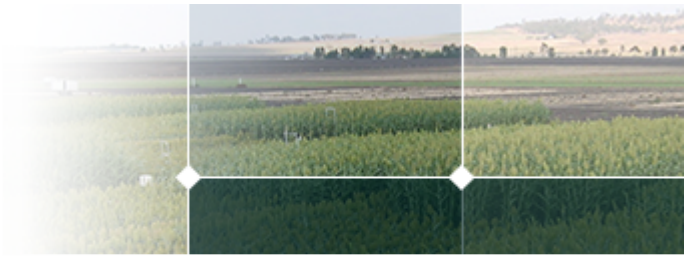


Version 0.0.0.0, built 2018-06-18

# 1 Chicory

A simulation model

The clock model

Reads in weather data and makes it available to other models.

This model collects the simulation initial conditions and stores into the DataStore. It also provides an API for writing messages to the DataStore.

The APSIM farming systems model has a long history of use for simulating mixed or intercropped systems. Doing this requires methods for simulating the competition of above and below ground resources. Above ground competition for light has been calculated within APSIM assuming a mixed turbid medium using the Beer-Lambert analogue as described by Keating et al., 1993. The MicroClimate Snow et al., 2004 model now used within APSIM builds upon this by also calculating the impact of mutual shading on canopy conductance and partitions aerodynamic conductance to individual species in applying the Penman-Monteith model for calculating potential crop water use. The arbitration of below ground resources of water and nitrogen is calculated by this model.

Traditionally, below ground competition has been arbitrated using two approaches. Firstly, the early approaches Adiku et al., 1995; Carberry et al., 1996 used an alternating order of uptake calculation each day to ensure that different crops within a simulation did not benefit from precedence in daily orders of calculations. Soil water simulations using the SWIM3 model Huth et al., 2012 arbitrate individual crop uptakes as part of the simulataneous solutions of various soil water fluxes as part of its solution of the Richards' equation Richards, 1931.

The soil arbitrator operates via a simple integration of daily fluxes into crop root systems via a Runge-Kutta calculation.

If Y is any soil resource, such as water or N, and U is the uptake of that resource by one or more plant root systems, then

$Y_{t+1} = Y_t - U$

Because U will change through the time period in complex manners depending on the number and nature of demands for that resource, we use Runge-Kutta to integrate through that time period using

$Y_{t+1} = Y_t + 1/6 \times (U_1 + 2xU_2 + 2xU_3 + U_4)$

Where $U_1$,$U_2$,$U_3$ and $U_4$ are 4 estimates of the Uptake rates calculated by the crop models given a range of soil resource conditions, as follows:

$U_1 = f(Y_t)$,

$U_2 = f(Y_t - 0.5xU_1)$,

$U_3 = f(Y_t - 0.5xU_2)$,

$U_4 = f(Y_t - U_3)$.

So $U_1$ is the estimate based on the uptake rates at the beginning of the time interval, similar to a simple Euler method. $U_2$ and $U_3$ are estimates based on the rates somewhere near the midpoint of the time interval. $U_4$ is the estimate based on the rates toward the end of the time interval.

The iterative procedure allows crops to influence the uptake of other crops via various feedback mechanisms. For example, crops rapidly extracting water from near the surface will dry the soil in those layers, which will force deeper rooted crops to potentially extract water from lower layers. Uptakes can notionally be of either sign, and so trees providing hydraulic lift of water from water tables could potentially make this water available for uptake by mutplie understory species within the timestep. Crops are responsible for meeting resource demand by whatever means they prefer. And so, leguminous crops may start by taking up mineral N at the start of the day but rely on fixation later in a time period if N becomes limiting. This will reduce competition from others and change the balance dynamically throughout the integration period.

The design has been chosen to provide the following benefits:

1) The approach is numerically simple and pure.

2) The approach does not require the use of any particular uptake equation. The uptake equation is embodied within the crop model as designed by the crop model developer and tester.

3) The approach will allow any number of plant species to interact.

4) The approach will allow for arbitration between species in any zone, but also competition between species that may demand resources from multiple zones within the simulation.

5) The approach will automatically arbitrate supply of N between zones, layers, and types (nitrate vs ammonium) with the preferences of all derived by the plant model code.

## 1.1 Field

A generic system that can have children

The Chicory model is constructed from the following list of software components. Details of the exact implementation and parameterisation are provided in the following sections.

**List of Plant Model Components.**

| Component Name | Component Type |
|---:|---:|
| Phenology | Models.PMF.Phen.Phenology |
| Arbitrator | Models.PMF.OrganArbitrator |
| Leaf | Models.PMF.Organs.SimpleLeaf |
| Stem | Models.PMF.Organs.GenericOrgan |
| Inflorescence | Models.PMF.Organs.GenericOrgan |
| Taproot | Models.PMF.Organs.GenericOrgan |
| Root | Models.PMF.Organs.Root |
| AboveGround | Models.PMF.CompositeBiomass |
| AboveGroundLive | Models.PMF.CompositeBiomass |
| BelowGround | Models.PMF.CompositeBiomass |
| BelowGroundLive | Models.PMF.CompositeBiomass |
| Total | Models.PMF.CompositeBiomass |
| PerPlantBelowGroundWt | Models.PMF.Functions.DivideFunction |
| ShootRootRatio | Models.PMF.Functions.PhaseLookup |
| TargetShootRootRatio | Models.PMF.Functions.PhaseLookup |
| StemsLeafRatio | Models.PMF.Functions.PhaseLookup |
| TargetStemsLeafRatio | Models.PMF.Functions.PhaseLookup |
| FlowerStemRatio | Models.PMF.Functions.PhaseLookup |

| Component Name | Component Type |
|---|---|
| TargetFlowerStemRatio | Models.PMF.Functions.PhaseLookup |
| TaprootRootRatio | Models.PMF.Functions.PhaseLookup |
| TargetTaprootRootRatio | Models.PMF.Functions.PhaseLookup |

### 1.1.1 Presentation

This model has been developed to simulate the growth of a forage chicory crop. The chicory model focus, thus, on describing primarily the vegetative growth, with a simplified account of the reproductive phase, without explicit considering flowers and seeds (these may be included in future releases). The model was built using the Plant Modelling Framework (PMF) described by Brown et al., 2014. To simulate the aboveground plant structure, including the photosynthesis process, the Chicory model uses the SimpleLeaf organ type of PMF. The model describes a semi-perennial crop, with phenology rewinding to the vegetative stage at the end of the reproductive phase.

### 1.1.2 Inclusion in APSIM simulations

A forage chicory crop can be included in a simulation the same as any other APSIM crop.

- - The chicory object can be dragged or copied from the Crop folder in the tool box into a Field in your simulation;
- - To become active, chicory needs to be sown using a manager script with a sowing rule. e.g.:

```
Chicory.Sow(cultivar: Puna, population: 200, depth: 10, rowSpacing: 150);
```

If a specified cultivar is not available, a fatal error will be thrown.

### 1.1.3 Harvest and biomass removal

Chicory biomass can be removed by raising one of the valid methods: Harvest, Cut, Graze, or Prune; this is done using a manager script, like for other crops. The proportion of the biomass of each organ that is removed from the system and/or added to the residue pools may be specified; otherwise defaults will be used. Note that the sum of fractions removed and added to residue should be <= 1.0. To specify the proportions for removal in a manager script, use a RemovalFractions class as shown below:

```
[EventSubscribe("Commencing")]
private void OnSimulationCommencing(object sender, EventArgs e)
{
  RemoveFraction = new RemovalFractions(Chicory.Organs);
}
[EventSubscribe("DoManagement")]
private void OnDoManagement(object sender, EventArgs e)
{
  if (Clock.Today.Date == HarvestDate)
  {
    RemoveFraction.SetFractionToRemove("Leaf", 0.80);
    RemoveFraction.SetFractionToRemove("Stem", 0.50);
    RemoveFraction.SetFractionToResidue("leaf",0.05);
    Chicory.Harvest(RemoveFraction);
  }
}
```

The RemovalFractions class can be sent with Harvest, Cut, Graze, or Prune events. All parameters are optional, defaults are used whenever any value is not specified.

