

Chapter 8

Yield formation

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Yield prediction is a goal of most crop models. Let's note that this chapter refers to the 'biological yield', as opposed to the 'farmer's yield', the latter being generally affected by losses of the combine harvester. By definition, yield is the weight and quality of the harvested organs. These organs can be reproductive organs – either grains (dehydrated) or fruits (hydrated) – or vegetative storage organs – either stems (sugarcane) or roots (tubers). Forage crops, where the total aboveground biomass (leaves, stems and sometimes grains) is harvested in its entirety, is also considered in the following sections. The determinate or indeterminate character (as defined within the STICS model¹) does not indicate the type of harvested organs. However, by convention, we will call the harvested organs of determinate species 'grains' and the harvested organs of indeterminate species 'fruit'.

Warren-Wilson (1972) suggested that the plant should be considered as a set of compartments playing the role of sources and/or sinks for assimilates. This concept can be applied to carbon, water, nitrogen or any metabolite of interest. However, hereafter we will use it only for carbon, though it is also thoroughly documented for nitrogen (Barbottin *et al.*, 2005; Jeuffroy *et al.*, 2000; Sinclair and de Wit, 1976). The source and sink compartments usually represent organs (e.g. roots, leaves, grains, etc.), which can change their function during a cycle: 'source then sink' for roots and trunks in perennial plants, or 'sink then source' for leaves. Application of this concept to crop models generates self-regulation of the system between the growth of different types of organs. It is particularly well-suited to crops with an indeterminate growth habit and to perennial crops, in which trophic competition exists between growing and storage organs (Jeuffroy and Warembourg, 1991; Munier-Jolain *et al.*, 1998). Source capacity includes both newly-formed assimilates and remobilised resources translocated from vegetative organs. Carbon sink strength, i.e. potential growth rate, is usually represented by a continuous or discrete function of the physiological age of the organ. The problems with this approach lie in determining the size of the source capacity and

1. Within STICS, 'indeterminate' denotes species for which there is significant trophic competition between vegetative organs and harvested organs.

STICS soil-crop model

remobilised resources, which is difficult to estimate experimentally. Furthermore, it is often necessary to introduce prioritisation between organs, thus reproducing the species strategy, and this may be speculative. One alternative is to impose a constant distribution of assimilates by phenological stage, which is frequently applied in determinate crops (Weir *et al.*, 1984). The source-sink approach is used, for example, by Ritchie and Otter (1985) or Jones *et al.* (2003).

A second alternative, proposed by Spaeth and Sinclair (1985), is to extend the notion of the final harvest index (ratio of grain biomass to total shoot biomass) to the dynamic accumulation of biomass in grains, understanding that a linear variation of the harvest index as a function of time could be assumed. This approach has the advantage of pooling the two sources of assimilates, and it is economical in terms of parameters. However, it is important to impose a threshold on this harvest index dynamic, in order to avoid simulating unrealistic remobilisation levels or exceeding the maximum filling allowed by the number of organs and the maximum weight of an organ. Apart from cereals, this approach can be used for very different species, such as pea (Lecoeur and Sinclair, 2001) or grapevine (Bindi *et al.*, 1999).

Both these approaches are implemented in the STICS model: the source/sink approach for indeterminate crops and the dynamic harvest index for determinate crops. The number of organs harvested is rarely simulated in crop models and, if so, is often calculated independently from yield simulation. In the STICS model, the number of harvested reproductive organs (grains or fruits) is explicitly calculated before the allocation of biomass to these reproductive organs and will act as a genetic limitation to yield.

►► 8.1 Quantitative yield

8.1.1 For determinate growth plants

In the case of plants with determinate growth, the hypothesis is made that the number and filling of organs for harvest do not depend on the other organs' growth requirements.

The number of grains is fixed during a phase of variable duration (**nbjgrain_p** in days), which precedes the onset of filling (**idrp_T**). This number depends on the mean growth rate of the canopy during this period (**vitmoy** in $g\ m^{-2}\ d^{-1}$), which in turns depends on dynamics specific to the particular species (Eq. (8.1)).

$$vitmoy(idrp_T) = \sum_{j=idrp_T-nbjgrain_p+1}^{idrp_T} \frac{dltams(j)}{nbjgrain_p} \quad (8.1)$$

The number of grains per m^2 (**nbgrains**) is defined at the **idrp_T** stage (Eq. (8.2)). It depends on i) the growth variable (**vitmoy** in $g\ m^{-2}$) that integrates the effect of the prevailing stresses during the period preceding the **idrp_T** stage, ii) three species-dependent parameters **cgrainv0_p** (unitless), **cgrain_p** (in $g^{-1}\ m^2$) and **nbgrmin_p** (in $grains\ m^{-2}$) and iii) a genetic-dependent parameter **nbgrmax_p** (in $grains\ m^{-2}$). The last two parameters define the limits of variation of **nbgrains**.

$$\text{nbgrains}(\text{idrp}_T) = [\text{cgrainv}_p + \text{cgrain}_p \cdot \text{vit moy}(\text{idrp}_T)] \cdot \text{nbgrmax}_p$$

$$\begin{cases} \text{nbgrains}(\text{idrp}_T) = \text{nbgrmax}_p, & \text{if } \text{nbgrains}(\text{idrp}_T) > \text{nbgrmax}_p \\ \text{nbgrains}(\text{idrp}_T) = \text{nbgrmin}_p, & \text{if } \text{nbgrains}(\text{idrp}_T) < \text{nbgrmin}_p \end{cases} \quad (8.2)$$

According to Eq. (8.2), the normalised value $\frac{\text{nbgrains}}{\text{nbgrmax}_p}$ varies between $\frac{\text{nbgrmin}_p}{\text{nbgrmax}_p}$ and 1 and its variability among species expresses the sensitivity of grain onset to growth conditions (Figure 8.1).

