in this part of the model is one hour and the produced assimilates are transferred hourly to the carbohydrate reserves, Figure 1.

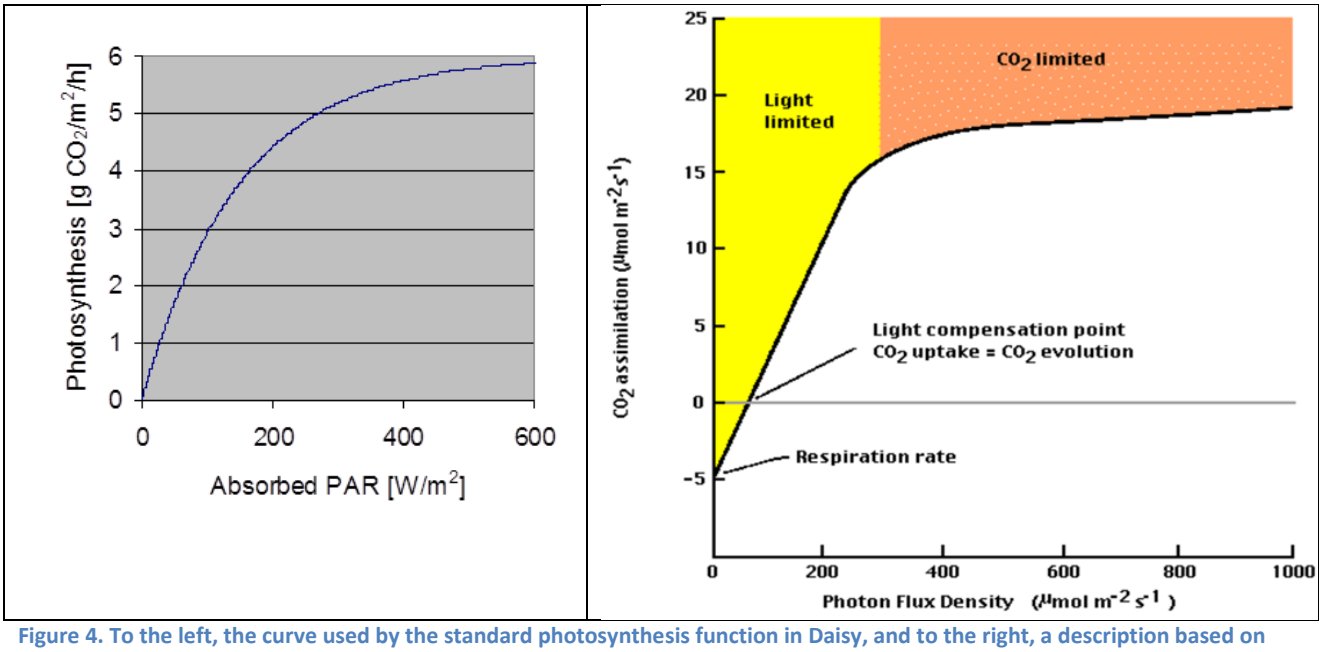


**Figure 4. To the left, the curve used by the standard photosynthesis function in Daisy, and to the right, a description based on plant physiology, as described in the Farquar-model (Section 10). $Q_{eff}$ corresponds to the slope during the light-limited phase, while $F_m$ equals the maximum rate, where $CO_2$ is limiting.**

Leaves require a certain amount of light to sustain them. The available light is reduced as it passes through the leaf layers. Leaves (at the bottom of the canopy) receiving less than "PARrel", which default is 5 % of the incoming light, die off (see also senescence, section 7.4.1).

The efficiency of the photosynthetic system may be influenced by temperature or by plant age. Both relationships are described as plf-functions. The temperature factor (TempEff) can be used to describe the relationship between gross assimilate production and temperature, and the age-factor can be described by DSEff, where the gross assimilate production is regulated with plant stage. This is substantiated in studies of e.g. winter wheat, particularly for the later part of the reproductive phase. I

$F_m$, $Q_{eff}$, TempEff and DSEff can be calibrated. Reflection and extinction coefficients should preferably be based on literature values or measurements.

Photosynthesis may be influenced by water and N-stress. The assimilate production when the plant is water stressed may be described as:

$$F_w = F_p * f\left(\frac{E_t + E_i}{E_{t,p} + E_{i,p}}\right) \qquad (7.2.3)$$

where

- $F_w$ = water-limited photosynthesis, [g $CO_2$ $m^{-2}$ $h^{-1}$]
- $F_p$ = potential photosynthesis, [g $CO_2$ $m^{-2}$ $h^{-1}$]
- $E_t$ and $E_{t,p}$ = actual and potential transpiration, [mm $h^{-1}$]
- $E_i$ and $E_{i,p}$ = actual and potential evaporation of intercepted water [mm $h^{-1}$]
- $f$ = a function that describes the crop response to water stress. Its Daisy name is wse []

The water stress function may be disabled all together (none), it may be described solely by the fraction in the brackets above (full), or it may be a modified function (partial), which is defined by the relative production level when the fraction in the brackets is 0.5.

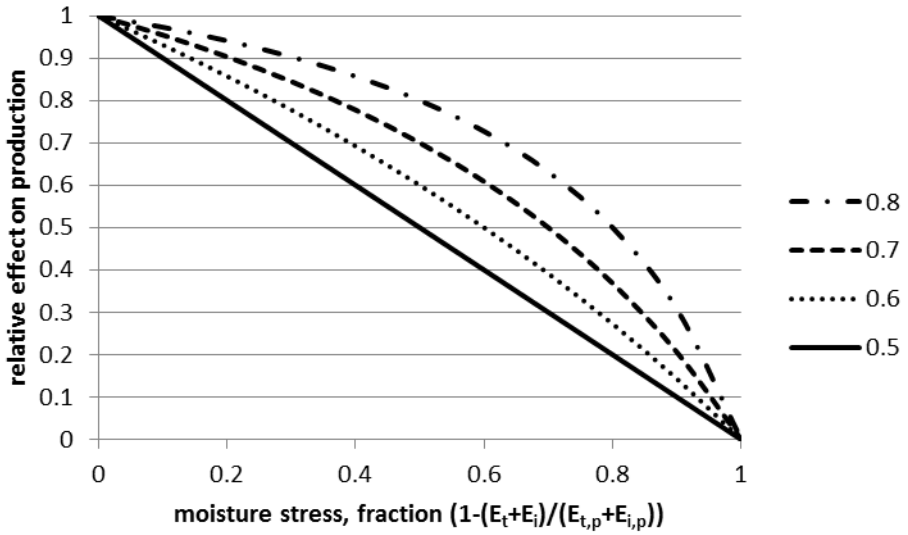


**Figure 5. Examples of effects of moisture stress on crop growth defined based on the reduction in production at a moisture stress fraction of 0.5. The straight line is equal to the default effect (full).**

The function describing the curves in Figure 5 is defined as

$$f = \frac{y_{0.5} * (1 - x)}{(1 - 2 * y_{0.5}) * x + y_{0.5}} \quad (7.2.4)$$

Where $y_{0.5}$ is the relative production level when the water stress fraction is 0.5.

However, before entering into a calibration of water stress, soil and weather conditions must be well described. This also applies to the governing factors for water uptake by the plant such as root development. The influence of nitrogen status on photosynthesis is described in section 7.7.1, equation (7.7.3).

#### *7.2.1.2 Measurements*

The photosynthetic active light (PAR makes up about half of the incoming radiation which is an absolute requirement for simulations. To quantify the absorbed photosensitive active radiation (PAR), the model requires a reflection and extinction coefficient of the crop canopy. These values may be found in literature or estimated from measurements under controlled conditions.