### 1.1.4 Crop termination

To fully terminate a crop the EndCrop event should be raised:

```
Chicory.EndCrop();
```

Once a crop has been ended the field is open to be used by another APSIM plant model, or another chicory crop. Note that ending chicory is not necessary before sowing another crop, competition for resources will take place between crops when there is more than one in the field.

### 1.1.5 Acknowledgements

This model was developed with help from Russel McAuliffe and Brittany Paton organising data and simulations. Datasets were kindly shared by Julia M. Lee, Hamish E. Brown, and the Forages for Reduced Nitrogen Leaching (FRNL) programme.

### 1.1.6 Phenology

This model simulates the development of the crop through successive developmental *phases*. Each phase is bound by distinct growth *stages*. Phases often require a target to be reached to signal movement to the next phase. Differences between cultivars are specified by changing the values of the default parameters shown below.

The duration of each phenologic phase in Chicory is controlled in general by the accumulation of thermal time; for the reproductive phase, vernalisation and photoperiod are also used.

**List of stages and phases used in the simulation of crop phenological development**

| Stage Number | Stage Name | Phase Name |
|---|---|---|
| 1 | Sowing | |
| | | Germinating |
| 2 | Germination | |
| | | Emerging |
| 3 | Emergence | |
| | | Vegetative |
| 4 | Vernalised | |
| | | Inductive |
| 5 | Bolting | |
| | | StemElongation |
| 6 | Flowering | |
| | | Reproductive |
| 7 | Ripening | |
| | | GotoPhase |
| 8 | Ripening | |

#### 1.1.6.1 Phenological Phases

##### 1.1.6.1.1 Germinating Phase

This phase goes from Sowing to Germination.

Germination will occur one day after sowing, provided that soil extractable water is greater than zero. Germination rates for chicory typically vary between 70 and 95% when sown close to the surface (<10mm), with plenty of moisture and at good temperature (Moot et al., 2000; Sanderson, 2000; Reed, 2008; Lee, 2015). The

chicory model assumes 100% germination, and therefore the user must correct sowing rate if variation between actual sowing rate and germination is considered important.

This model assumes that germination will be completed on any day after sowing if the extractable soil water is greater than zero.

#### 1.1.6.1.2 Emerging Phase

This phase goes from Germination to Emergence.

This phase simulates time to emergence as a function of sowing depth. The *ThermalTime Target* from Sowing to Emergence is given by:
*Target = SowingDepth x ShootRate + ShootLag*
Where:
*ShootRate* = 10 (deg day/mm),
*ShootLag* = 75 (deg day),
and *SowingDepth* (mm) is sent from the manager with the sowing event.

Chicory has small seeds and emergence has been shown to be strongly affected by sowing depth (Peri et al., 2000; Sanderson, 2000), with best performace for seeds at <10mm and practically no emergence from a depth of 60 mm (for forage cultivars). This effect is not explicitly simulated by the chicory model in the current version.

Progress toward emergence is driven by Thermal time accumulation where thermal time is calculated as:

*ThermalTime = [Phenology].ThermalTime*

#### 1.1.6.1.3 Vegetative Phase

This phase goes from Emergence to Vernalised.

It uses a *ThermalTime Target* to determine the duration between development *Stages*. *ThermalTime* is accumulated until the *Target* is met and remaining *ThermalTime* is forwarded to the next phase.

During this phase the plant only partitions biomass to leaf and root+taproot organs. The phase start initially after emergence, but it is also re-called after the end of the reproductive phase (phenology reset). It ends when a minimum level of vernalisation has been reached.
Most leaf chicory cultivars (e.g. Radicchio) seem to have a facultative or quantitative response to vernalisation, that is, flowering can occurs without it if other conditions are right, but flowering will be hastened and enhanced by vernalisation (Gianquinto, 1997; Dielen et al., 2005). Root cultivars have an absolute need for vernalisation and also seem to require a certain age to be able to be vernalised, whereas leaf cultivars can be vernalised at any age (Gianquinto, 1997; Schittenhelm, 2001). Forage chicory seem to be in between these two extremes, with reports that at least some vernalisation is required (Hare et al., 1990; Moloney et al., 1993). The chicory model considers that a minimum vernalisation is needed, but this is quite small (mostly based on data from Gianquinto, 1997). Vernalisation will have a greater effect on the extent of stem and flowers growth (Wiebe, 1989; Gianquinto, 1997; Dielen et al., 2005), and thus vernalisation accumulation is considered throughout the inductive phase.

*Target = 10 (°Cd)*

*ThermalTime = [Phenology].Vernalisation.TodaysVernalisation*

#### 1.1.6.1.4 Inductive Phase

This phase goes from Vernalised to Bolting.

It uses a *ThermalTime Target* to determine the duration between development *Stages*. *ThermalTime* is accumulated until the *Target* is met and remaining *ThermalTime* is forwarded to the next phase.

This phase represents the period when the plant awaits for the cue to start of the reproductive growth, for chicory this is given by photoperiod (Wiebe, 1990; Moloney et al., 1993). For forage chicory the end of this phase seem to occur when the daylight is around 12-14 hours (Hare et al., 1990; Moloney et al., 1993; Gianquinto, 1997; Clapham et al., 2001). During this phase the plant still only allocates biomass to leaf and root+taproot organs. Vernalisation continues to accumulate throught this phase and will have an effect on the extent that biomass partition changes during reproductive growth (Wiebe, 1989; Gianquinto, 1997; Sanderson, 2003; Dielen et al., 2005).

*Target = 30 (°Cd)*

#### 1.1.6.1.5 StemElongation Phase

This phase goes from Bolting to Flowering.

It uses a *ThermalTime Target* to determine the duration between development *Stages*. *ThermalTime* is accumulated until the *Target* is met and remaining *ThermalTime* is forwarded to the next phase.

During this phase the chicory plant switches biomass partitioning, strongly prioritising stem organs, although leaf and root+taproot can still grow. Stem growth intensity decreases when flower buds start to appear (Hare et al., 1990; Clapham et al., 2001). In the USA, stem growth of forage chicory has been observed to occur for a period of time equivalent to the accumulation of thermal time of about 800-1000 oCd after bolting (Clapham et al., 2001 ). These values agreed well with the qualitative description of chicory development in New Zealand (Hare et al., 1990).

*Target = 800 (°Cd)*

*ThermalTime = [Phenology].ThermalTime*

#### 1.1.6.1.6 Reproductive Phase

This phase goes from Flowering to Ripening.

It uses a *ThermalTime Target* to determine the duration between development *Stages*. *ThermalTime* is accumulated until the *Target* is met and remaining *ThermalTime* is forwarded to the next phase.