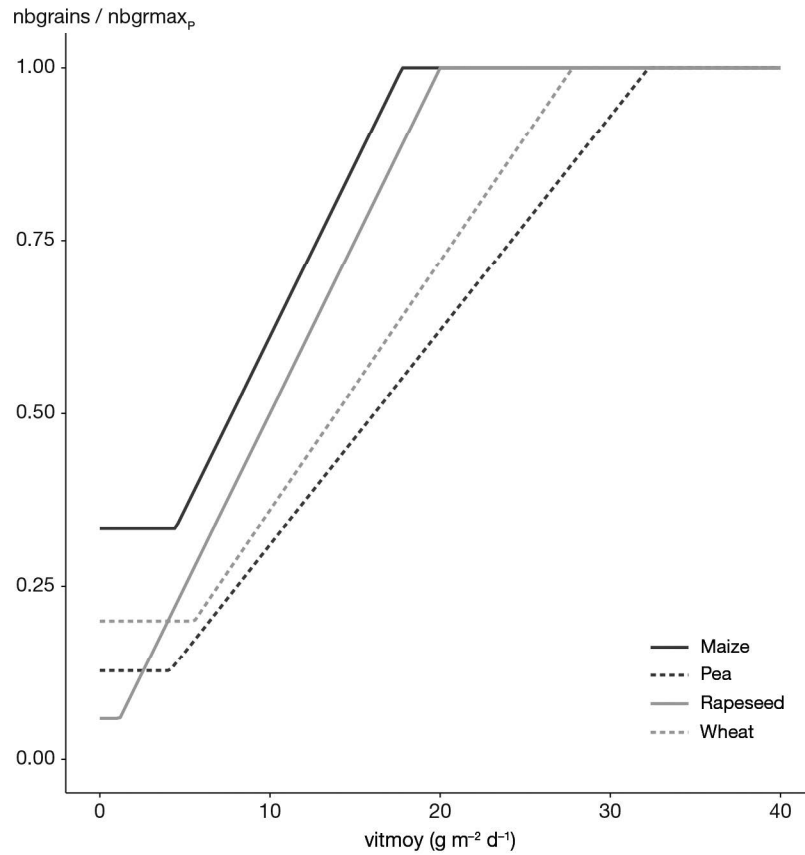


Figure 8.1. Proportion of grain number, for the maximum allowed by the variety ($\frac{\text{nbgrains}}{\text{nbgrmax}_p}$), as a function of growth during the pre-grain filling period. Examples are provided for maize (solid black line: $\text{cgrainv}_p=0.111$, $\text{cgrain}_p=0.050$, $\text{nbgrmin}_p=1500$, $\text{nbgrmax}_p=4500$), pea (dash-dotted black line: $\text{cgrainv}_p=0.000$, $\text{cgrain}_p=0.031$, $\text{nbgrmin}_p=447$, $\text{nbgrmax}_p=3500$), rapeseed (solid grey line: $\text{cgrainv}_p=0.000$, $\text{cgrain}_p=0.050$, $\text{nbgrmin}_p=50000$, $\text{nbgrmax}_p=850000$) and wheat (dash-dotted grey line: $\text{cgrainv}_p=0.000$, $\text{cgrain}_p=0.036$, $\text{nbgrmin}_p=6000$, $\text{nbgrmax}_p=30000$).

After the idrp_T stage, the grain number can be reduced in the event of frost (Eq. (8.3) and § 4.4.4) and the daily proportion of grains affected is $(1-\text{fgelflo})$, whatever their state of growth. The corresponding weight (pgraingel in $g\ m^{-2}$) is deducted from the

STICS soil-crop model

grain weight (Eq. (8.6)), using the elementary current grain weight (pgrain in g) defined in Eq. (8.7).

$$\text{for } t > \mathbf{idrp}_T \begin{cases} \mathbf{nbgraingel}(t) = \mathbf{nbgrains}(t-1) \cdot (1 - f_{\mathbf{gelflo}}(t)) \\ \mathbf{nbgrains}(t) = \mathbf{nbgrains}(\mathbf{idrp}_T) - \sum_{j=\mathbf{idrp}_T+1}^t \mathbf{nbgraingel}(j) \end{cases}$$

$$\mathbf{pgraingel}(t) = \sum_{j=\mathbf{idrp}_T+1}^t \mathbf{pgrain}(j-1) \cdot \mathbf{nbgraingel}(j) \quad (8.3)$$

The quantity of dry matter accumulated in grains is calculated by applying a progressive 'harvest index' to the dry weight of the plant. This \mathbf{ircarb} index (defined in Eq. (8.4)) increases linearly with time ($\mathbf{vitircarb}_p$ in $g_{\text{grain}} g_{\text{biomass}}^{-1} d^{-1}$), from the \mathbf{idrp}_T day to the \mathbf{imat}_T day and the final harvest index is restricted to the \mathbf{irmax}_p parameter. The dynamics of \mathbf{ircarb} for various species are depicted in Figure 8.2.

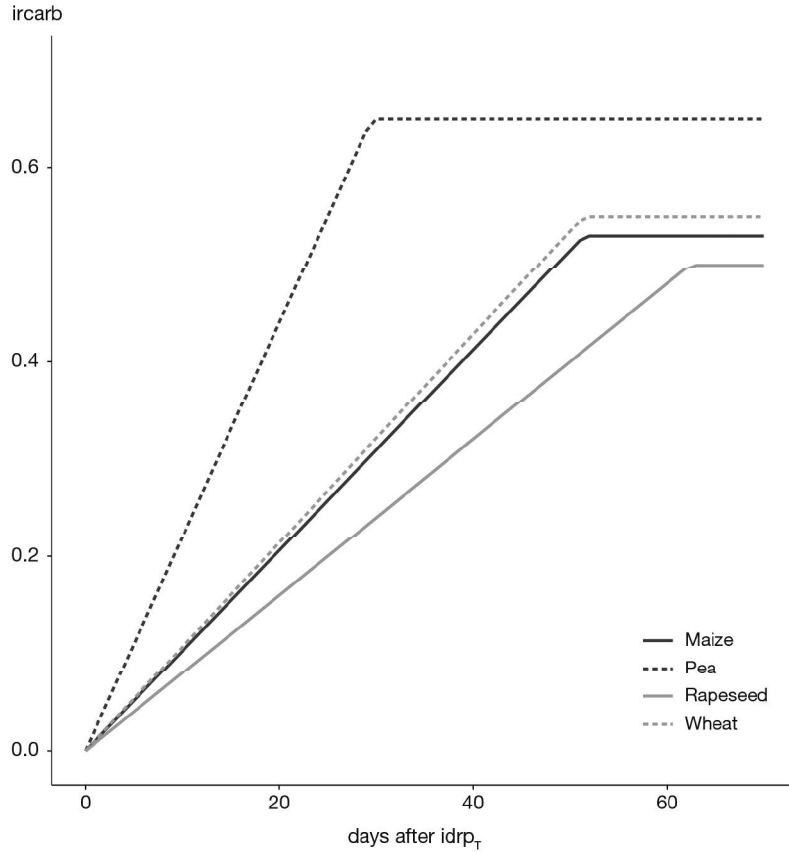


Figure 8.2. Dynamics of the grain to shoot biomass ratio (\mathbf{ircarb}), as a function of time since the stage \mathbf{idrp}_T . Examples are provided for maize (solid black line: $\mathbf{vitircarb}_p=0.0103$ and $\mathbf{irmax}_p=0.53$), pea (dash-dotted black line: $\mathbf{vitircarb}_p=0.022$ and $\mathbf{irmax}_p=0.65$), rapeseed (solid grey line: $\mathbf{vitircarb}_p=0.008$ and $\mathbf{irmax}_p=0.50$) and wheat (dash-dotted grey line: $\mathbf{vitircarb}_p=0.0107$ and $\mathbf{irmax}_p=0.55$).

$$\begin{aligned} \text{ircarb}(t) &= \text{vitircarb}_p \cdot (t - \text{idrp}_T + 1) \\ \text{ircarb}(t) &= \text{imax}_p, \text{ if } \text{ircarb}(t) > \text{imax}_p \end{aligned} \quad (8.4)$$

A transposition of the formalism has also been developed to account for thermal time. Under this formalisation, Eq. (8.4) is adapted: ircarb is computed by taking $\text{vitircarb}T_p$ as the input parameter, and the thermal time accumulation between idrp_T and imat_T as the dynamic variable of time.