The most commonly used photosynthesis description in Daisy require a value for the quantum efficiency at low light ($Q_{eff}$) [(g $CO_2$/$m^2$/h)/(W/$m^2$)], a maximum assimilation rate ($F_m$) [g $CO_2$/$m^2$/h] and a temperature factor for assimilate production, described as a piecewise linear function (plf). Such information may also stem from experiments under controlled conditions or literature. Typically, photosynthesis is not expected to take place below the freezing point and is hampered at high temperatures, but more detailed information about the temperature response may be available from plant physiological studies. The decrease of photosynthetic efficiency that often takes place towards the end of the growth period may also be determined in the laboratory or indirectly from regular crop cuts and weight determination of the different crop components. The same is the case with photosynthetic capacity of other storage organs. For spring barley, for example, the photosynthetic capacity of the storage organ itself (flag leaf and green parts) appear to have been necessary elements to reach the observed yield in some calibrations.

Eddy covariance measurements have been used to estimate $CO_2$-fluxes to and from a canopy and compare to Daisy simulations, but the rate of photosynthesis is generally not measured in field experiments. $F_m$ then becomes a calibration factor.

Chapter 2.1 of Penning de Vries et al. (1989) (http://edepot.wur.nl/108856) describes $Q_{eff}$, observed temperature dependency for $Q_{eff}$ for C3 and C4-plants and levels of $F_m$ at optimal temperature for a number of crops. However, it should be noted that particularly the temperature response may be altered through plant breeding.

It is important to remember that indirect measurements such as biomass are functions of photosynthesis, respiration and modifying factors all together.

Table 7 .Measurements of parameters for photosynthesis.

| | Minimum req. | Better | Comment |
|---|---|---|---|
| Photosynthetic efficiency over time<br>$Q_{eff}$<br>$F_m$ | From literature | Measured under controlled conditions or in the field | <br>[(g $CO_2$/$m^2$/h)/(W/$m^2$)]<br>[g $CO_2$/$m^2$/h]<br>Calibrated in field experiments |
| Reflection coefficient of crop canopy | From literature | Measured under controlled conditions or in the field | Seldom calibrated, [] |
| Extinction coefficient of crop canopy | From literature | Measured under controlled conditions or in the field | Seldom calibrated, [] |
| Temperature effect on photosynthesis | From literature | Measured under controlled conditions | []. For many crops, this effect is altered over time through plant breeding. |
| Contribution to photosynthetically active area from green stems or storage organs | Often not considered | Measured under controlled conditions or in the field | May be important. The flag leaf is part of the reproductive organ in barley and contributes significantly. |

## 7.3 Respiration and partitioning

### 7.3.1 Maintenance Respiration

#### *7.3.1.1 What does Daisy do?*

Respiration is assumed to comprise growth and maintenance respiration (McCree, 1974). Maintenance respiration is assumed to have priority over growth respiration; hence production only takes place if the available carbohydrate reserves exceed the required maintenance respiration. If a surplus of carbohydrate reserves exists, then this surplus is partitioned between the considered crop components, viz. root, stem, leaf and storage organs, and growth respiration is subtracted in order to calculate net production.

Maintenance respiration is assumed to be proportional to the dry weight of the plant components and each component is assumed to be characterized by a maintenance respiration coefficient, which is temperature dependent:

$$R_m^{component} = r_m^{component}(T) W_{component} \quad (7.3.1)$$

where

- $R_m$ is the maintenance respiration as fraction of the dry matter of the organ [g DM m$^{-2}$],
- $r_m(T)$ is the maintenance respiration coefficient [d$^{-1}$] (the Daisy names are r_Root, r_Leaf, r_Stem and r_SOrg) at the temperature $T$, and
- $W$ is the dry weight of the considered crop component [g DM m$^{-2}$].

The crop maintenance respiration is the accumulated maintenance respiration originating from the maintenance respiration of the individual crop components. The temperature relationship is hard-coded and is described as shown below:

$$f(t) = max\left(0.0,\ 0.4281 * \left(exp(0.57 - 0.024 * T + 0.0020 * T * T) - exp(0.57 - 0.042 * T - 0.0051 * T * T)\right)\right) \quad (7.3.2)$$

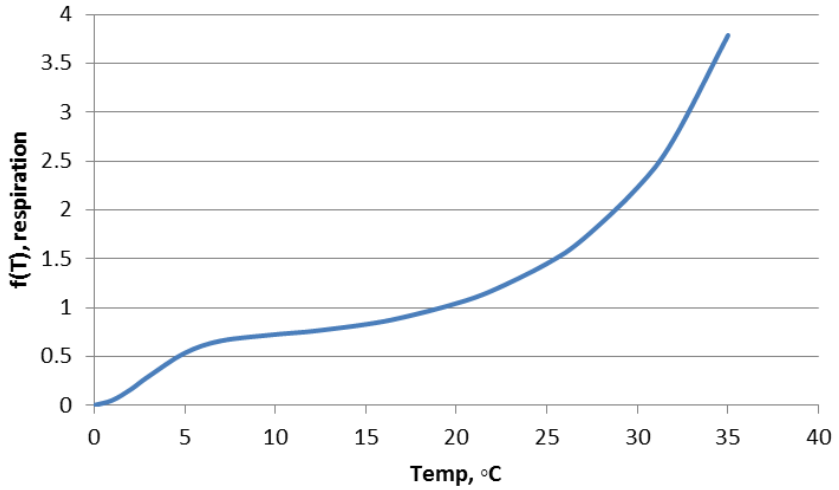


**Figure 6. The dependency of maintenance respiration on temperature.**

### *7.3.1.2 Measurements*

Measurement of maintenance respiration are strictly done under controlled conditions, e.g. in phytotrons. It is usually not calibrated, but the rates can be – and probably should be - updated if variety specific or study-specific information is available. Some examples of values for maintenance respiration can be found in Table 9.

Table 8 .Measurements of maintenance respiration.

| | Minimum req. | Better | Comment |
|---|---|---|---|
| Organ respiration | From new literature, presently Penning de Vries et al., 1989. | Advanced measurements under controlled conditions. | Seldom calibrated, but may be different between lines and cultivars of the same crop |
| Temperature effect on respiration | Use the model as it is. | New studies available? | Hard-coded in Daisy, see above. |

Table 9. Examples of maintenance respiration values and conversion efficiencies (growth respiration) from Penning de Vries et al., 1989

| Organ | Maintenance respiration | Conversion efficiency (growth respiration) |
|---|---|---|
| | $r_m$ at 20 °C<br>g $CH_2O$ / g DM | $^iE$ at 20 °C<br>g $CH_2O$ / g DM |
| Root | 0.015 | 0.69 |
| Stem | 0.010 | 0.66 |
| Leaf | 0.030 | 0.66 |
| Grain (cereals) | 0.010 | 0.70 |
| Beet | 0.010 | 0.70 |
| Oil Seed | 0.030 | 0.50 |

### 7.3.2 Partitioning of assimilate and Growth respiration

#### *7.3.2.1 What does Daisy do?*

The model only considers determinate crops. Furthermore, it is assumed that stress factors do not influence the assimilate partitioning; hence it can be assumed that partitioning is a function of the growth stage (DS) only. In the model the partitioning is described by piecewise linear functions, $\gamma_r(DS)$, $\gamma_s(DS)$, $\gamma_l(DS)$, and $\gamma_o(DS)$, representing the allocation to root, stem, leaf and storage organ, respectively. Note that first $\gamma_r(DS)$ is allocated to the root and then $1-\gamma_r(DS)$ is allocated to the shoot, which is assumed to comprise stem, leaf and storage organs. Then the allocation to the shoot is distributed among stem, leaf and storage organ, hence $\gamma_s(DS)+\gamma_l(DS)+\gamma_o(DS)=1$.