During this phase the plant is partitioning biomass to all organs, but prioritising reproductive organs (flowers and seed). In the current model, seeds are not explicitly described and only a generic organ refered to as inflorescence is defined. This was done partly due to lack of data and partly because of the complex physiology of chicory. There is a great level of variability among chicory plants on when and for how long flowering occurs, plus even the same plant can have flowers, young seeds, as well as ripen seeds at the same time (Hare et al., 1990; Moloney et al., 1993; Clapham et al., 2001).
Data from the USA and New Zealand suggest that the reproductive phase lasts for the equivalent of the accumualtion of thermal time of about 800-1000oCd (Hare et al., 1990; Clapham et al., 2001).

*Target = 800 (°Cd)*

*ThermalTime = [Phenology].ThermalTime*

#### 1.1.6.1.7 GotoPhase Phase

This phase goes from Ripening to Ripening.

For chicory, the phase used to reset phenology is 'Vegetative'.

A special phase that jumps to another phase.

#### 1.1.6.2 ThermalTime

The thermal time is calculated from the daily average temperature using three cardinal temperatures: minimum, maximum, and optimum. Crop development acelerates as temperature increases from minimum to optimum and slows down after that, stopping completely when maximum temperature is reached. For chicory, the minimum temperature seems to be around 3-5oC (Amaducci et al., 1998; Moot et al., 2000; Clapham et al., 2001), although growth and emergence have been reported to be greatly reduced for temperatures below 10-14oC (Jung et al., 1996; Schittenhelm, 2001). Optimum temperature is reported to be around 20-25oC (Moot et al., 2000; Schittenhelm, 2001; Mathieu et al., 2014) whereas the maximum temperature should be close to 35oC (Mathieu et al., 2014; Langworthy et al., 2015).

### 1.1.7 Photoperiod

Returns the value of today's photoperiod calculated using the specified latitude and twilight sun angle threshold. If a variable called ClimateControl.PhotoPeriod is found in the simulation, it will be used instead.

*Twilight = -6 (degrees)*

### 1.1.8 Vernalisation

Vernalisation model

Vernalisation is the process whereby the plant acquires the ability to go into reproductive phase after been exposed to a period of time at low temperatures (Wiebe, 1990; Demeulemeester et al., 1998). For chicory the temperature range for vernalisation is between 0 and 12oC, with optimum about 4-6oC (Wiebe, 1989; Wiebe, 1990; Gianquinto, 1997; Dielen et al., 2005).
The reversal of vernalisation, or de-vernalisation, can happen on chicory (Wiebe, 1990; Gianquinto, 1997), if plants are exposed to sufficiently high temperatures soon after the period under vernalisation the effects of vernalisation are cancelled out. Most plants show small reversal at relatively lower temperatures (above

something in between 15 and 20oC), and larger at temperatures above 30oC. For chicory, the more effective temperature to reverse vernalisation seem to be around 30-35oC (Gianquinto, 1997; Goodger, 2013). Intermediate temperatures stabilise the vernalisation, and after 5-10 days reversal is no longer possible. The number of days required for full vernalisation is quite variable in chicory and specific to each cultivar, with 30-50 days often given for full vernalisation (Wiebe, 1990; Gianquinto, 1997; Dielen et al., 2005). However, some plants of leafy cultivars can go into reproductive phase if exposed to cold conditions for about a week or less (Gianquinto, 1997). For forage chicory (cv. Puna) at field conditions in the USA, about 50-60% of the plants reached reproductive stage after winter (Clapham et al., 2001; Sanderson, 2003), and plants that bolted on one year tended to remain vegetative the following year and vice-versa. In New Zealand conditions, reproductive phase seems to occur every year after winter (Hare et al., 1990), although the extent of it has not been reported. The data published suggest a minimum number of days for vernalisation (approximately 10 days) and a progressive increase in the number of plants vernalised as the number of days the plants are kept under cold conditions increases. This is simulated by the model by assuming that the change in biomass fixation during stem elongation and reproductive phases (prioritising stems and flowers) is a function of vernalisation.

#### 1.1.8.1 DaysToStabilise

*DaysToStabilise = 10 (days)*

The Arbitrator class determines the allocation of dry matter (DM) and Nitrogen between each of the organs in the crop model. Each organ can have up to three differnt pools of biomass:

- **Structural biomass** which remains within an organ once it is partitioned there.
- **Metabolic biomass** which generally remains within an organ but is able to be re-allocated when the organ senesses and may be re-translocated when demand is high relative to supply.
- **Storage biomass** which is partitioned to organs when supply is high relative to demand and is available for re-translocation to other organs whenever supply from uptake, fixation and re-allocation is lower than demand.

The process followed for biomass arbitration is shown in Figure 1. Arbitration responds to events broadcast daily by the central APSIM infrastructure:

1. **doPotentialPlantGrowth**. When this event is broadcast each organ class executes code to determine their potential growth, biomass supplies and demands. In addition to demands for structural, non-structural and metabolic biomass (DM and N) each organ may have the following biomass supplies:
2. **Fixation supply**. From photosynthesis (DM) or symbiotic fixation (N)
3. **Uptake supply**. Typically uptake of N from the soil by the roots but could also be uptake by other organs (eg foliage application of N).
4. **Retranslocation supply**. Storage biomass that may be moved from organs to meet demands of other organs.
5. **Reallocation supply**. Biomass that can be moved from senescing organs to meet the demands of other organs.
6. **doPotentialPlantPartitioning.** On this event the Arbitrator first executes the DoDMSetup() method to establish the DM supplies and demands from each organ. It then executes the DoPotentialDMAllocation() method which works out how much biomass each organ would be allocated assuming N supply is not limiting and sends these allocations to the organs. Each organ then uses their potential DM allocation to determine their N demand (how much N is needed to produce that much DM) and the arbitrator calls DoNSetup() to establish N supplies and Demands and begin N arbitration. Firstly DoNReallocation() is called to redistribute N that the plant has available from senescing organs. After this step any unmet N demand is considered as plant demand for N uptake from the soil (N Uptake Demand).
7. **doNutrientArbitration.** When this event is broadcast by the model framework the soil arbitrator gets the N uptake demands from each plant (where multiple plants are growing in competition) and their potential uptake from the soil and determines how much of their demand that the soil is able to provide. This value is then passed back to each plant instance as their Nuptake and doNUptakeAllocation() is called to distribute this N between organs.
8. **doActualPlantPartitioning.** On this event the arbitrator call DoNRetranslocation() and DoNFixation() to satisify any unmet N demands from these sources. Finally, DoActualDMAllocation is called where DM allocations to each organ are reduced if the N allocation is insufficient to achieve the organs minimum N conentration and final allocations are sent to organs.