Yet these dynamics may not be the actual grain filling dynamics since threshold translocation temperatures defining the thermal stress ftemprep (tminremp_p and tmaxremp_p , see § 4.4.4) may stop the carbon filling of harvested organs. Consequently, grain filling (dltags in $t \text{ ha}^{-1}$) is calculated at a daily time step, in order to account for the effect of a potential thermal stress (as defined by Eq. (8.5)).

$$\begin{aligned} \text{dltags}(t+1) &= [\text{ircarb}(t+1) \cdot \text{masec}(t+1) \\ &\quad - \text{ircarb}(t) \cdot \text{masec}(t)] \cdot \text{ftemprep}(t) \end{aligned} \quad (8.5)$$

The daily grain filling is then accumulated within the mafruit (in $t \text{ ha}^{-1}$) variable, as defined in Eq. (8.6). The mass of each grain is finally calculated as the ratio of the mass to the number of grains, although this cannot exceed the genetic pgrainmaxi_p limit, as defined in Eq. (8.7).

$$\begin{aligned} \text{mafruit}(t) &= \sum_{j=\text{idrp}_T}^t \text{dltags}(j) - \frac{\text{pgraingel}(t)}{100} \\ \text{mafruit}(t) &= \text{pgrainmaxi}_p \cdot \text{nbgrains}(t), \\ \text{if } \text{mafruit}(t) &> \text{pgrainmaxi}_p \cdot \text{nbgrains}(t) \end{aligned} \quad (8.6)$$

$$\begin{aligned} \text{pgrain}(t) &= \frac{\text{mafruit}(t)}{\text{nbgrains}(t)} \cdot 100 \\ \text{pgrain}(t) &= \text{pgrainmaxi}_p, \text{ if } \text{pgrain}(t) > \text{pgrainmaxi}_p \end{aligned} \quad (8.7)$$

8.1.2 For indeterminate growth plants

These species go on growing leaves while producing and growing harvested organs (fruits) during a period of time. The STICS model thus accounts for a trophic interaction between the growth of various groups of organs and among successive cohorts of harvested organs via the source/sink approach, using the notion of trophic stress defined in § 4.4.3). Both processes of organ setting and filling are concerned, assuming that abortion cannot occur during the filling phase.

The simulation technique adopted in the STICS model was inspired from the ‘boxcar-train’ technique (Goudriaan *et al.*, 1986) that is used in the TOMGRO model (Jones *et al.*, 1991). During growth, the fruits go through nboite_p compartments corresponding to increasing physiological ages. The time fruits spend in a compartment depends on temperature. In each compartment, fruit growth is equal to the product of a ‘sink-strength’ function and the source-sink ratio. The fruit sink strength is the derivative of a logistic function that takes the genetic growth potential of a fruit into consideration (Bertin and Gary, 1993).

8.1.2.1 Fruit setting

Fruits are set between the *idrps* stage and the *inous* stage (end of setting), defined by the **stdrpnou_p** phasic course. If this setting period lasts a long time, then the number of simultaneous compartments (i.e. fruits of different ages) is high, which indicates that there must be agreement between the values of **stdrpnou_p** and **nboite_p**.

During this setting period, on each day, the number of set fruits (*nfruitnou*) (Eq. (8.8)) depends on **afruitpot_p**, a varietal parameter expressed as the potential number of set fruits per inflorescence and per degree-day; the daily development rate (*upvt*); the number of inflorescences per plant (**nbinflo_p**); the plant density (*densite*); the trophic stress index (*spfruit*); and the frost stress index acting on fruits from flowering (*fgelflo*). Introducing the concept of inflorescence (group of fruits) into the model is only useful when technical or trophic regulation occurs at the inflorescence level (e.g. in grapevine). Furthermore, the number of fruit/flowers can also be modified (reduced) by human interventions (see § 13.2.3.2).

$$nfruitnou(t) = \mathbf{afruitpot}_p \cdot upvt(t) \cdot \mathbf{nbinflo}_p(t) \cdot densite(t) \cdot spfruit(t) \cdot fgelflo(t) \quad (8.8)$$

If the number of inflorescences is more than 1 (e.g. in the case of grapevine, inflorescences=bunches), it can either be prescribed (**nbinflo_p**), or calculated (*nbinflo_recal*) as a function of the trophic status of the plant at an early stage (we have chosen *iamfs*). In the latter case, *nbinflo_recal* is calculated using the **pentinflores_p** and **inflomax_p** parameters (see Eq. (8.9)).

$$nbinflo_reca(iamfs) = \frac{\mathbf{pentinflores}_p}{densite(iamfs)} \cdot [masec(iamfs) + resperenne0(iamfs)] \quad (8.9)$$

$$nbinflo_reca(iamfs) = \mathbf{inflomax}_p, \text{ if } nbinflo_reca(iamfs) > \mathbf{inflomax}_p$$

where *resperenne* (§ 7.3.1.1.2) is the amount of carbon reserves for perennial species coming from the previous cycle. Pruning is not accounted for in this calculation.

8.1.2.2 Fruit filling

The time spent by each fruit in a given compartment is $\frac{\mathbf{dureefruit}_p}{\mathbf{nboite}_p}$, where **dureefruit_p** is the total duration of fruit growth expressed in developmental units. In the last box (or age class), the fruits no longer grow and the final dry mass of the fruit has been reached: the fruit is assumed to have reached physiological maturity. A concrete example is shown in Figure 8.3.