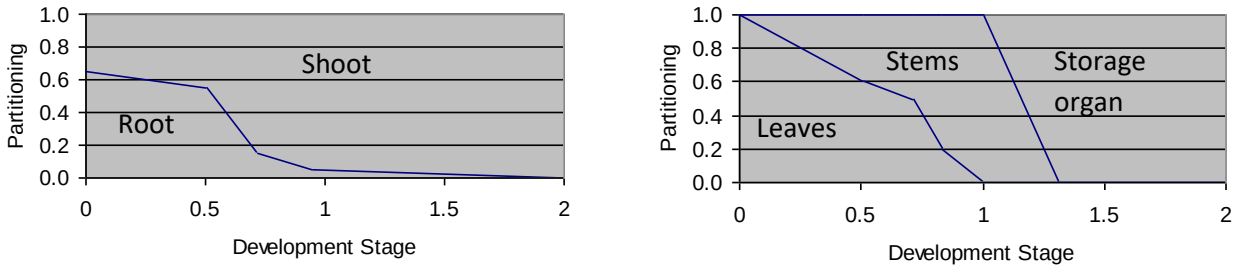


**Figure 7.Example of partitioning between 1) root and shoot, and 2) individual parts of the shoot as function of the development stage.**

The growth respiration rate is assumed to depend only on the end product formed; hence it can be characterized by a conversion efficiency. After subtraction of growth respiration, the net production for a specific crop component yields:

$$\left(\frac{\Delta W_{component}}{\Delta t}\right) = E^{component}\gamma^{component}\left(F - \sum_{j}^{components} R_m^j\right) \qquad (7.3.3)$$

where

- $(\Delta W/\Delta t)$ = the net production rate [g DM $d^{-1}$],
- $E^{component}$ = the conversion efficiency [],The Daisy names are E_Root, E_Leaf, E_Stem and E_SOrg)
- $\gamma^{component}$ = (combined) fraction of assimilate allocated to the considered crop component (*component* = *root, leaf, stem*, and *storage organ*) [].,
- F = the assimilate flow from the carbohydrate reserves [g DM $d^{-1}$]. F is released from the carbohydrate reserve pool using 1st order kinetics.

During the reproductive phase, plants may reallocate dry matter resources from the stem to the storage organ. The parameter ShldResC [] describes the fraction of stem dry matter that can be classified as "reserve to be mobilised". ReMobilDS [DS] is the DS-value at which the remobilization can be initiated. The rate of remobilization is described via the parameter ReMobilRt [$d^{-1}$]. In Daisy, the reallocation takes place without an additional conversion cost.

### *7.3.2.2 Measurements*

The partitioning can only be determined indirectly, through biomass cuts at different times and analysis of the components. Features such as length of straw and Harvest Index (HI), which are influenced by plant breeding, are linked to assimilate partitioning. Functions that influence partitioning depending on the N-content have been included for potatoes and winter wheat (*nitrogen_stress_limit* which allocate all assimilate to the storage organ at the specified N-stress level when DS>1 (Heidmann et al., 2008) and NNI_crit, which modifies stem/leaf-partitioning (J.Gyldengren, in prep.)), but this requires plant physiological knowledge and detailed data to develop.

However the actual growth depends on both the assimilate partitioning and the growth respiration, as the observed growth is the net value of the two. The conversion efficiencies can be calculated based on biochemical analysis (Penning de Vries et al., 1989), see Table 9 for some examples. Methods to estimate the conversion efficiency are discussed on Penning de Vries et al. (1989), p. 60-63. The conversion efficiency can be updated if the content of e.g. seeds is known to have changed due to plant breeding.

In practice, it is difficult to distinguish between the maintenance- and growth respiration in measurements, as both processes develop $CO_2$.

Biomass cuts can be made under controlled conditions or in the field. In many cases, the growth has to be calibrated based on field data only.

**Table 10 .Measurements for assimilate allocation.**

| | Minimum req. | Better | Comment |
|---|---|---|---|
| Conversion efficiency at partitioning | From literature. | | [] Can be obtained from biochemical analysis (Penning de Vries et al., 1989) |
| Partitioning to different organs | From literature, but changes with plant breeding. | Detailed measurements are very complication. Measured indirectly through crop cuts in field experiments | [] Can be influenced by environmental conditions too. |

## 7.4 Senescence

### 7.4.1 What does Daisy do?

During the growing season, it is assumed that root and leaf material is lost during growth due to senescence and shading. The rate at which dry matter is lost is assumed to be proportional to the leaf weight. The proportionality factor is divided into two components. One component is assumed to be a piecewise linear functions of DS. This is described as by the plf-function LfDR, which specifies the death rate of leaves [$d^{-1}$] as a function of DS. Another component, being constant (PARrel), is only brought into play when the irradiance received by the lower shaded leaves falls below a certain threshold, i.e. when transmission of light falls below a predefined value, typically around 5 % (Montheith and Unsworth, 1990). In Daisy, the parameter ExfoliationFac regulates the loss of dead leaves from the plant to the surface. The default value is 1, causing all dead plants to fall to the ground.

The estimation of the death rate is indirect, based on measurement of dead leaves on and below the plant, see section 7.5.

## 7.5 Data from field measurements

Measurements required to describe emergence have already been discussed in chapter 6. In field experiments we generally collect overall information that can be used to calibrate the governing

parameters, rather than the parameters themselves. The following description primarily concerns above-ground biomass.

The dry matter (and N-content) of above ground organs as function of time is a key measurement for calibration. It can be established from cuts of plant material, preferably divided into the different parts. The N-content of the same cuts is useful for the calibration of N-uptake and concentration ranges for the different organs, see later.

The leaf mass generated when assimilate is allocated to the leaves is transformed to LAI through the specific leaf area (SpLAI, $m^2/g$), which may change over time, in Daisy as a function of DS. Specific leaf area can be established from measurements of Leaf area (image scanner mobile applications (Petiole, Easy Leaf Area), and dry matter. The N-content of leaves may be estimated using an APAD Chlorophyll-meter. It is very useful to have coordinated measures of LAI and biomass.

LAI can be measured non-destructively using a CI-110 Plant Canopy Analyzer [1] from CID Bio-Science, LAI-2200 Plant Canopy Analyzer [2] from LI-COR Biosciences and the LP-80 LAI ceptometer [3] from Decagon Devices (Wikipedia). The remote measurements tend to be less accurate when the plant cover is dense. Some studies also use RVI (Ratio vegetation index) derived from measurements of spectral reflectance at 780 and 670 nm, but the relationship between LAI and RVI also depends on N-status of the leaves.

There is an increasing amount of articles on the use of remote sensing for establishment of these growth parameters, and this can undoubtedly become interesting for crop calibration, see box 1.

Senescence and the decreasing efficiency of the photosynthetic system are difficult to estimate, but may be inferred from falling N-content and low biomass increase. The estimation of the death rate is indirect, based on measurement of dead leaves on and below the plant.

It is useful also to keep track of plant height over time. Plant height plays a role at harvest, as the division between stubble and straw removed is based on this. It also plays a role if more than one crop is grown on the field. In this case, three values are important: The height, where the leaves start to branch out, and the heights between which the cover is at maximum. Daisy apply values for this height distribution at emergence, and DS1 (LAIDist0 and LaiDist1), see section 7.1.1.