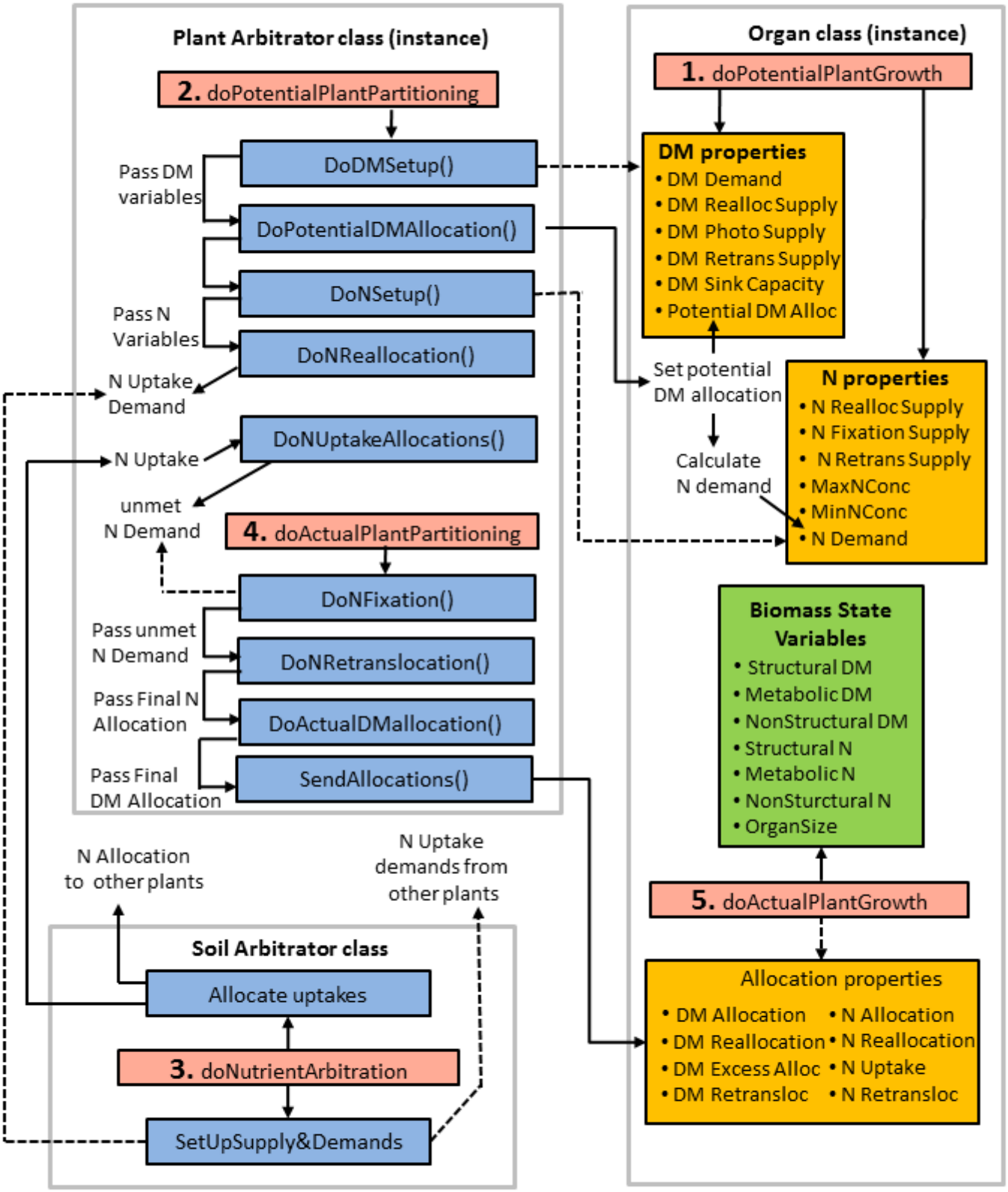

Plant Arbitrator class (instance)
2. doPotentialPlantPartitioning
DoDMSetup()
Pass DM variables
DoPotentialDMAllocation()
DoNSetup()
Pass N Variables
DoNReallocation()
N Uptake Demand
DoNUptakeAllocations()
N Uptake
unmet N Demand
4. doActualPlantPartitioning
DoNFixation()
Pass unmet N Demand
DoNRetranslocation()
Pass Final N Allocation
DoActualDMallocation()
Pass Final DM Allocation
SendAllocations()
Organ class (instance)
1. doPotentialPlantGrowth
DM properties
• DM Demand
• DM Realloc Supply
• DM Photo Supply
• DM Retrans Supply
• DM Sink Capacity
• Potential DM Alloc
Set potential DM allocation
Calculate N demand
N properties
• N Realloc Supply
• N Fixation Supply
• N Retrans Supply
• MaxNConc
• MinNConc
• N Demand
Biomass State Variables
• Structural DM
• Metabolic DM
• NonStructural DM
• Structural N
• Metabolic N
• NonSturctural N
• OrganSize
5. doActualPlantGrowth
Allocation properties
• DM Allocation
• N Allocation
• DM Reallocation
• N Reallocation
• DM Excess Alloc
• N Uptake
• DM Retransloc
• N Retransloc
N Allocation to other plants
N Uptake demands from other plants
Soil Arbitrator class
Allocate uptakes
3. doNutrientArbitration
SetUpSupply&Demands

**Figure 1:** Schematic showing procedure for arbitration of biomass partitioning. Pink boxes are events that are broadcast each day by the model infrastructure and their numbering shows the order of procedure. Blue boxes are methods that are called when these events are broadcast. Orange boxes contain properties that make up the organ/arbitrator interface. Green boxes are organ specific properties.

#### 1.1.8.1 NArbitrator

Controls the allocation of N to each of the plant's organs. Partition is based on:

Relative allocation rules used to determine partitioning

Arbitration is performed in two passes for each of the supply sources. On the first pass, biomass or nutrient supply is allocated to structural and metabolic pools of each organ based on their demand relative to the demand from all organs. On the second pass any remaining supply is allocated to non-structural pool based on the organ's relative demand.

#### 1.1.8.2 DMArbitrator

Controls the allocation of biomass to each of the plant's organs. Partition is based on:

Relative allocation rules used to determine partitioning

Arbitration is performed in two passes for each of the supply sources. On the first pass, biomass or nutrient supply is allocated to structural and metabolic pools of each organ based on their demand relative to the demand from all organs. On the second pass any remaining supply is allocated to non-structural pool based on the organ's relative demand.

### 1.1.9 Root

The generic root model calculates root growth in terms of rooting depth, biomass accumulation and subsequent root length density in each soil layer.

#### Root Growth

Roots grow downwards through the soil profile, with initial depth determined by sowing depth and the growth rate determined by RootFrontVelocity. The RootFrontVelocity is modified by multiplying it by the soil's XF value; which represents any resistance posed by the soil to root extension. Root depth is also constrained by a maximum root depth.

Root length growth is calculated using the daily DM partitioned to roots and a specific root length. Root proliferation in layers is calculated using an approach similar to the generalised equimarginal criterion used in economics. The uptake of water and N per unit root length is used to partition new root material into layers of higher 'return on investment'.

#### Dry Matter Demands

A daily DM demand is provided to the organ abitrator and a DM supply returned. By default, 100% of the dry matter (DM) demanded from the root is structural. The daily loss of roots is calculated using a SenescenceRate function. All senesced material is automatically detached and added to the soil FOM.

#### Nitrogen Demands

The daily structural N demand from root is the product of total DM demand and the minimum N concentration. Any N above this is considered Storage and can be used for retranslocation and/or reallocation as the respective factors are set to values other then zero.

#### Nitrogen Uptake

Potential N uptake by the root system is calculated for each soil layer (i) that the roots have extended into. In each layer potential uptake is calculated as the product of the mineral nitrogen in the layer, a factor controlling the rate of extraction (kNO3 or kNH4), the concentration of N form (ppm), and a soil moisture factor (NUptakeSWFactor) which typically decreases as the soil dries.

$$NO3\ uptake = NO3_i \times kNO3 \times NO3_{ppm,\,i} \times NUptakeSWFactor$$

$$NH4\ uptake = NH4_i \times kNH4 \times NH4_{ppm,\,i} \times NUptakeSWFactor$$

Nitrogen uptake demand is limited to the maximum daily potential uptake (MaxDailyNUptake) and the plants N demand. The demand for soil N is then passed to the soil arbitrator which determines how much of the N uptake demand each plant instance will be allowed to take up.

**Water Uptake**

Potential water uptake by the root system is calculated for each soil layer that the roots have extended into. In each layer potential uptake is calculated as the product of the available water in the layer (water above LL limit) and a factor controlling the rate of extraction (KL). The values of both LL and KL are set in the soil interface and KL may be further modified by the crop via the KLModifier function.