Each day, in each growth compartment (*K*), the fruit growth (*croifruit*) depends on the number of fruits in the *Kth* compartment (e.g. in the first compartment: *nfruit(t,1)*) multiplied by the growth of each fruit, i.e. the elementary fruit sink strength (*fpft*), the trophic stress index (*sourcepuits*) and the thermal stress index (*ftemprem*) as given in Eq. (8.10).

$$croifruit(t, K) = nfruit(t, K) \cdot fpft(K) \cdot sourcepuits(t) \cdot ftemprem(t) \quad (8.10)$$

The fruit sink strength function is the derivative of the potential growth of a fruit (*potcroifruit*) plotted against the fruit development stage (*dfr*). There are two successive phases in fruit growth; the first corresponds to a cell division phase while the

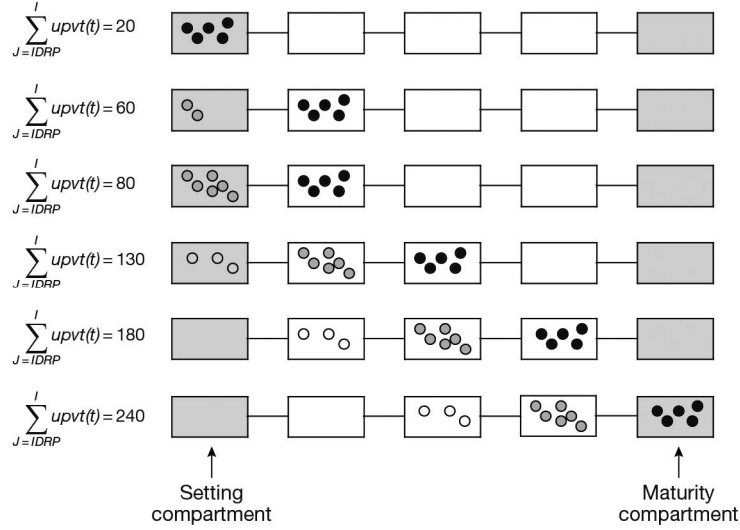


Figure 8.3. Illustration of the dynamics of fruit cohorts using the boxcartrain simulation technique. In this example $\text{stdrpno}_p = 130$, $\text{nboite}_p = 5$, $\text{dureefruit}_p = 300$.

second is devoted to expansion of the cells already set. In order to account for this double dynamic, the fruit potential cumulative growth is defined as the sum of two functions, as specified in Eq. (8.11) and illustrated in Figure 8.4:

- an exponential-type function describing the cell division phase (using the parameters $\text{c}pf_p$ and $\text{d}pf_p$)
- a logistic-type function describing the cell elongation phase (using the parameters $\text{a}pf_p$ and $\text{b}pf_p$)

$$\frac{\text{potcroifruit}(\text{dfr}(K))}{\text{pgrainmaxi}_p} = \text{d}pf_p \cdot \left(1 - \exp\left(-\text{c}pf_p \cdot \text{dfr}(K)\right) \right) + \frac{\alpha}{1 + \exp\left(-\text{b}pf_p \cdot (\text{dfr}(K) - \text{a}pf_p)\right)} - \beta \quad (8.11)$$

In Eq. (8.11), α and β are calculated so that the following conditions are respected (Eq. (8.12)):

$$\begin{cases} \text{potcroifruit}(0) = 0 \\ \text{potcroifruit}(1) = \text{pgrainmaxi}_p \end{cases} \quad (8.12)$$

where pgrainmaxi_p is the genetic-dependent maximal weight of the fruit and dfr stands for the fruit development stage of each age class, varying between 0 and 1; this value is calculated for each age class (K) in a discrete way (Eq. (8.13)).

$$\text{dfr}(K) = \frac{K}{\text{nboite}_p} \quad (8.13)$$

This double dynamic is particularly interesting for grapevine (García de Cortázar Atauri *et al.*, 2009b; 2006). In many other cases (tomato, sugar beet, sugarcane), the cell division phase is so fast that the logistic function is enough to describe fruit growth (in this case, one of the parameters $\text{c}pf_p$ or $\text{d}pf_p$ must be zero).

STICS soil-crop model

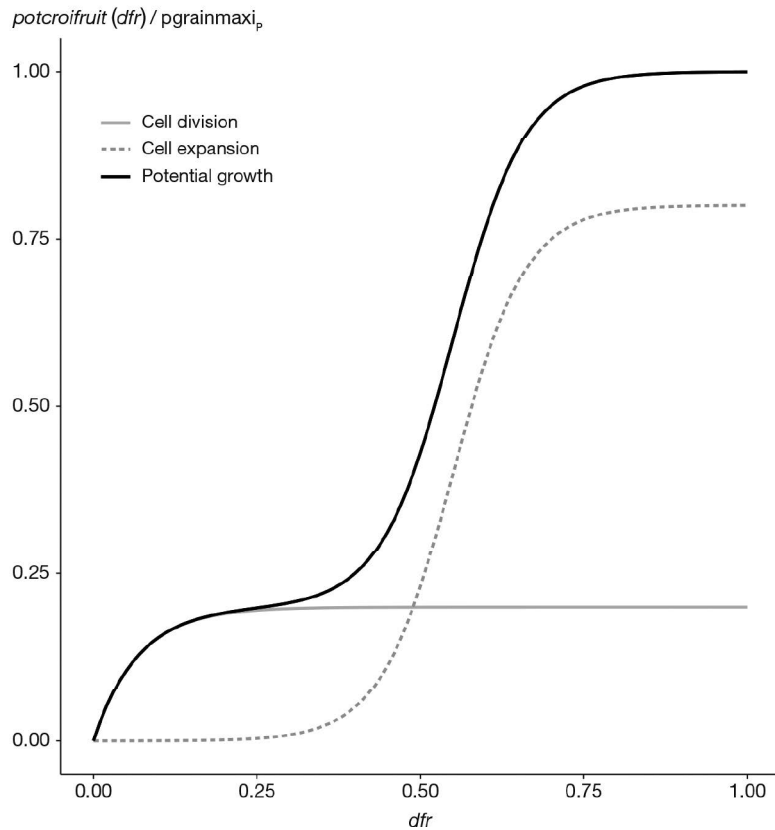


Figure 8.4. Normalised potential fruit growth ($\frac{\text{potcroifruit}}{\text{pgrainmaxi}_p}$) versus fruit development status (dfr) with its two components: the exponential dynamic representing cell division and the logistic-type dynamic representing cell expansion. In this example, we used grapevine values: $\text{afpf}_p=0.55$, $\text{bfpf}_p=18$, $\text{cfpf}_p=15$ and $\text{dfpf}_p=0.20$.

If the potential fruit growth is represented by a simple logistic curve, Figure 8.5 shows that when varying the parameters afpf_p and bfpf_p , various dynamics, including linear dynamic, can be represented.

The daily fruit sink strength function (fpft) is then calculated for each age class, according to Eq. (8.14), accounting for the duration of fruit growth from setting to maturity, expressed in developmental units (dureefruit_p).