Plant cover % is can be measured in the field non-destructively, based on photographic images. It is a log-variable of the bioclimate model (*canopy_cover*, as fraction of the area), and measurements can therefore be compared to simulations. Plant cover is used for calculation of colloid release from the surface.

Box 1. Some examples of articles on remote sensing of relevant parameters

Knoblauch C, Watson C, Berendonk C, Becker R, Wrage-Mönnig N, Wichern F. Relationship between Remote Sensing Data, Plant Biomass and Soil Nitrogen Dynamics in Intensively Managed Grasslands under Controlled Conditions. *Sensors (Basel, Switzerland)*. 2017;17(7):1483. doi:10.3390/s17071483.

Lefsky, M.A., Cohen , W.B., Parker, G.G., Harding, D.J. Lidar Remote Sensing for Ecosystem Studies: Lidar, an emerging remote sensing technology that directly measures the three-dimensional distribution of plant canopies, can accurately estimate vegetation structural attributes and should be of particular interest to forest, landscape, and global ecologists . *BioScience*, Volume 52, Issue 1, 1 January 2002, Pages 19–30, https://doi.org/10.1641/0006-3568(2002)052[0019:LRSFES]2.0.CO;2Freeman, K.W., Girma, K., Arnall, D.B., Mullen, R.W., Martin, K.L., Teal, R.K., and Raun, W.R. By-Plant Prediction of Corn Forage Biomass and Nitrogen Uptake at Various Growth

Stages Using Remote Sensing and Plant Height. Agron. J. 99:530–536 (2007). Remote Sensing. doi:10.2134/agronj2006.0135.

Yansong Bao, Wei Gao, Zhiqiang Gao. Estimation of winter wheat biomass based on remote sensing data at various spatial and spectral resolutions.Frontiers of Earth Science in China, March 2009, 3:118

Lalit Kumar, Priyakant Sinha, Subhashni Taylor, Abdullah F. Alqurashi, "Review of the use of remote sensing for biomass estimation to support renewable energy generation," J. Appl. Rem. Sens. 9(1) 097696 (16 June 2015).

## 7.6 Roots

### 7.6.1 What does Daisy do?

The description of roots in Daisy is at present rather simple. The root system is characterized by root weight, rooting depth, and root density distribution. At germination, the plant is usually assigned a root depth of 10 cm. Root penetration is assumed to take place if the following conditions are fulfilled:

- daily net root production is positive;
- the soil temperature at the root tip is above a certain threshold temperature, typically 4°C; and
- actual rooting depth is less than a maximum rooting depth.

Maximum rooting depth is determined either by the plant species itself or by the chemical or mechanical properties of the particular soil considered.

When the daily net root production is positive, the soil temperature at the root tip is above a threshold temperature (default 4 °C) and the actual rooting depth is below the maximum rooting depth specified for the soil or the crop (MaxPen [cm]), the daily root growth can be described as:

$$\left(\frac{\Delta d_r}{\Delta t}\right) = \begin{cases} 0 & T_s \le T_p \\ \alpha_r \left(T_s - T_p\right) & T_s > T_p \end{cases} \qquad (7.6.1)$$

**Table 11 .Measurements of above-ground plant material in field experiments.**

| | Minimum req. | Better | Comment |
|---|---|---|---|
| Growth stage monitoring | Date of sowing, flowering/earing and maturity | Many growth stages | |
| LAI at emergence | Measured | | We assume that all seed have been placed properly and germinate. Poor germination has to be regulated through "kg of seed applied". |
| LAI over time | Measured | More than one year | |
| Specific leaf area, over time | As a minimum from literature but preferably measured a few times during the growing season | | This value determines the relationship between biomass in leaves and LAI in the model, and is therefore very important. |
| Biomass over time, preferably per organ | Measured | More than one year if relations with temperature relationships and DSeff should be calibrated | It is beneficial to measure biomass and LAI by two independent methods.<br><br>For some plants, leaves die off during the growing season. This has to be quantified, as it is important for the total biomass balance and the soil organic matter balance.<br>Daisy transforms dead leaves to AOM using an exfoliation Factor, which by default is 0.7 [unit?]. |
| Plant height over time | Yes, at least at harvest | Measurements at intervals during the growing season | The height is used to calculate biomass in stubble at harvest and is of interest if more crops are grown together. It is used to define the crop spatial shape of the crop. |
| Plant cover % over time | Is calculated but measurements are useful for comparison | | Can be estimated from pictures |
| Dead plant material | Literature values | Measured | The value is likely to be variety-dependent and it is particularly important for a crop like rape seed, which has a high turn-over of leaves. |
| Weather data, soil data, field management and initialization. | Obligatory | More than one year | See section 2. |

where

- $\Delta d_r/\Delta t)$ = the increment in root depth [cm] in the timestep [$d^{-1}$]
- $T_s$ = the soil temperature at the root tip [deg C],
- $T_p$ = the threshold temperature (PenPar2 [dg C]) and
- $\alpha_r$ = the root penetration parameter (PenPar1 [cm/dg C/d]). The rate of penetration can be modified using plf-functions to describe the influence of clay (PenClayFac) eller by the relative water content (PenWaterFac).

The distribution of roots with depth is described using an exponential curve. The total root length is proportional to root weight (which is calculated based on allocation of assimilates and root respiration) and can be calculated using the specific root length:

$$l_r = S_r W_r \tag{7.6.2}$$

where

- $l_r$ = total root length [m $m^{-2}$]
- $W_r$ = root dry matter [kg $m^{-2}$]
- $S_r$: = specific root length [m $kg^{-1}$] (SpRtLength with a default value of 100 [m $g^{-1}$])

The root length at a given depth can be described using a logarithmic function:

$$L_z = L_0 e^{-a_z z} \tag{7.6.3}$$

Where

- $L_z$ = root density at soil depth z [m $m^{-3}$]
- $L_0$ = root density at soil surface [m $m^{-3}$]
- $z$ = soil depth [m]
- $\alpha_z$ = root density distribution parameter [$m^{-1}$]

The total root length is then the integration of the root density in the root zone and equal to the total length calculated above.

$$l_r = S_r W_r = \int_0^{d_r} L_z dz = \frac{L_0}{a_z}(1 - e^{-a_z d_r}) \tag{7.6.4}$$

where

- $d_r$ = root depth [m]

Assuming that the root density at the potential rooting depth ($L_d$) is 0.1 cm $cm^{-3}$, the equation can be solved for $\alpha_z$ and $L_0$ for each time step (Gerwitz and Page, 1974).

If the root depth is limited by soil properties, then the actual root density distribution is calculated again by assuming the Gerwitz and Page distribution and setting the root density at the actual rooting depth equal to the density obtained from the potential distribution at this depth, see Figure 8.