*SW uptake = ($SW_i$ - $LL_i$) x $KL_i$ x KLModifier*

**Note:** this represents all the fine roots of the plant.
There is no distinction of age, but root biomass is allocated separately for each soil layer within the root zone. The depth of the root zone can change over time as root grows.

#### 1.1.9.1 RemobilisationCost

*RemobilisationCost = 0*

#### 1.1.9.2 InitialDM

*InitialDM = 0.001 (g/plant)*

The model assumes that 2/3 of the seed biomass is converted to root biomass by the time of emergence. The weight of chicory seeds varies From 1.4 to 1.7 g/1000 seeds (Hare et al., 1990; Reed, 2008).

#### 1.1.9.3 StructuralFraction

*StructuralFraction = 1 (g/g)*

This is the default value for PMF.

#### 1.1.9.4 MinimumNConc

*MinimumNConc = 0.014 (gN/gDM)*

This lowest N concentration for roots and represents the N content for structural tissues. Published values suggest that the concentration in roots is much less variable than for taproots and it is on average higher too. The lower values vary around 1.4% (Bausenwein et al., 2001; Zagal et al., 2001; Jurgonski et al., 2011).

#### 1.1.9.5 MaximumNConc

*MaximumNConc = 0.016 (gN/gDM)*

The upper limit for N concentration in chicory roots seem to be similar to that of taproots and published data suggest values around 1.6-1.7% (Bausenwein et al., 2001; Zagal et al., 2001; Jurgonski et al., 2011).

### 1.1.10 DMDemandFunction

This is the Partition Fraction Demand Function which returns the product of its PartitionFraction and the total DM supplied to the arbitrator by all organs.

#### 1.1.10.1 PartitionFraction

The chicory model allocates biomass below ground following a simple approach. The amount allocated to below ground is computed based on the [TargetShootRootRatio].Value, and then the partiton between roots and taproot is controlled by the [TaprootRootRatio].Value). There is only a few data in literature about the relative amounts of fine roots and taproots (Li et al., 1997; Labreveux, 2002; Alloush et al., 2003), so the parameterisation of DM partition should be revised when more data is available.

The value of PartitionFraction from Emergence to Ripening is calculated as follows:

*RootFraction = Numerator / Denominator*

Where:

*Numerator = [ShootRootRatio] x [TaprootRootRatio]*

*Denominator = SRs x TRs*

Where:

*SRs = TargetSRs + [ShootRootRatio]*

Where:

*TargetSRs = [TargetShootRootRatio] x [TargetShootRootRatio]*

*TRs = TargetTRs + [TaprootRootRatio]*

Where:

*TargetTRs = [TargetTaprootRootRatio] x [TargetTaprootRootRatio]*

PartitionFraction has a value of zero for phases not specified above

#### 1.1.10.1 DMConversionEfficiency

*DMConversionEfficiency = 1 (/day)*

This is the default value for PMF.

#### 1.1.10.2 MaintenanceRespirationFunction

*MaintenanceRespirationFunction = 0 (/day)*

This is the default value for PMF.

#### 1.1.10.3 MaximumRootDepth

*MaximumRootDepth = 2000 (mm)*

Chicory is typically describe as a deep rooted species and values of about 2.0 m have been reported (Li et al., 2005; Brown, 2004; Sapkota et al., 2012).

#### 1.1.10.4 RootFrontVelocity

Growth of roots are a priority for plants after germination and should slow down as plants grow; when in the reproductive phase growth is very much focused on above ground biomass. Thus the chicory model assumes that growth rate of roots vary with phenological phase. No estimate value for the parameter was found, so it was set based on available information (Brown, 2004; Sapkota et al., 2012) and general knowledge from other models.

##### 1.1.10.4.1 PreEmergence

The value of RootFrontVelocity from Germination to Emergence is calculated as follows:

*ReferenceVelocity = 5 (mm/day)*

##### 1.1.10.4.2 Vegetative

The value of RootFrontVelocity from Emergence to Bolting is calculated as follows:

*ReferenceVelocity = 10 (mm/day)*

##### 1.1.10.4.3 Reproductive

The value of RootFrontVelocity from Bolting to Ripening is calculated as follows:

*ReferenceVelocity = 1 (mm/day)*

RootFrontVelocity has a value of zero for phases not specified above

#### 1.1.10.5 SpecificRootLength

*SpecificRootLength = 40 (m/g)*

The PMF model converts root biomass into root length using the specific root length (SRL), and this may be used to regulate uptake processes. Available data for chicory is highly variable and the disticntion between fine roots and taproot is not always considered, value range from 10 m/g for seedlings up to 100 m/g (Sanderson, 2000; Labreveux, 2002; Sapkota et al., 2012; Liu et al., 2015; Cranston et al., 2016).

#### 1.1.10.6 SenescenceRate

The rate of senescence for chicory roots is not really know, but it should be affected to enviromental factors, such as temperature and soil moisture. Currently the reference rate is adjusted for temperature only, following general knowledge from other plant models.

*SenescenceRate = ReferenceRate x TemperatureFactor x SoilMoistureFactor x SoilAerationFactor*

Where:

*ReferenceRate = 0.005 (/day)*

#### 1.1.10.6.1 SoilMoistureFactor

*SoilAerationFactor = 1*

#### 1.1.10.7 DMRetranslocationFactor

*DMRetranslocationFactor = 0 (/day)*

This is the default value for PMF.

#### 1.1.10.8 DMReallocationFactor

*DMReallocationFactor = 0 (/day)*

This is the default value for PMF.

#### 1.1.10.9 NRetranslocationFactor

*NRetranslocationFactor = 0 (/day)*

This is the default value for PMF.

#### 1.1.10.10 NReallocationFactor

*NReallocationFactor = 0 (/day)*

This is the default value for PMF.

#### 1.1.10.11 MaxDailyNUptake

*MaxDailyNUptake = 10 (kgN/ha)*

This represent the upper limit for N uptake, its value should be affected by soil type (capacity for supply, or transport) as well as plant type (capacity to explore the soil volume). The value used is based on general knowledge from other models.
Note that atual uptake is regulated by soil water content and may be due to root density, so the value here is just the uppr limit.

#### 1.1.10.12 NUptakeSWFactor

This is used to down-regulate N uptake when there is water limitations in the soil, it accounts for the fact that transport of nutrient is reduced when soil moisture is low.

#### 1.1.10.13 BiomassRemovalDefaults

This organ will respond to certain management actions by either removing some of its biomass from the system or transferring some of its biomass to the soil. The following table describes the proportions of live and dead biomass that are transferred for a range of management actions.

| Method | % Live Removed | % Dead Removed | % Live To Residue | % Dead To Residue |
|---|---|---|---|---|
| Cut | 0 | 0 | 5 | 0 |
| Graze | 0 | 0 | 5 | 0 |
| Harvest | 0 | 0 | 5 | 0 |
| Prune | 0 | 0 | 5 | 0 |

#### 1.1.10.14 CarbonConcentration

*CarbonConcentration = 0.4*

### 1.1.11 AboveGround Biomass

This is a composite biomass class. *i.e.* a biomass made up of 1 or more biomass objects.

This contains the sum of all biomass (live and dead) of Leaf, Stem and Inflorescence.

AboveGround is a composite of the following biomass objects:

- [Leaf].Live
- [Leaf].Dead
- [Stem].Live
- [Stem].Dead
- [Inflorescence].Live
- [Inflorescence].Dead

#### 1.1.12 AboveGroundLive Biomass

This is a composite biomass class. *i.e.* a biomass made up of 1 or more biomass objects.