The sensitivity of the model for subdividing fruit growth into discrete units (nboite_p parameter) also depends on the potcroifruit dynamics, as shown in Figure 8.6. Consequently, three elements must be taken into account to give a value to the parameter nboite_p : the fruit setting duration, the fruit growth dynamics and the location of the idebdess stage allowing the fruit water dynamics to be initiated.

$$f_{pf}(t, K) = p_{grainmaxi_p} \cdot devjour(t) \left[df_{pf_p} \cdot cf_{pf_p} \cdot \exp(-cf_{pf_p} \cdot dfr(K)) + \frac{bf_{pf_p} \alpha Y}{(1+Y)^2} \right]$$

$$\text{with } \begin{cases} Y = \exp(-bf_{pf_p} \cdot (dfr(K) - af_{pf_p})) \\ devjour(t) = \frac{t_{cult}(t) - t_{dmin_p}}{dureefruit_p} \end{cases} \quad (8.14)$$

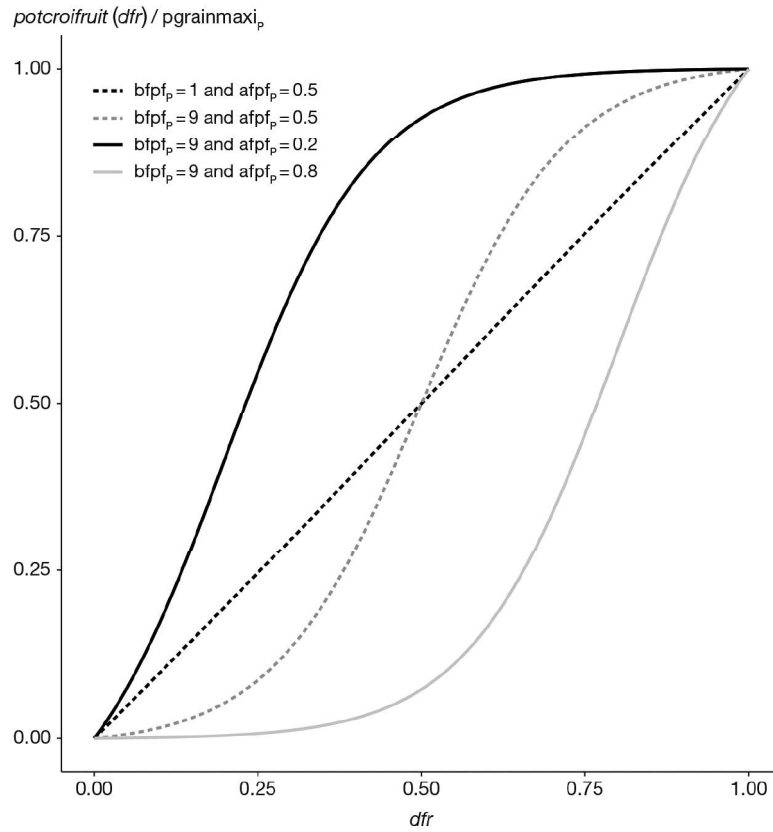


Figure 8.5. Normalised potential logistic fruit growth ($\frac{potcroifruit}{pgrainmaxi_p}$) versus fruit development status (dfr) with various parameterisations corresponding to af_{pf_p} and bf_{pf_p} values.

STICS soil-crop model

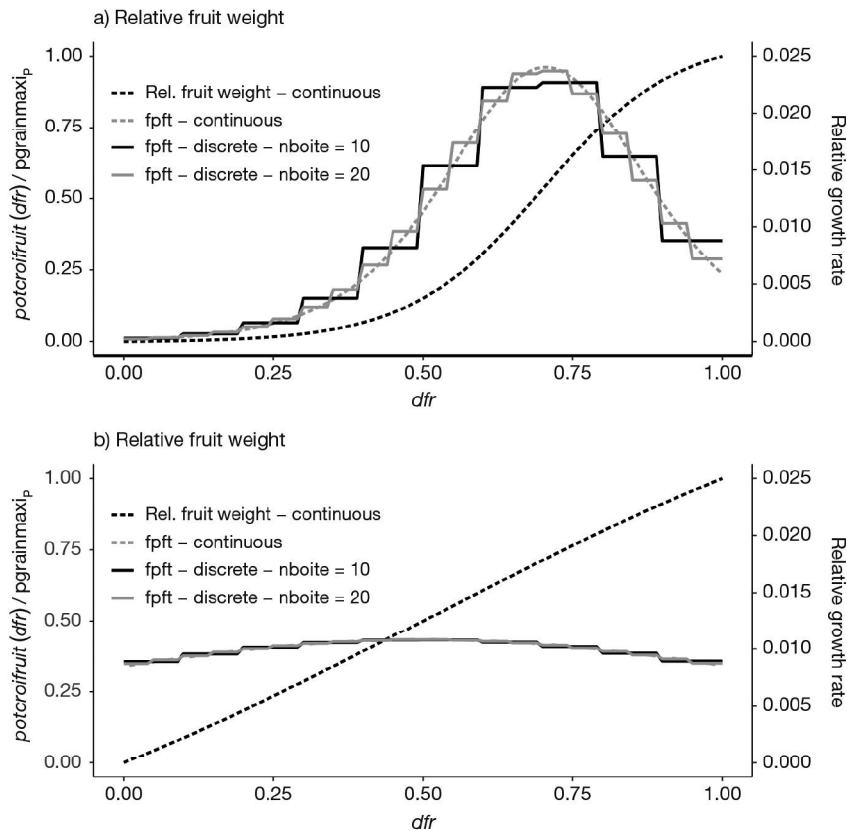


Figure 8.6. Influence of the discretisation of fruit growth through the number of boxes ($nboite_p$) in relation to the form of the dynamics: “S” shape in panel a): ($afpf_p=0.7$ and $bpf_p=9$) or nearly linear in panel b): ($afpf_p=0.5$ and $bpf_p=2$).

If allocation to fruits ($allocfruit$ variable calculated in Eq. (8.15)) exceeds the $allocfrmax_p$ threshold, the $sourcepuits$ variable is reduced in proportion to the $\frac{allocfruit}{allocfrmax_p}$ ratio. In the last box, the fruits are ripe and stop growing. The number of fruits on the plant, known as fruit load, is represented by $chargefruit$ variable. If the $codefrmur_G$ is set to 1, then $chargefruit$ will take into account the fruits in the last box (ripe); if not, it will only take into account the $(N-1)$ first boxes.

$$allocfruit(t) = \frac{\sum_{K=1}^{nboite_p-1} croifruit(t, K)}{dltams(t)} \quad (8.15)$$

8.1.3 The special case of forage crop

8.1.3.1 General considerations

Like all crops, grasslands/pastures establish aerial and underground organs, whether they are natural and already established or newly sown, and whether they are monoculture or multi-specific and composed of grasses or legumes.