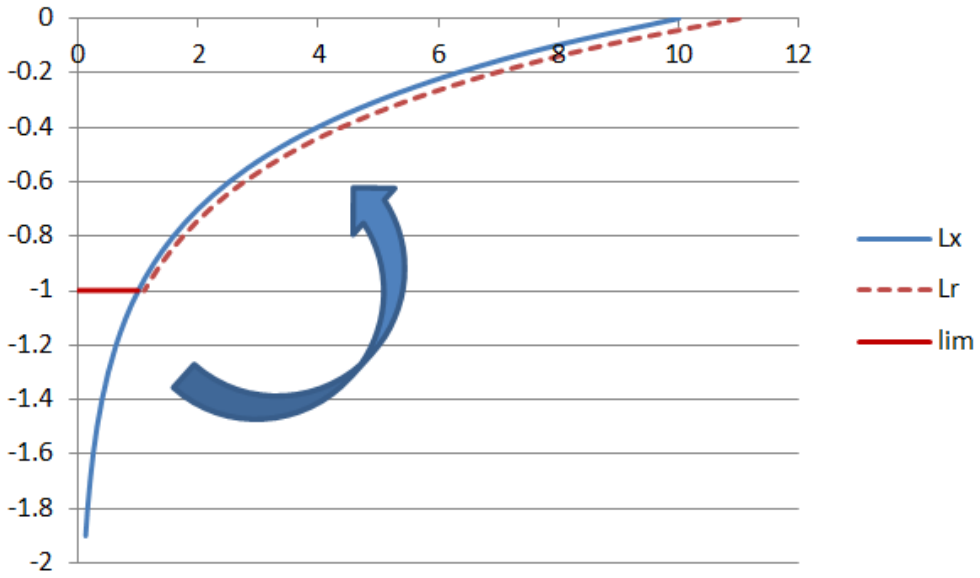


**Figure 8. Redistribution of root mass if the penetration is limited by soil properties. The blue line shows the distribution without limitation, while the red curves show the same root mass redistributed due to a limiting layer at 1 m's depth.**

The main parameters determining the root growth and distribution are therefore $T_p$, $\alpha_r$ and the $S_r$, the specific root length as well as the allocation of assimilates to the roots, determining the total biomass.

Roots may die off over time, particularly in the later stages of the growing period. In Daisy this is described as a death rate of roots [$d^{-1}$], specified as a plf-function, e.g.

(RtDR (0.00 0.00) (0.60 0.00) (1.20 0.01) (2.00 0.01))

In this case, 1 % of the root biomass dies off every day between DS-stage 1.2 and 2. A parameter called Large_RtDR [$d^{-1}$] allows for faster death rate of roots when the root/shoot ratio becomes large, typically due to cutting of e.g. grass.

The root depth, density and distribution determine the possible uptake of water and nitrate/ammonium in a given soil. These processes are described elsewhere. However, three root-related parameters which have to do with these processes occur in the input file. These are Rad, the effective root radius, which by default is 0.005 [cm], h_wp, representing the matrix potential at wilting point (-15000 [cm] by default) and Rxylem, which is the transport resistance in the xylem []. The two first are hardly ever changed. The last parameter influence the uptake of water from the soil and detailed measurements of weather and soil data, including continuous recording of moisture conditions or soil suction is required for calibration. Details can be found in Hansen and Abrahamsen (2009).

### 7.6.2 Measurements

The rate of root penetration ($\alpha_r$) can be established from measurements in mini-rhizotrons. It may also be possible to deduce when roots reach a certain depth from measurements of soil moisture or pressure

potential. The growth rate is expected to be a function of temperature at the root tip. Temperature relationships may be deduced based on measured or modelled soil temperature. The threshold temperature for root growth ($T_p$) can be established based on observations.

Estimation of the allocation of assimilate to the roots require some knowledge of the total root biomass. This is a very difficult parameter to establish. Around germination, the fraction is typically large and drops during the growth season (Figure 7).

The root death rate is rather uncertain. There are different estimates in literature. Some of these values are rather high and may not be realistic considering the assimilate production required to maintain the root network during the growing period.

## 7.7 Nitrogen in the plant

### 7.7.1 What does Daisy do?

The uptake of nitrate and ammonia in the plant is determined by demand and supply. The demand is determined by the biomass and the potential N-concentration ($C_{pot}$) of each plant organ. The potential N-content of the plant can thus be calculated as:

$$N_{pot} = \sum W_i * C_{pot,i} \qquad (7.7.1)$$

where

- $N_{pot}$ = the potential N-content of the plant [g m$^{-2}$],
- $W_i$ = the biomass of "organ i" (i may be leaf, stem, root or storage organ) [g DM m$^{-2}$],
- $C_{pot,i}$ = the potential N-concentration of organ i [g N (g DM)$^{-1}$].

Three other N-concentrations are required for the description of the N-state of the plant: the critical ($C_{crit}$), the non-functional ($C_{nonf}$) and the actual concentration ($C_{act}$).

- $C_{act}$ is the actual concentration of N in each plant organ [g N (g DM)$^{-1}$].
- The critical concentration ($C_{crit}$) which is the concentration below which growth is subject to N-stress. N-uptake resulting in concentrations between $C_{crit}$ and $C_{pot}$ is luxury uptake.
- The concentration below which the plant will die ($C_{nonf}$). Between $C_{nonf}$ and $C_{crit}$, the plant will experience N-stress.

- The actual crop content can be calculated as: $N_{Act} = \sum W_i * C_{act,i}$. The potential crop content, the critical crop content and the non-functional crop content are calculated in a similar fashion, using the respective concentrations, which are described as plf-functions of the development stage (DS). The maximum nitrogen uptake rate determined by the demand is described as:

- $$N_{demand} = (N_{pot} - N_{act}) / \Delta t \qquad (7.7.2)$$

Table 12. Root parameters related to roots.

| | Minimum req. | Better | Comment |
|---|---|---|---|
| Threshold temperature for root growth | From literature | From laboratory studies. | As it is most likely a physiological threshold, it could be established in climate chambers or the like. |
| Root depth over time | From literature | Measurements with mini-rhizotrons, or through moisture or potential sensors at different depths. If temperature relationships are to be determined, data from more than one year are preferable. | The growth is temperature dependent, thus the soil temperature must be known. Furthermore, other factors (soil moisture or high resistance to growth should not be present when the aim is to establish the "natural" growth rates. |
| Root density, root biomass and Specific root weight | From literature | Excavation of roots at different growth stages. Measurement of total weight and root length | |
| Stressors | From literature | Studies of root growth as function of water content or different types of mechanical stres | The relevance of this depends on the purpose of the study. Root growth is typically hampered on very sandy soil with low organic matter content, very wet soils or very compact soils. |
| Death rate of roots | | | Very difficult to establish! Some very high estimates exist in literature, but do not agree with a mass balance of assimilate. |
| Rxylem | Default | Requires detailed measurements of soil moisture (TDR) and/or soil suction together with good weather data. | Seldom calibrated |
| Weather and soil data | Obligator | | See section 2 |

If $N_{act}$ is lower than $N_{crit}$, the plant will be subject to N-stress, which influences the photosynthesis. In that case, the "water limited" photosynthesis ($F_w$) will be reduced as described below:

$$F_N = F_w \frac{(N_{crit} - N_{act})}{(N_{crit} - N_{nonf})} \tag{7.7.3}$$

where

- $F_N$ is the photosynthesis when both water and N-limitations have been taken into account.

The supply of nitrate and ammonia is determined by the transport to the root via mass flow (with water) and diffusion due to a concentration gradient towards the root. This is described elsewhere. There are, however, some key parameters to consider. The maximum uptake rates for ammonia and nitrogen per unit root length (MxNO3Up and MxNH4Up [g/cm/h]) provide the upper limit to the possible uptake. Traditionally, we have typically used a "zero sink", meaning that the plant could reduce the concentration at the root surface to 0. It is also possible to specify a minimum value (NO3_root_min or NH4_root_min) for the concentrations at the root surface.

In the most recent versions of Daisy [from version 5.29], an additional process has been added, describing the transport across the root as a function of two different transport pathways, 1) a high affinity system with low capacity, dominating at low concentrations, and 2) a low affinity system with high capacity, dominating at higher concentrations of nitrate in the soil moisture. This is described by two combined Michaelis-Menten kinetics equations (Tsay et al., 2007).