This contains the sum of live biomass of Leaf, Stem and Inflorescence.

AboveGroundLive is a composite of the following biomass objects:

- [Leaf].Live
- [Stem].Live
- [Inflorescence].Live

#### 1.1.13 BelowGround Biomass

This is a composite biomass class. *i.e.* a biomass made up of 1 or more biomass objects.

This contains the sum of all biomass (live and dead) of Taproot and Root.

BelowGround is a composite of the following biomass objects:

- [Root].Live
- [Root].Dead
- [Taproot].Live
- [Taproot].Dead

#### 1.1.14 BelowGroundLive Biomass

This is a composite biomass class. *i.e.* a biomass made up of 1 or more biomass objects.

This contains the sum of live biomass of Taproot and Root.

BelowGroundLive is a composite of the following biomass objects:

- [Root].Live
- [Taproot].Live

#### 1.1.15 Total Biomass

This is a composite biomass class. *i.e.* a biomass made up of 1 or more biomass objects.

This contains the sum of all plant biomass, live and dead of Leaf, Stem, Inflorescence,Taproot, and Root.

Total is a composite of the following biomass objects:

- [Leaf].Live
- [Leaf].Dead
- [Stem].Live
- [Stem].Dead
- [Inflorescence].Live
- [Inflorescence].Dead
- [Root].Live
- [Root].Dead
- [Taproot].Live
- [Taproot].Dead

#### 1.1.16 PerPlantBelowGroundWt

This represents the live biomass dry weight below ground for a specific plant (in g/plant)

*PerPlantBelowGroundWt = [BelowGroundLive].Wt / [Chicory].Population*

### 1.1.17 ShootRootRatio

#### 1.1.17.1 AllPhases

The value of ShootRootRatio from Emergence to Ripening is calculated as follows:

##### 1.1.17.1.1 CurrentSR

*CurrentSR = [AboveGroundLive].StructuralWt / [BelowGroundLive].StructuralWt*

ShootRootRatio has a value of zero for phases not specified above

### 1.1.18 TargetShootRootRatio

The target shoot:root ratio is used by the chicory model to ensure prompt regrowth after a defoliation event. The model will change the allocation of new growth attempting to keep a balance in organ biomass distribution. This is a simplified approach to biomass allocation plasticity (e.g. Wilson, 1988; Levang-Brilz et al., 2002), it assumes that the plant adjusts the allocation biomass whenever the current shoot:root ratio differs from the target value. Estimated values for the shoot:root ratio of chicory based on published data vary considerably and are linked to cultivar (e.g. Li et al., 1997; Zagal et al., 2001; Belesky et al., 2004). Varieties bred for root harvesting can have shoot:root ratios al low as 1.0 whereas for leaf cultivars the values may be up to around 5.0. Data for forage chicory suggest values around 2.0 for adult plants (Li et al., 1997; Labreveux, 2002; Alloush et al., 2003; Cranston, 2015). This value is likely to be affected by environmental conditions, with water or nutrient deficit causing a shift towards root growth, while leaf growth is favoured during low light conditions. However, these relationships can vary considerably in different plants or cultivars and little data is available for forage chicory. The model currently does not account fort the influence of environmental factors on the shoot:root partition, but it does account for vernalisation.
Stem elongation, or bolting, only occurs when chicory is vernalised and it has been shown happen in only a fraction of the plants in a sward each year (Clapham et al., 2001; Sanderson, 2003; Dielen et al., 2005). This variation seems to be linked to the extent of vernalisation (Gianquinto, 1997; Dielen et al., 2005). Thus, to account for the growth of both bolting and non-bolting plants, the chicory model assumes that the changes in biomass allocation are a function of vernalisation as well as phenological phase.

#### 1.1.18.1 Vegetative

The value of TargetShootRootRatio from Emergence to Vernalised is calculated as follows:

*TargetSR = 1.5 (g/g)*

#### 1.1.18.2 InductiveElongation

The value of TargetShootRootRatio from Vernalised to Flowering is calculated as follows:

##### 1.1.18.2.1 TargetSR

*TargetSR = [TargetShootRootRatio].Vegetative.TargetSR + DeltaTarget*

Where:

*DeltaTarget = MaximumIncrease x VernalisationEffect x StageEffect*

Where:

*MaximumIncrease = MaxTargetSR - [TargetShootRootRatio].Vegetative.TargetSR*

Where:

*MaxTargetSR = 4 (g/g)*

#### 1.1.18.3 Reproductive

The value of TargetShootRootRatio from Flowering to Ripening is calculated as follows:

##### 1.1.18.3.1 TargetSR

*TargetSR = [TargetShootRootRatio].Vegetative.TargetSR + PlusTarget*

Where:

*PlusTarget = DeltaTarget x StageEffect*

Where:

*DeltaTarget = [TargetShootRootRatio].InductiveElongation.TargetSR - [TargetShootRootRatio].Vegetative.TargetSR*

TargetShootRootRatio has a value of zero for phases not specified above

### 1.1.19 StemsLeafRatio

#### 1.1.19.1 AllPhasesWithStems

The value of StemsLeafRatio from Bolting to Ripening is calculated as follows:

##### 1.1.19.1.1 CurrentSL

*CurrentSL = StemFlowerDM / [Leaf].Live.Wt*

Where:

*StemFlowerDM = [Stem].Live.Wt + [Inflorescence].Live.Wt*

StemsLeafRatio has a value of zero for phases not specified above

### 1.1.20 TargetStemsLeafRatio

The chicory model will change the allocation of biomass above ground attempting to keep a given proportion among the various organs. The allocation of biomass to leaves is defined primarily by the target shoo:root ratio, but during the stem elongation and reproductive phases, the partition is modified favouring stems and inflorescence. This is controlled by the target ratio of stems+inflorescence to leaves. This ratio may be affected by defoliation (Clark et al., 1990; Li et al., 1994; Quijada, 2015) and is probably affected by enviromental factors too. There is not enough data to describe these interactions.
The allocation of biomass to stems is difficult to inferr because there are many confounding issues, such as growth stage, vernalisation level, graze intensity, etc. Under lax grazing conditions and after some vernalisation, stem fraction is about 25-50%, but can be as high as 70%, values around 15-25% are reported for intensive grazing (Clark et al., 1990; Li et al., 1994; Jung et al., 1996; Li et al., 1997; Li et al., 1997). The Stem:leaf ratio is thus between 0.25 and 1.0 for grazed plants. Bolting only occur in a fraction of plant each year, around 50% ( Clapham et al., 2001; Sanderson, 2003; Dielen et al., 2005). So, as a compromise, it assumed in the chicory model that the stem:leaf ratio increases sharply at the beginning of the stem elongation phase, reaching a maximum value and then is constant until near the end of flowering when if decreases again. This maximum should be not too high to account for non bolting plants.