Unlike annual crops, where harvest means the death of the plant, grasslands/pastures are perennial crops. This means that after harvest of the exploitable yield, the plant will grow back. Accordingly, there are some specificities regarding the crop (re-)growth (§ 4) and yield elaboration (discussed in this section).

‘Exploited grasslands’ (agronomically speaking), also called mown grasslands, can be defined as perennial crops partially harvested by ‘cutting’ operations. Cutting can be achieved through machinery – here, we mean the actual operation of mowing using human-made tools – or via animals – i.e. grazing.

It will therefore be necessary to determine what is exported during a cut (i.e. the harvested part) and what remains in place, which is referred to as the remaining dry matter or the residual dry matter (see § 7.7).

In its current version, the STICS model is distributed with species of the functional type B, namely tall fescue (*Lolium arundinaceum*), orchard grass (*Dactylis glomerata*) or permanent pasture. The functional type B is defined by Duru, Tallowin and Cruz (2005) as a group of species with a capture strategy, rather than conservation, and with a slow organ recycling rate (Cruz *et al.*, 2002). In a broader context, according to their ‘habitat preference and use-value’, type B species are defined as ‘species of fertile environments, that are fairly large in size, have a medium-to-early phenological development, are suitable to achieve a fairly early and good quality forage’ (Cruz *et al.*, 2010).

The results presented in the following section are based on the standard parameter set distributed with the STICS soil-crop model and described in Ruget *et al.* (2006), which is itself based on considerations proposed by Diaz and Cabido (1997) to account for the functional type B species. Other functional types of grassland species could, of course, be re-parameterised to run the model. Finally, the STICS model has recently been successfully used to simulate C and N dynamics in alfalfa (*Medicago sativa* in Strullu *et al.*, 2020).

The following sections will describe how the decision to cut is taken (§ 8.1.3.2) and how the biomass is pooled into the different organs to constitute the harvestable/harvested organs and the residual dry matter (§ 8.1.3.3)

8.1.3.2 Decision to initiate cutting

A cut might be attempted when at least a given date has been reached. However, it is only undertaken if the dual conditions of minimal quantities to be left on the field and to be harvested are met.

Regarding the cutting date, two possibilities are offered, depending upon the nature of the work envisioned:

- If the calendar cutting dates are known, the ‘calendar in days’ option should be used. Each cutting date is then entered in the model immediately as a day of the year (**julfauche_T**);
- If the user wishes to perform cuts at similar grassland development under variable pedoclimatic contexts, the cutting dates should be defined at specific phenological stages (**tempfauche_T**), i.e. according to thresholds of cumulated upvt (§ 3.3), which must be initialised at sowing or reinitialised after the last cut (Duru *et al.*, 1993; Theau *et al.*, 1998).

STICS soil-crop model

A synthesis of the user-defined options related to forage cutting management is summarized at § 13.2.4.1. This section also describes a third option to perform cuts, using an automatic computation option.

Furthermore, the user must define what remains on the ground. This information can be entered in the model in two ways:

- From the height of the crop that has to remain on the field after cutting, i.e. the user-defined cutting height **hautcoupe_T**;
- Alternatively, from the values of leaf area index (LAI) and biomass that the user would want to leave on the field after the cutting. These parameters are known respectively as the residual LAI - variable **lairesiduel_T** - and the residual biomass - variable **msresiduel_T**.

If the user enters the height, the residual LAI and biomass will not be read as input parameters even though they would have been defined. When height is stipulated, **lairesiduel_T** and **msresiduel_T** are calculated according to Eq. (8.16) and Eq. (8.17), that specify the relationships and changes in dry matter and LAI as a function of height (Brougham, 1956; see also § 7.7).

$$\mathbf{lairesiduel}_T = \frac{-1}{\mathbf{khaut}_p} \cdot \log\left(1 - \frac{\mathbf{hautcoupe}_T - \mathbf{hautbase}_p}{\mathbf{hautmax}_p}\right) \quad (8.16)$$

$$\mathbf{msresiduel}_T = \mathbf{coefmshaut}_p \cdot (\mathbf{hautcoupe}_T - \mathbf{hautbase}_p) \quad (8.17)$$

In these equations, **khaut_p** is the extinction coefficient, assumed to be plant-independent, connecting LAI to crop height (see § 9.2.1.1), **hautbase_p** and **hautmax_p** are plant-dependent parameters defining the lower and upper limits of foliage growth and **coefmshaut_p** accounts for the relationship between crop biomass and crop height.

Finally, additional conditions have to be met to ensure the cut can actually be performed:

- The LAI state reached by the crop must be higher than the LAI the user wants to leave on the field (i.e. **lairesiduel_T**);
- Similarly, the actual biomass state reached by the crop must be higher than the biomass the user wants to leave on the field (i.e. **msresiduel_T**);
- Finally, the harvestable fractions, called **msrec_fou** (§ 8.1.3.3), must be greater than a minimum amount that the user is willing to accept to harvest (**mscoupemini_T**).

In the actual model version, **mscoupemini_T** is defined by a unique parameter value that is specified for all cuts referring to a given management itinerary. Contrarily, the parameters **lairesiduel_T** and **msresiduel_T** are defined individually at each cut.

By modulating these criteria, cutting can be postponed until all three criteria (**lairesiduel_T**, **msresiduel_T** and **mscoupemini_T**) are met. These options were designed to allow adaptation of the management according to seasons or farmers' decisions, in order to match the harvest with needs.

8.1.3.3 Biomass pools, harvestable and harvested organs

The three biomass pools of interest in this section are the total crop biomass (**masec**) the biomass considered as potentially harvestable (**mafruit**) and the biomass that will actually be harvested (**msrec_fou**).

The variable *masec* represents the total aboveground biomass that exists on a given day. This biomass is the result of different sources (Eq. (8.18)):

- the residual biomass from the previous cut (**msresiduel_T**) that is still photosynthetically active;
- the newly produced biomass since the previous cut that is still photosynthetically active (*masecneo*).
- a dead fallen pool, which refers to a fraction of the biomass that might experience senescence and undergo abscission (*mafeuiltombe*, see § 7.3.1.1.1).

$$\begin{aligned} masec(t) &= [\mathbf{msresiduel}_T(nc) + masecneo] - mafeuiltombe \\ &= [\mathbf{msresiduel}_T(nc) + \sum_{i=nc_{day}+1}^n dltams(t)] - mafeuiltombe \end{aligned} \quad (8.18)$$

where *nc* is the number that corresponds to the last cut and *masecneo* is the sum of the daily increase in biomass (*dltams*) since the day following the last cut (**nc_{day}**) till day *n*.