The dual-affinity uptake kinetics can be described as:

$$I = \frac{F_1 C_r}{K_1 + C_r} + \frac{F_2 C_r}{K_2 + C_r} \tag{7.7.4}$$

where

- $I$ is the root uptake [g N (cm root)$^{-1}$ h$^{-1}$],
- $F$ [g N (cm root)$^{-1}$ h$^{-1}$]and $K$ [g N cm$^{-3}$] refer to the max uptake rate and the half-saturation constant, respectively, and the subscripts 1 and 2 refer to the high affinity system and low affinity system, respectively.
- $C_r$ is the concentration at the root surface [g N cm$^{-3}$].

In Daisy, MxNO3Up specifies the total max rate ($F_1$+$F_2$) and a parameter (F_relative) specifies which fraction of the maximum rate is allocated to the high-affinity system. The default value of F-relative is 0.1, but we have little experience with the use of this system. In this case, the supply is limited by the combined effect of transport towards the root and transport across the root. . See http://daisy.ku.dk/publications/Root_uptake_and_solute_movement_to_root_surfaces.pdf a more detailed description.

Regardless of the submodel, the final uptake is described as

N-uptake = min(supply, demand)

The nitrogen taken up by the plant functions as one pool, but is allocated to the different organ based on their respective governing concentrations, so that all organs experience the same relative level of supply.

### 7.7.2 Measurements

The potential N-concentration for the different organs can be derived from experiments, where there are no stresses and N is in freely available. This may be done in water culture, where it is also possible to analyze plant roots. $C_{pot}$ usually changes over time. For leaves, stems and roots $C_{pot}$ tends to drop as the storage organs develop. Particularly for the storage organ, $C_{pot}$ is not necessarily the highest concentration obtained. If dry matter production stops due to stress and dry matter is lost due to respiration, the end concentration of N may end up being higher than $C_{pot}$.

The critical concentration can be established from experiments receiving different levels of nitrogen. It is the lowest concentration required to obtain the maximum dry matter yield. As above, the critical concentration changes over time for most organs.

It is possible to establish minimum levels of nitrogen present in crops with little or no fertilization, but experience shows that the $C_{nonf}$ has to be based on calibration. The nitrogen stress induced in the simulation does not allow the concentration in the plant to drop to the level of the specified $C_{nonf}$.

The different concentration levels may typically be determined though analysis of biomass cuts, split up into the different plant organs. Remote sensing of chlorophyll may be an additional option to follow the development over time in leaves and stems.

Some studies exist of rates of root uptake of nitrate and ammonia. These are often conducted in water culture, which provides a better contact between the root and the water than what is found in the soil. The default values provided in the model stem from such studies and it can usually be reduced by a factor 10 without any effect on the modelled N-uptake. Robinson et al. (1991) found that between 11 and 3.5 % of the total root length was involved in N-uptake, and this fits nicely with the fact that the model is sensitive when the uptake is reduced by a factor 1/10-1/30. Studies of the Michaelis-Menten kinetics of root uptake may be available for plant physiological studies, but we have not yet been able to identify much on common crops.

Table 13. Measurements of nitrogen-related parameters

| | Minimum req. | Better | Comment |
|---|---|---|---|
| N-concentration in biomass over time, preferably by organ | From literature or earlier studies | From field experiments with your specific crop/variety and different N-levels. | The different concentration levels have to be determined indirectly, based on the measurements. |
| | | Greenhouse studies of the crop under optimal water and N-conditions | Potential concentrations can only be established under high-N-conditions. |
| Nitrate- and ammonia-uptake rates | The default values<br>Information from plant physiology concerning fraction of active roots (as a function of time | | As described above, the conditions in soil are different from water culture, and it is therefore difficult to extrapolate from studies in water culture. The rates are therefore often calibrated. At least in the vegetative state, it seems that plants are able to function as "0-sinks". At the end of the growing period, the model often overestimate N-uptake, but it is not clear whether this is due to an underestimation of root death rate, an overestimation of the uptake rates or wrong assessment of the demand. |
| Michaelis-Menten parameters | Plant physiological studies | | We have limited experience with this function at the moment. |
| The history of the field | Initialisation is extremely important | | See section 2.5. Mineralisation may affect the N-availability significantly. |

# 8 Measurements at harvest

## 8.1 Yield, primary and secondary product

### 8.1.1 What does Daisy do?

When the harvest function is specified, the user also specifies “stub” [cm] which causes leaves and stem below this value to remain in the field. It is possible to specify the fractions of leaves, stem and storage organ above stub level that should be harvested. If it is not harvested, it is left behind.

To go from the growing or mature storage organ to the harvested crop, a conversion factor is required. This is because the storage organ may not be the pure product (e.g. threshed grain is only part of the spike). The “EconomicYield_W” specifies the fraction of the dry matter of the storage organ that counts as the actual yield, and “EconomicYield_N” specifies the fraction of the N-content of the storage organ, that should follow the actual yield. The N-fraction is usually higher than the dry matter-fraction. Make sure to check whether you consider the harvest fraction and the Economic Yield parameters reasonable for your study, as the values influence the simulated yield components.

Most crops die at harvest. This can be regulated using DSmax, which specifies the maximal development stage for which the crops survives harvest, which is particularly relevant for grass or grass/clover mixtures. If the crop survives, the development stage will be reset to DSnew. When a crop is cut, the leaves may not be able to supply the root system with assimilates. The plf-function RSR allows a description of the maximal root/shoot ratio as a function of development stage. If the root/shoot ratio is above this, the roots will start dying. The parameter described in **Error! Reference source not found.** called Large_RtDR then determines the death rate of the roots until the maximal root/shoot ratio is reached.

When the crop dies, the different crop residues return to the soil as “added organic matter” (AOM).

### 8.1.2 Measurements

At the time of harvest, the yield components should be established. Yield components would be the storage organ (grain, potatoes, beet root, pea-pods etc) and straw or other relevant organic components Note, that there is a difference between what you harvest by hand and machine, because the stubble height is different and losses may be different too.

Table 14 .Measurements of above-ground plant material in field experiments.

| | Minimum req. | Better | Comment |
|---|---|---|---|
| Date of maturity | Assessed | | |
| Date of harvest | Measured | | |
| Harvested storage organ and secondary product | Dry matter and N-content of storage organ | Dry matter and N-content of secondary products. | |
| Stubble height | estimated | Measured | |
| Losses left behind in the field | estimated | Measured | |
| Economic yield of dry matter and N | estimated | Measured | |

## 8.2 Mineralisation parameters for left over material

### 8.2.1 What does Daisy do?

Root exudates are allocated to the "Added organic matter pools" (AOM)immediately, and so are dead roots. Dead leaves, stubble and non-harvested straw become plant residues on the surface, and may be incorporated when ploughing or through bioincorporation. At this point they turn into AOM. They enter into the pools with their specific content of C and N. There are, by default, two AOM-pools, AOM 1, which has a half-life of 144 days and AOM 2, with a half-life of 12 days. It is necessary to specify which fraction of each type of the material goes to AOM1, and with which C/N-ratio. The rest of the material will be added to AOM2 with the remaining N-content. By default, the AOM-pools are broken down via the fast "Soil Microbial Biomass"-pool (SMB2), while losing 50 % of the carbon to $CO_2$ in the process. The breakdown rates have been calibrated in earlier studies. (Müller et al. 1997 and 1998).

The default value for the fraction going to AOM1 is 80 %, with a C/N-ratio of 90. However, other parameters are used for e.g. ryegrass.