#### 1.1.20.1 AllPhasesWithStems

The value of TargetStemsLeafRatio from Bolting to Ripening is calculated as follows:

##### 1.1.20.1.1 TargetSL

*TargetSL = MaximumSL x [TargetShootRootRatio].InductiveElongation.TargetSR.DeltaTarget.VernalisationEffect x StageEffect*

Where:

*MaximumSL = 1 (g/g)*

TargetStemsLeafRatio has a value of zero for phases not specified above

### 1.1.21 FlowerStemRatio

#### 1.1.21.1 Reproductive

The value of FlowerStemRatio from Flowering to Ripening is calculated as follows:

##### 1.1.21.1.1 CurrentFS

*CurrentFS = [Inflorescence].Live.Wt / [Stem].Live.Wt*

FlowerStemRatio has a value of zero for phases not specified above

### 1.1.22 TargetFlowerStemRatio

The allocation of biomass during the reproductive phase will attempt to keep a ratio between stem and inflorescence biomass. This ratio is difficult to define as there is little data available and because of the flowering behaviour of chicory (plants can have ripe seeds as well as young flower buds at the same time). Inference from published values suggest that the ratio of flower biomass to stems should be around 0.1 (Hare et al., 1990; Clark et al., 1990; Jung et al., 1996; Clapham et al., 2001).

#### 1.1.22.1 Reproductive

The value of TargetFlowerStemRatio from Flowering to Ripening is calculated as follows:

##### 1.1.22.1.1 TargetSL

*TargetSL = MaximumFS x StageEffect*

Where:

*MaximumFS = 0.1 (g/g)*

TargetFlowerStemRatio has a value of zero for phases not specified above

### 1.1.23 TaprootRootRatio

#### 1.1.23.1 AllPhases

The value of TaprootRootRatio from Emergence to Ripening is calculated as follows:

##### 1.1.23.1.1 CurrentTR

*CurrentTR = [Taproot].Live.Wt / [Root].Live.Wt*

TaprootRootRatio has a value of zero for phases not specified above

### 1.1.24 TargetTaprootRootRatio

The chicory model assumes that biomass is allocated to the various organs in a manner to mantain a given proportion each each organ (this can vary with phenological phase and other factors). The ratio between taproot and root biomass is assumed to increase as the biomass below ground per plant increases, but it approaches a maximum target asymptotically. This is a simple approach and can describe the general behaviour of chicory plants, it may be upgraded if deemed necessary when more data becomes available.

#### 1.1.24.1 AllPhases

The value of TargetTaprootRootRatio from Emergence to Ripening is calculated as follows:

##### 1.1.24.1.1 TargetTR

*TargetTR = MaximumTR x BiomassFactor*

Where:

*MaximumTR = 2 (g/g)*

TargetTaprootRootRatio has a value of zero for phases not specified above

### 1.1.25 Cultivars

Choice, Puna

### 1.1.26 Puna

Cultivar class for holding cultivar overrides.

*Puna* is the basic forage chicory cultivar. It represents one of the first chicory cultivars selected for seed production and it has been used for forage grazing, in monoculture or in mixed swards, in several countries worldwide.

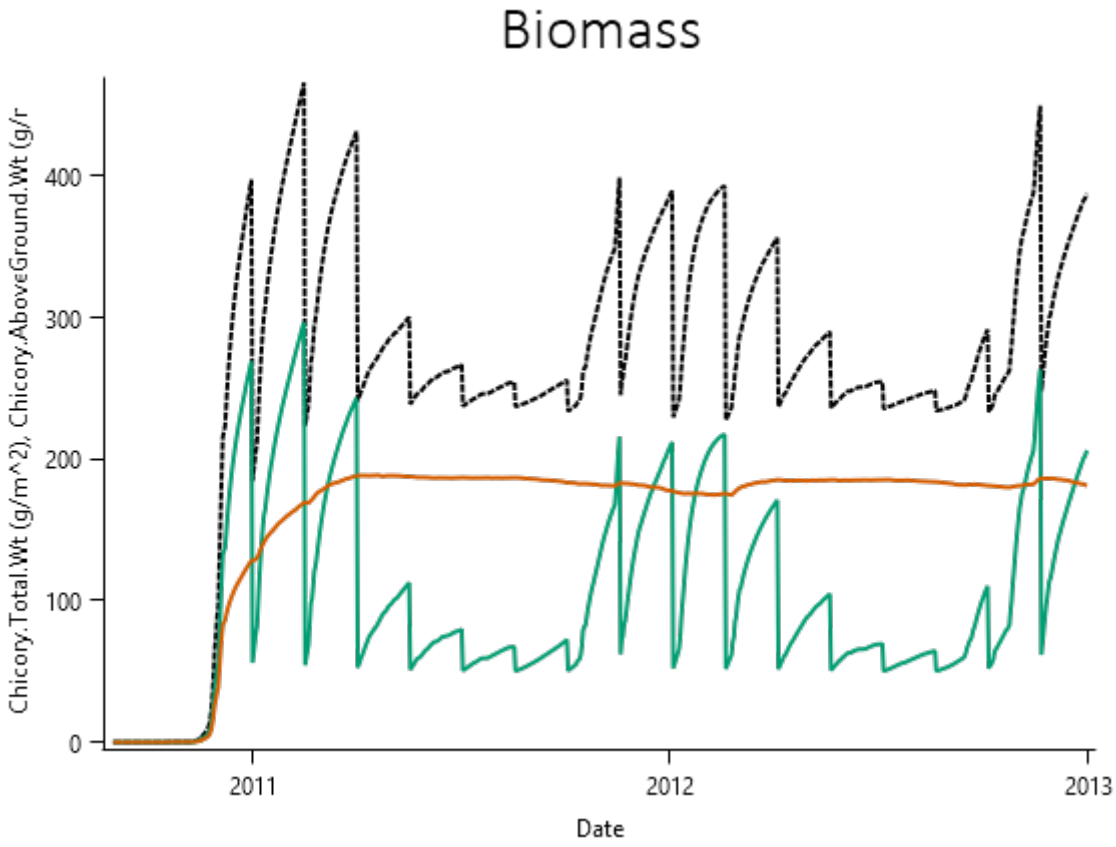
### 1.1.27 Choice

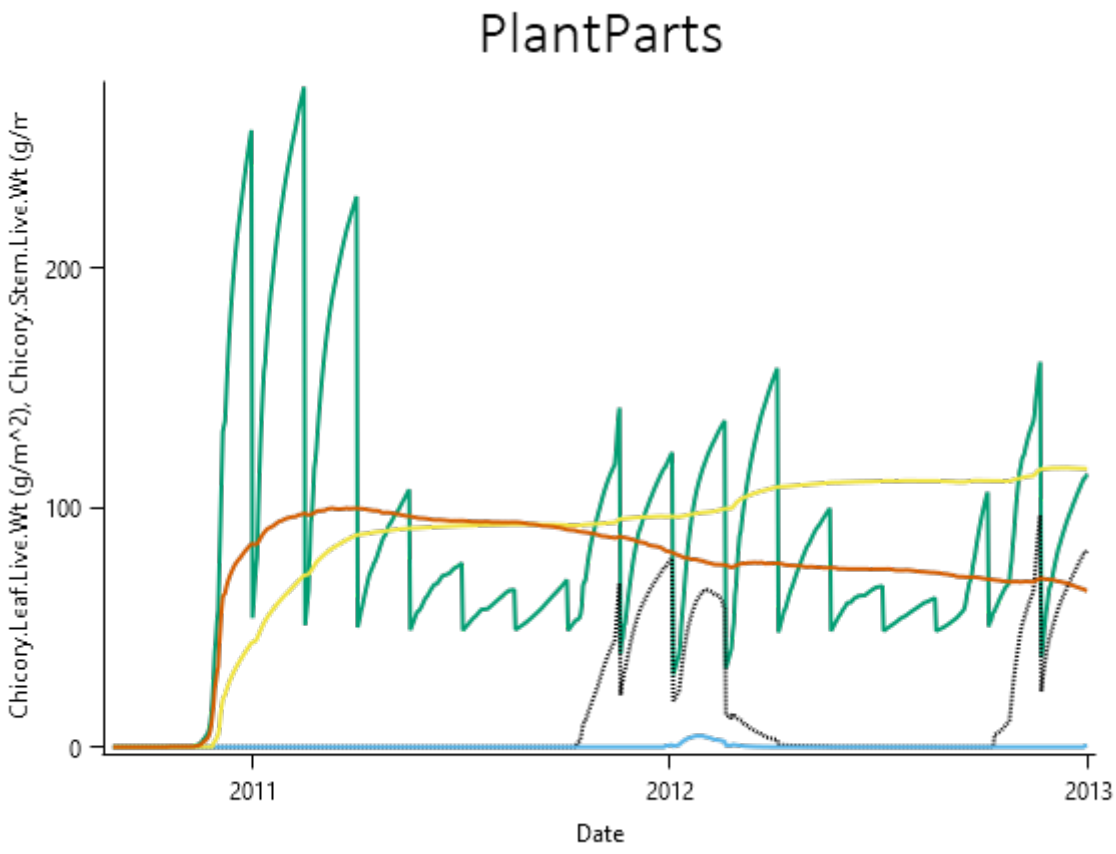
Cultivar class for holding cultivar overrides.