In the case of forage, the non-senescent potentially harvestable biomass (*mafruit*, Eq. (8.19)) will be constituted by the non-senescent aboveground biomass which offers a use-value, i.e. which is photosynthetically active. The senescent tissues are considered as having no-value – they serve no purpose and/or will likely be lost during harvest. They must be removed from the aboveground biomass. In line with the two fractions comprising *masec*, the senescent tissues are pooled as follows:

- Senescent or dead pool coming from the residual biomass (*msresjaune*)
- The (non-fallen) senescent fraction of the newly formed biomass (*msneojaune*). It should be noted that *msneojaune* is assimilated to *mafeuiljaune* (§ 7.3.1.1.1).

$$mafruit = masec(t) - [msresjaune + msneojaune] \quad (8.19)$$

Finally, the harvested fraction *msrec_fou* (Eq. (8.20)) will be constituted by the non-senescent potentially harvestable biomass (*mafruit*) from which the fraction that will remain on the field/pasture after the next cut (**msresiduel_T**) must be removed.

$$msrec_fou = mafruit - \mathbf{msresiduel}_T \quad (8.20)$$

An additional variable integrating the whole forage produced is also outputted from the model (*masectot*). It accounts for all the biomass that has been produced (non-dead or senescent) and harvested along the cropping season.

Figure 8.7 shows the evolution over a cropping season of the variables related to forage production, including four cutting events, illustrating the differences between total aboveground biomass, harvestable and harvested biomass – namely *masec*, *mafruit* and *msrec_fou* – and showing the year-to-date production (*masectot*). Figure 8.7 illustrates how the harvested dry matter (*msrec_fou*) increases every day, and might, due to its mathematical construction, become negative when what is harvestable (*mafruit*) is lower than what should remain on the ground at the next cut (**msresiduel_T**). This usually occurs in periods of low productivity when senescence is active, i.e. mainly during dry summer.

STICS soil-crop model

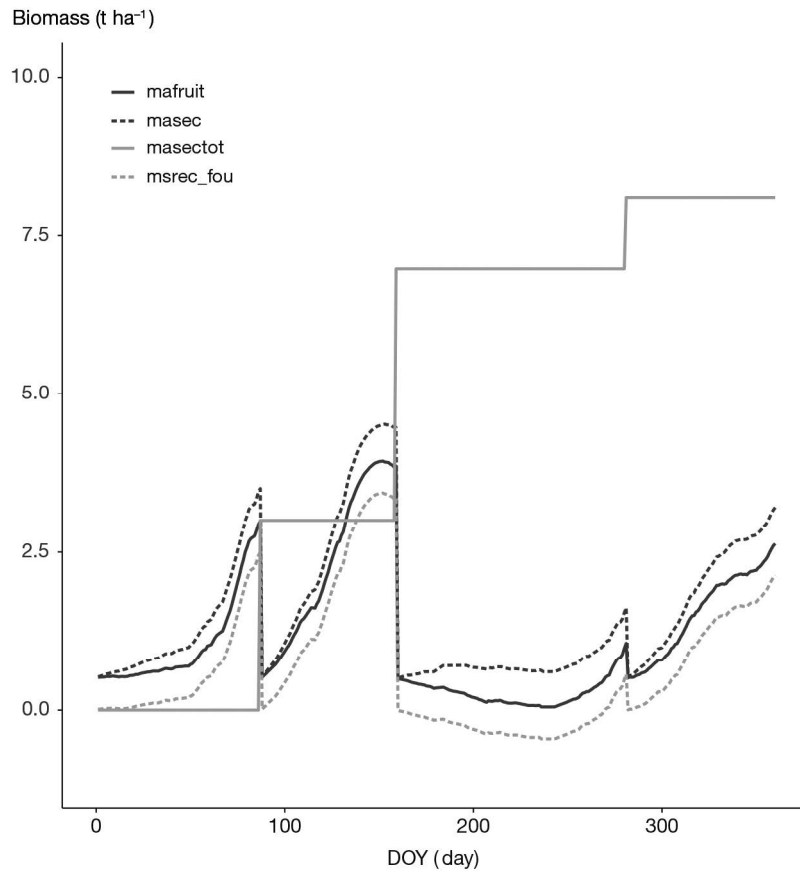


Figure 8.7. Evolution of biomass pools along a cropping season (Lusignan, France, 1991). In this example, three cuts are performed.

►► 8.2 Yield quality

8.2.1 Water content of organs

For non-harvested organs, the water contents are assumed to be constant. The corresponding parameters are called $h2ofeuilverte_p$, $h2ofeuiljaune_p$, $h2otigestruc_p$ and $h2oreserve_p$ for green leaves, dead leaves, stems and reserves, respectively: they are expressed in terms of fresh weight (hereafter referred to as 'FM'), i.e. in $g_{water} \cdot g_{FM}^{-1}$. They are used to calculate the fresh weight of each organ: mafraisfeuille (for all green and yellow leaves), mafraistige (stems) and mafraisres (reserves).

For harvested organs, it is assumed that the water content is constant ($h2ofrvert_p$) up to the stage $idebdds$ (§ 3). This stage may occur before physiological maturity. For indeterminate plants, it does not occur at the same time for all fruit cohorts but it corresponds to one of the age classes. We shall call this stage 'onset of fruit water dynamics', which can be hydration or dehydration and which results from the concomitant water and dry matter influx into the fruit or grain. From this stage, we assume

that there is a ‘programmed’ time course in the water content of fruits, and so this is expressed using the **deshybase_p** parameter (in $g_{\text{water}} g_{FM}^{-1} d^{-1}$), which will modify the fruit water content (teaugrain) day after day from its initial value **h2ofrvert_p**. For dehydration, **deshybase_p** is positive; if the programme evolution tends towards hydration, **deshybase_p** is negative. Dehydration may be accelerated (or provoked) by water stress, which is characterised by the difference between the crop and air temperatures. The proportionality coefficient is called **tempdeshyd_p** (in $g_{\text{water}} g_{FM}^{-1} \text{ } ^\circ\text{C}^{-1}$). In summary, the water content (teaugrain) is the result of Eq. (8.21) where the index K (for the box number) is of no use for determinate plants. An example is provided for grapevine in Figure 8.8.

$$\text{teaugrain}(t, K) = \text{h2ofrvert}_p - \text{deshybase}_p \cdot (t - \text{idebdess}(K) + 1) - \sum_{j=\text{idebdess}(K)}^t (\text{tempdeshyd}_p \cdot (t_{\text{cult}}(j) - t_{\text{air}}(j))) \quad (8.21)$$