### 8.2.2 Measurements

These values can only be determined indirectly from mineralization experiments, where the pool allocations are fitted. The C/N-ratio of the original material and at different stages of breakdown can be determined in the laboratory by measuring $CO_2$-development in climate chambers and fitting the required breakdown parameters to the generated data.

Table 15 .Measurements of above-ground plant material in field experiments.

| | Minimum req. | Better | Comment |
|---|---|---|---|
| Amount of each plant component left behind | Estimated by the model | Measured | Equal to entry in Table 14 |
| C/N-value of the different types of material | Estimated by the model | Measured | |
| Breakdown curve | ? | ? | Lars and Sander |

# 9 Special issues: N-fixation

# 10 Advanced crop modeling using Farquar photosynthesis and the SSOC model

# 11 Crop calibration

When starting crop calibration process, it is important to be very clear about the purpose of the investigation for which the crop module is to be used and the level of precision required. Is it mainly the yield that is important or is the exact development of the plant over time with respect to dry matter and N also important? Should the model be used to evaluate detailed fertilization techniques or levels of organic matter input into the soil? Emphasis during the calibration phase needs to be placed on the components that are most important in the final evaluation for which the model should be used.

## 11.1 How to structure the calibration

### 11.1.1 Step 1: Collection of all relevant material

First step in a calibration process is to collect all relevant material in the form of earlier calibrations, preferably accompanied with descriptions of the basis of the calibration and literature. For the parameters that are not measured in your calibration dataset, go through literature to determine whether new information has become available that can be used to improve earlier parameterizations. Plant breeding influence plant height, temperature relationships, photosynthetic rate, root growth rate, and assimilate allocation etc., so it is worthwhile exploring all possible data sources.

It is important already at this stage to determine which parameters have well defined values that has been/can be measured with a reasonable degree of certainty. Such values should be considered “given” in the subsequent calibration.

### 11.1.2 Step 2: Ensure that your weather and soil data are adequate

Plant growth is extremely dependent on weather conditions and soil so when working with field experiments, make sure that you are working with local weather files, (preferably with hourly resolution,) that the rainfall is corrected to ground level and that the description of the soil is correct. This also includes knowledge of the lower boundary condition for water (drained/not drained, groundwater level, etc.). Knowledge of earlier cropping history of the field will help getting the model initialized correctly. A plot with 0-fertilizer also helps establishing the mineralization level in the soil. If the model produces water or nitrogen stress, when it should not be there (or the other way around), it will influence your crop calibration.

### 11.1.3 Step 3: Calibration of crop phenology

Start with calibration of the crop phenology. The phenology is relatively robust, and mainly a function of temperature and photoperiod. A particular DS-value should correspond to a particular growth stage measured in the field. Sowing, emergency, flowering/earing and maturity are your first fixpoints, and if you have more BBCH-stages noted, use those as fixpoints too. Your growth rates and the related modifyers (temperature, photoperiod, vernalisation etc., should be calibrated here.

### 11.1.4 Model sensitivity and uncertainty

In the following steps you should consider carrying out sensitivity analyses on the parameters in question to determine their importance for the calibration and whether the model is sensitive to parameter changes within the realistic span for the parameter. Your measured parameters will be subject to uncertainty, which you should also consider in this process. The more important a parameter is, the more you should try to tie it to earlier studies or own measured values.

The sensitivity of a specific parameter depends on the conditions surrounding the plant. If, for example, nitrogen is available in sufficient amount, parameters related to nitrogen are not likely to be particularly sensitive.

Calibration of different parameters may interact. Therefore, sensitive parameters may be optimized together, using optimization software.

### 11.1.5 Potential production

The next step is to get the potential dry matter production over time right, without limiting factors. This is mainly a factor of the incoming radiation, temperature and allocation of assimilate. The experiments to use for this are well watered and well fertilized. Compare to measurements of LAI and biomass, preferably of different plant components over time. You can calibrate the photosynthesis parameters and the allocation of carbon to different parts of the plant. Remember, that material can be lost due to respiration, leaf death and root death, the last two particularly at the later stages of plant growth.

### 11.1.6 Water Stress

If you have experiments that differ with respect to water availability, with no other limiting factors, you can test the description of water stress. Water stress affects photosynthesis as described in equation (7.2.3). This will require a very good description of the weather and soil for the experiment. Apart from the stress function itself, the rate of root growth, maximum rooting depth, root density and Rxylem may be some of the factors to consider here.

### 11.1.7 N-uptake

The last step in the calibration is the N-uptake and the distribution of N between the different organs over time. The uptake is governed by supply and demand. As described earlier, the demand is determined by dry matter of the different organs and the three governing concentrations ($C_{pot}$, $C_{crit}$ and $C_{nonf}$), which may require calibration. Uptake of nitrate and ammonia can also be regulated through the maximum uptake-rates. The supply has to do with fertilization and available N in the soil as well as denitrification, and if your model plant is much stressed, you should investigate whether these different components are reasonably described.