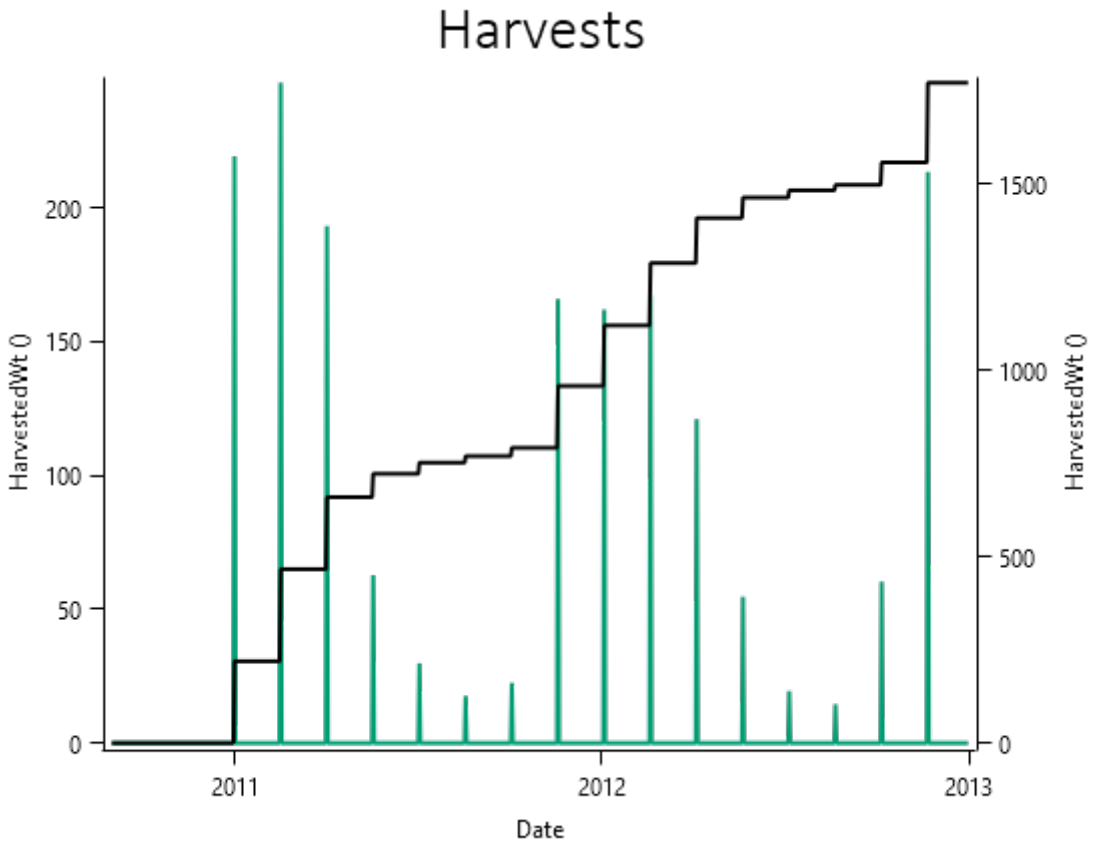
*Choice* is forage chicory cultivar derived from *Puna*, to which it is very similar. It has advertised as a winter active forage and is commonly used in monoculture swards.

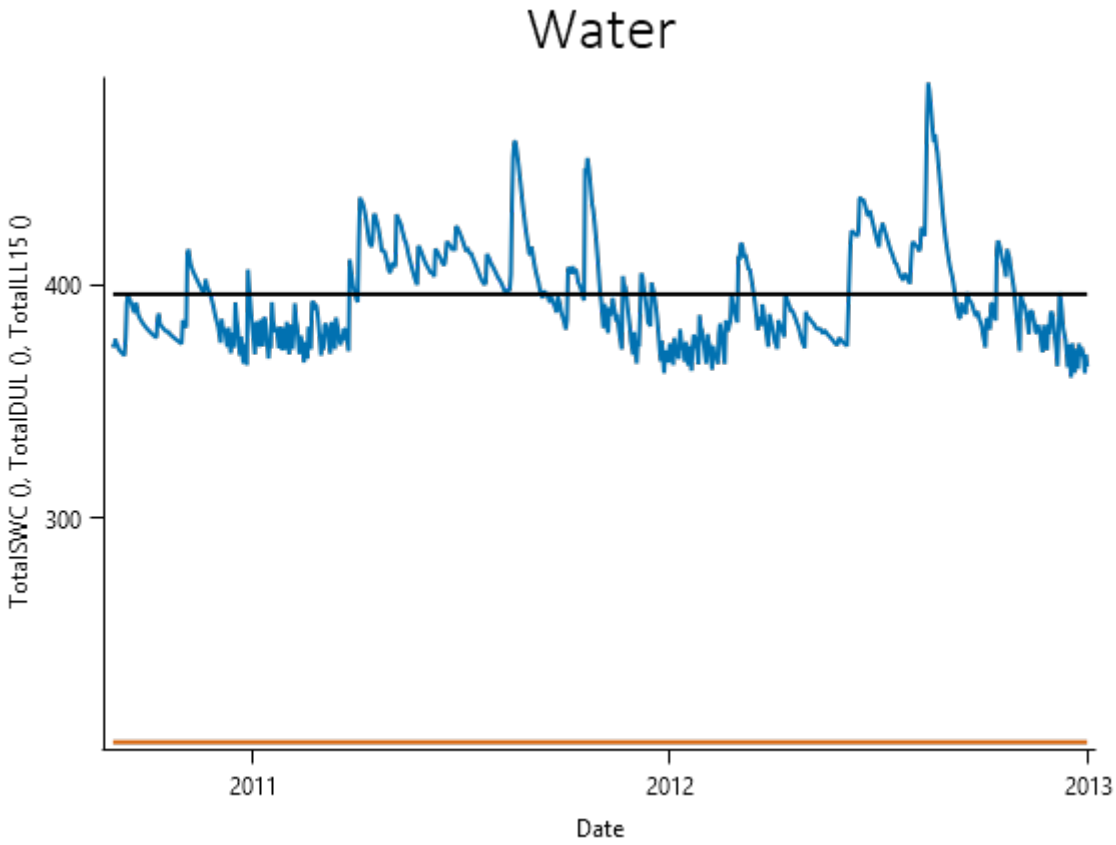
A report class for writing output to the data store.

Manages access to solutes.



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