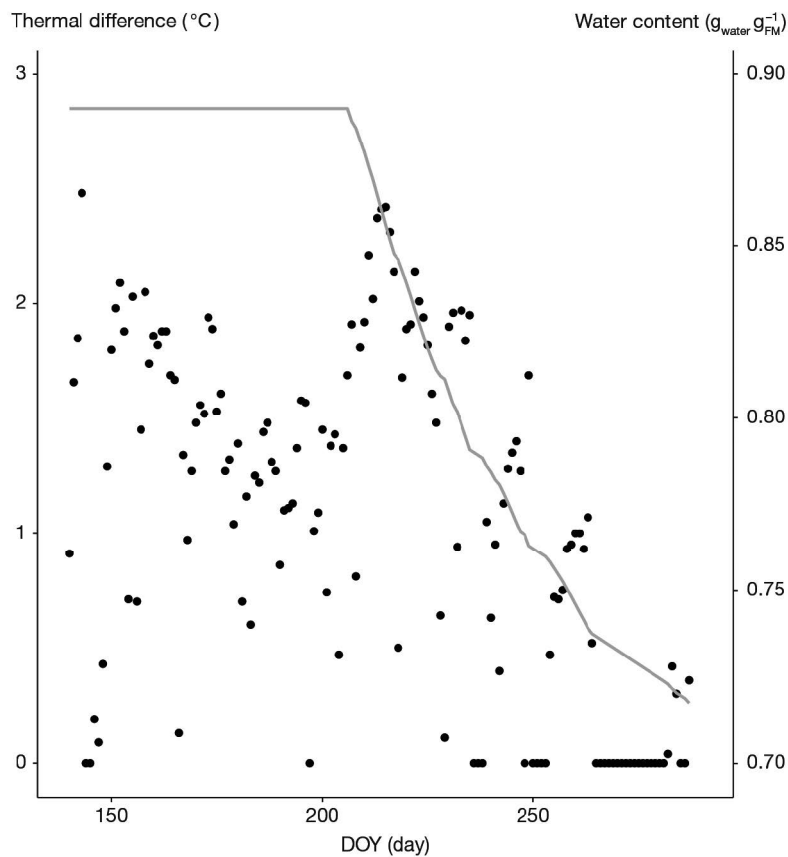


Figure 8.8. Evolution of the thermal difference ($t_{\text{cult}} - t_{\text{air}}$, black points) and the grape water content (solid grey line) for the 2003 season in Montpellier, France, influenced by the phenological course (the dynamic started on 26 July).

8.2.2 Biochemical composition

The quantity of nitrogen in harvested organs, both for determinate and indeterminate species (QN_{grain}), is an increasing proportion ($irazo$ computed in Eq. (8.22)) of the quantity of nitrogen in the biomass (QN_{plante}): the concept of the harvest index is extended to nitrogen (Lecoeur and Sinclair, 2001), using the parameter **vitirazo_p** (see also §6.1.2.2). Obviously, as for carbon, the grain/fruit nitrogen filling can be affected by thermal stress which requires a daily calculation ($dltazo$ computed in Eq. (8.23)). The temperature effect on nitrogen grain filling is assumed to be the same as for carbon. The nitrogen harvest index is assumed to be limited to a parameter **irazomax_p**, as explained in Eq. (8.22).

$$\begin{aligned} irazo(t) &= \text{vitirazo}_p \cdot (t - \text{idrp}_T + 1) \\ irazo(t) &= \text{irazomax}_p, \text{ if } irazo(t) > \text{irazomax}_p \end{aligned} \quad (8.22)$$

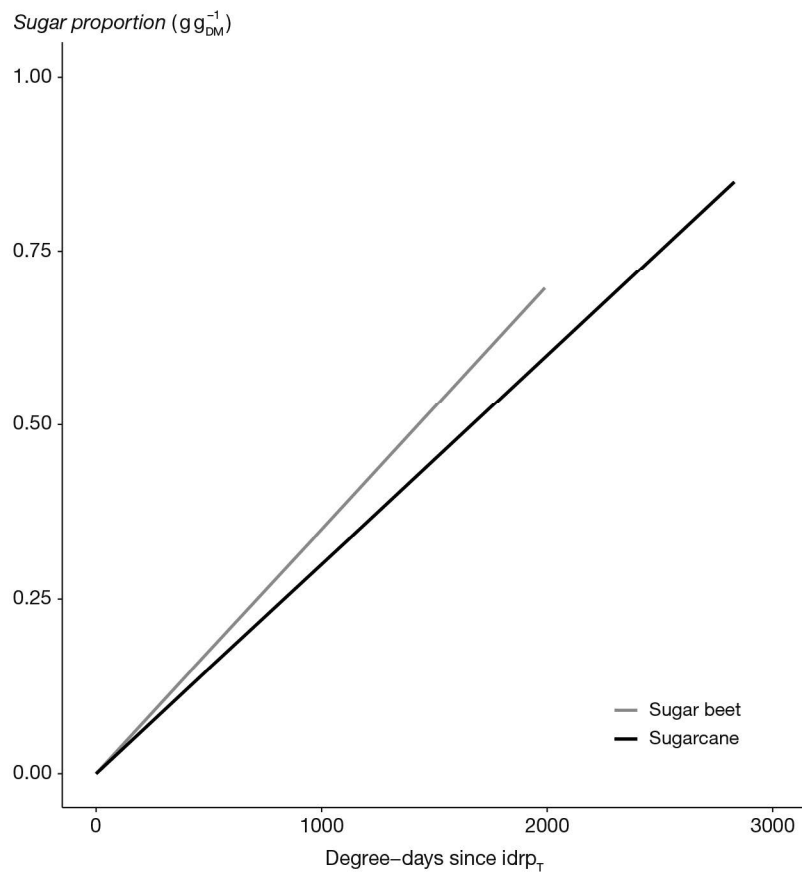


Figure 8.9. Evolution of sugar content in relation to fruit development for sugarcane ($\text{vitpropsucre}_p = 0.00030$) and sugar beet ($\text{vitpropsucre}_p = 0.00035$).

$$\begin{aligned} d\text{tazo}(t+1) = & [\text{irazo}(t+1) \cdot QN\text{plante}(t+1) \\ & - \text{irazo}(t) \cdot QN\text{plante}(t)] \cdot \text{ftemp}(t) \end{aligned} \quad (8.23)$$

To complete the quality components of simulated harvested organs, we propose a very simple estimate of the sugar and oil contents. From the beginning of fruit/grain filling until physiological maturity, we assume that there is a gradual increase in the proportions of these two types of components in the fruit dry matter. This increase is determined using the **vitprosucre_p** (Figure 8.9) and **vitprohuile_p** parameters expressed in $g\ g_{DM}^{-1}\ degreeday^{-1}$. The combination of this evolution and the evolution in the water content in fruits produces contents based on fresh matter, which depends on the development of each crop.

For indeterminate crops, the calculation is made for each age class separately, and then combined for all age classes. Finally, for the special case of grapevine, it should be noted that a new formalism was developed to compute and predict the sugar content, which will influence the alcohol content, based on the evolution of water content (García de Cortázar Atauri *et al.*, 2009b).

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