## 11.2 Software.

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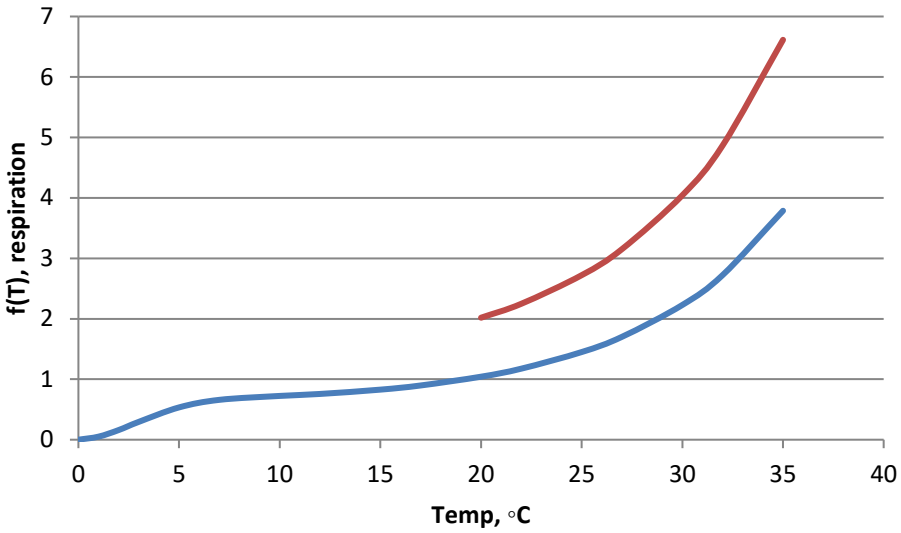
## Annex 1 Sample of Daisy crop file, including units

```
(defcrop "Std. Winter Wheat" default
  (Devel default (EmrTSum  100 [dg C d])
      (DS_Emr   0.010  [DS])
      (DSRate1  0.0185 [DS/d])
      (TempEff1 (-10. [dg C] 0.01 []) (0.00 [dg C] 0.01 [])
                (20.0 [dg C] 0.90 []) (25.0 [dg C] 1.00 [])
                (35.0 [dg C] 1.20 []))
      (PhotEff1 (10.0 [h] 0.29 [])    (11.0 [h] 0.55 [])
                (12.0 [h] 0.75 [])    (13.0 [h] 0.89 [])
                (14.0 [h] 1.00 [])    (15.0 [h] 1.08 [])
                (16.0 [h] 1.14 [])    (17.0 [h] 1.18 [])
                (24.0 [h] 1.18 []))
      (DSRate2  0.0225 [DS/d])
      (TempEff2 ( 0.0 [dg C] 0.00 []) (10.0 [dg C] 0.14 [])
                (15.0 [dg C] 0.66 []) (20.0 [dg C] 1.00 [])
                (25.0 [dg C] 1.23 [])))

  (Vernal default
          (DSLim 0.25 [DS])
          (TaLim 5.00 [dg C])
          (TaSum -50.0 [dg C d]))

  (LeafPhot original (Fm 5.00 [g CO2/m^2/h])
            (Qeff   0.0500 [(g CO2/m^2/h)/(W/m^2)])
            (TempEff (-20.0 [dg C] 0.00 []) (4.00 [dg C] 0.00 [])
                     ( 10.0 [dg C] 1.00 []) (25.0 [dg C] 1.00 [])
                     ( 35.0 [dg C] 0.01 []) (50.0 [dg C] 0.00 [])))

  (Seed LAI (DSLAI05   0.15 [DS]))
  (Canopy
      (SpLAI     0.022 [(m^2/m^2)/(g DM/m^2)])
      (LAIDist0 0.00 [] 0.00 [] 1.00 [])
      (LAIDist1 0.00 [] 0.20 [] 0.90 [])
      (PARref   0.06 [])
      (PARext   0.60 [])
      (PARrel   0.05 [])
      (EPext    0.50 [])
      (HvsDS   (0.00 [DS] 1 [cm]) (1.00 [DS] 80 [cm]) (2.00 [DS] 100
[cm])))

  (Root (DptEmr     10 [cm])
      (PenPar1    0.25 [cm/dg C/d])
      (PenPar2     4.0 [dg C])
      (MaxPen      120 [cm])
      (Rad        0.005 [cm])
      (h_wp       -15000 [cm])
      (Rxylem     10.0 [])
      (MxNH4Up     2.5E-0007 [g/cm/h])
      (MxNO3Up     2.5E-0007 [g/cm/h]))
```

```
  (Partit
      (Root (0.00 [DS] 0.50 []) (0.33 [DS] 0.50 []) (0.53 [DS] 0.45 [])
            (1.00 [DS] 0.00 []) (2.00 [DS] 0.00 []))
      (Leaf (0.00 [DS] 0.70 []) (0.40 [DS] 0.70 []) (0.55 [DS] 0.70 [])
            (0.62 [DS] 0.50 []) (0.77 [DS] 0.20 []) (0.95 [DS] 0.10 [])
            (1.38 [DS] 0.05 []) (2.00 [DS] 0.00 []))
      (Stem (0.00 [DS] 0.30 []) (0.40 [DS] 0.30 []) (0.55 [DS] 0.30 [])
            (0.62 [DS] 0.50 []) (0.77 [DS] 0.80 []) (0.95 [DS] 0.90 [])
            (1.00 [DS] 0.00 []) (1.38 [DS] 0.00 []) (2.00 [DS] 0.00 []))
      (RSR  (0.00 [DS] 0.50 []) (1.00 [DS] 0.50 []) (2.00 [DS] 0.25 [])))

  (Prod (NCrop 0.4 [g N/m^2])
        (E_Root     0.69 [g DM-C/g Ass-C])
        (E_Leaf     0.68 [g DM-C/g Ass-C])
        (E_Stem     0.66 [g DM-C/g Ass-C])
        (E_SOrg     0.70 [g DM-C/g Ass-C])
        (r_Root     0.015 [d^-1])
        (r_Leaf     0.016 [d^-1])
        (r_Stem     0.010 [d^-1])
        (r_SOrg     0.010 [d^-1])
        (ShldResC   0.40 [])
        (ReMobilDS  1.50 [DS])
        (ReMobilRt  0.03 [d^-1])
        (Large_RtDR 0.05 [d^-1])
        (ExfoliationFac 0.7 [])
        (LfDR (0.00 [DS] 0.00 [d^-1]) (0.10 [DS] 0.00 [d^-1]) (0.25 [DS]
0.00 [d^-1])
              (0.50 [DS] 0.01 [d^-1]) (0.90 [DS] 0.01 [d^-1]) (1.20 [DS]
0.02 [d^-1])
              (1.80 [DS] 0.05 [d^-1]) (2.00 [DS] 0.05 [d^-1]))
        (RtDR (0.00 [DS] 0.00 [d^-1]) (0.60 [DS] 0.00 [d^-1]) (1.20 [DS]
0.01 [d^-1])
              (2.00 [DS] 0.01 [d^-1])))

  (CrpN
      (PtRootCnc (0.00 [DS] 0.0120 [g N/g DM]) (1.00 [DS] 0.0120 [g N/g
DM])
                 (2.00 [DS] 0.0100 [g N/g DM]))
      (CrRootCnc (0.00 [DS] 0.0100 [g N/g DM]) (1.00 [DS] 0.0100 [g N/g
DM])
                 (2.00 [DS] 0.0090 [g N/g DM]))
      (NfRootCnc (0.00 [DS] 0.0070 [g N/g DM]) (1.00 [DS] 0.0070 [g N/g
DM])
                 (2.00 [DS] 0.0070 [g N/g DM]))

      (PtLeafCnc (0.34 [DS] 0.0600 [g N/g DM]) (0.50 [DS] 0.0360 [g N/g
DM])
                 (1.28 [DS] 0.0330 [g N/g DM]) (1.52 [DS] 0.0288 [g N/g
DM])
                 (1.93 [DS] 0.0194 [g N/g DM]))
      (CrLeafCnc (0.34 [DS] 0.0210 [g N/g DM]) (0.50 [DS] 0.0210 [g N/g
DM])
```

```
                (1.28 [DS] 0.0210 [g N/g DM]) (1.52 [DS] 0.0190 [g N/g
DM])
                (1.93 [DS] 0.0183 [g N/g DM]))
      (NfLeafCnc (0.34 [DS] 0.0080 [g N/g DM]) (0.50 [DS] 0.0080 [g N/g
DM])
                (1.28 [DS] 0.0080 [g N/g DM]) (1.52 [DS] 0.0080)
                (1.93 [DS] 0.0080 [g N/g DM]))
      (PtStemCnc (0.50 [DS] 0.0200 [g N/g DM]) (1.12 [DS] 0.0125 [g N/g
DM])
                (1.28 [DS] 0.0093 [g N/g DM]) (1.53 [DS] 0.0085 [g N/g
DM])
                (1.93 0.0057 [g N/g DM]))
      (CrStemCnc (0.50 [DS] 0.0064 [g N/g DM]) (1.12 [DS] 0.0049 [g N/g
DM])
                (1.28 [DS] 0.0043 [g N/g DM]) (1.53 [DS] 0.0041 [g N/g
DM])
                (1.93 [DS] 0.0035 [g N/g DM]))
      (NfStemCnc (0.50 [DS] 0.0030 [g N/g DM]) (1.12 [DS] 0.0030 [g N/g
DM])
                (1.28 [DS] 0.0030 [g N/g DM]) (1.53 [DS] 0.0030 [g N/g
DM])
                (1.93 [DS] 0.0030 [g N/g DM]))
      (PtSOrgCnc (1.12 [DS] 0.0250 [g N/g DM]) (2.00 [DS] 0.0300 [g N/g
DM]))
      (CrSOrgCnc (1.12 [DS] 0.0150 [g N/g DM]) (2.00 [DS] 0.0150 [g N/g
DM]))
      (NfSOrgCnc (1.12 [DS] 0.0140 [g N/g DM]) (2.00 [DS] 0.0140 [g N/g
DM])))

  (Harvest
        (EconomicYield_W 0.80 [])
        (EconomicYield_N 0.94 [])))
```




Comparison microbiology and respiration tempærelationship: Are they adapted to different standard temperatures?? (microbiology to 10 degrees, respiration to 20 ??