1 The APSIM Plantain Model

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1.1 Preamble

Plantain (*Plantago lanceolata*), also know as English plantain, ribgrass, or ribwort, is a herbaceous perennial herb with a broad distribution in the native grasslands of Eurasia (Sagar et al., 1964; Stewart, 1996). It is now common around the world in suitable habitats with temperate and subtropical climates. The plant consists of a rosette of basal semi-erect leaves which may have one or more flowering stalks. The leaves are green to grey-green in colour, have a characteristic lanceolate shape with 3 to 5 parallel veins along the length and have few or no hairs. The stems are leafless, growing some 10-15cm above the leaves and have scattered hairs toward the base of the plant. Each stalk terminates in an ovoid inflorescence containing many small flowers each with a pointed bract. The inflrescence is 1-4cm long and changes shape over time (from a cone to a cilinder) as the flowers mature from the based to the top, the colour also changes from the initial grey-green to light brown when mature. The flowering period goes from late spring to early fall and varies between plants, it can last several months for a population of plants in a given locale. Plantain does not need vernalisation to trigger flowering. The flowers are wind-pollinated and are replaced by a small seed capsule containing two small seeds, with weight varying between 1.5 and 2.0 mg per seed. Seeds have an oblong shape and the colour varies from dark brown to black. The root system consists of a relatively shallow crown of coarse fibrous roots including adventitious roots (Sanderson, 2000) and although technically a taprooted species it does not have the typical solid deep taproot. Plantain can allocate greater proportion of roots at depth, giving a competitive advantage over shallow root grasses (Stewart, 1996; Nie et al., 2008; van den Berge, 2014).

Selection of plantain cultivars for use as forage have focused mostly on narrow leaf varieties, which have an erect, bushy, growth habit and ability to tiller under grazing (Stewart, 1996), more recently some emphasis has also been put on the ability to growth over cold periods. Forage plantain can grow large leaves, up to around 40cm instead of typical 15-25cm, and these are highly palatable to grazing animals, being specifically targeted by sheep (Sagar et al., 1964; Stewart, 1996; Rumball, 1997; Quijada, 2015). Reproductive organs are less palatable and mature stalks are avoided by grazers (Stewart, 1996; Moorhead, 2009; Ayala et al., 2011). Plantain is highly nutritious, has good digestibility, and the mineral composition usually is higher than ryegras-clover swards (Stewart, 1996; Jacobs et al., 2010; Elgersma, 2014; Lee, 2015). Potential medicinal effects of plantain have been suggested and few bio-active compounds that may alter rumen fermentation and N partitionin in the animal are being investigated (Stewart, 1996; Quijada, 2015; Jansma, 2016).

Objective: The model presented here has been built using the Plant Modelling Framework (PMF) of Brown et al., 2014 to simulate the growth of a forage plantin crop. Currently, the focus is on describing biomass accumulation and regrowth after harvest on monocultural swards. As part of APSIM's PMF, using plantain in mixed swards is possible, but this has not been properly tested yet. Likewise, describing the effect of population decrease on plant growth was not attempted; for swards free of weeds and within typical population ranges, the changes in plant size (number of tillers) and LAI should compensate for loss of population, but competition with weeds and others would alter this pattern significantly. Simulating variations in plant N concentration (seasonal or due to changes in soil status) is not a major focus of the current model. Further development of PMF's supply/demand processes are needed for capturing the variations in N content typically seen in perennial species.

1.2 Presentation

This model has been built using the Plant Modelling Framework (PMF) of Brown et al., 2014 to simulate the growth of a forage plantain crop (*Plantago lanceolata*). The 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). To simulate the aboveground plant structure, including the photosynthesis process, the plantain model uses the SimpleLeaf procedure of PMF. The model describes a semi-perennial crop, with phenology rewinding to the vegetative stage at the end of the reproductive phase.

1.3 Inclusion in APSIM simulations

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

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

```
Plantain.Sow(cultivar: Tonic, population: 300, depth: 10, rowSpacing: 150);
```

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

1.4 Harvest and biomass removal

Plantain biomass can be removed by raising one of the valid methods: Harvest, Cut, Graze, or Prune; this is done using a manager script, similarly to 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(Plantain.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);
Plantain.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.

1.5 Crop termination

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

```
Plantain.EndCrop();
```

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

1.6 Acknowledgements

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

The model has been developed using the Plant Modelling Framework (PMF) of Brown et al., 2014. This new framework provides a library of plant organ and process submodels that can be coupled, at runtime, to construct a model in much the same way that models can be coupled to construct a simulation.This means that dynamic composition of lower level process and organ classes(e.g.photosynthesis, leaf) into larger constructions(e.g.maize, wheat, sorghum) can be achieved by the model developer without additional coding.

The model is constructed from the following list of software components. Details of the implementation and model 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

Component Name	Component Type
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
PerPlantBelowGroundWt	Models.Functions.DivideFunction
ShootRootRatio	Models.Functions.PhaseLookup
TargetShootRootRatio	Models.Functions.PhaseLookup
StemsLeafRatio	Models.Functions.PhaseLookup
TargetStemsLeafRatio	Models.Functions.PhaseLookup
FlowerStemRatio	Models.Functions.PhaseLookup
TargetFlowerStemRatio	Models.Functions.PhaseLookup
TaprootRootRatio	Models.Functions.PhaseLookup
TargetTaprootRootRatio	Models.Functions.PhaseLookup
MortalityRate	Models.Functions.Constant

1.7 Phenology

The phenological development is simulated as the progression through a series of developmental phases, each bound by distinct growth stage.

The duration of each phenologic phase in plantain is controlled either by the accumulation of thermal time or photoperiod.

1.7.1 ThermalTime

ThermalTime is the average of sub-daily values from a XYPairs.

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. There is very little information about these thresholds for plantain, the minimum temperature seem to be quite variable as one of the main traits that vary among cultivars is the growth over winter. For "chinese plantain" (*Plantago asiatica*) the minimum temperature varies between 3 and 14 oC (Ishikawa et al., 2007), which gives an idea of potential variations for this parameter in plantain. Plantain is tolerant to high temperatures (Stewart, 1996; Nie et al., 2008) and outgrows ryegrass over summer in subtropical climate (Moorhead, 2009). The data for chinese plantain suggest similar growth, and thus the optimum and maximum temperature for it, 30 and 38oC respectively (Ishikawa et al., 2007), should give a good indication of the values for forage plantain.

Firstly 3-hourly estimates of air temperature (Ta) are interpolated using the method of Jones et al., 1986 which assumes a sinusoidal temperature. pattern between Tmax and Tmin.

Each of the interpolated air temperatures are then passed into the following Response and the Average taken to give daily ThermalTime

X	ThermalTime
9.0	0.0
30.0	25.0
38.0	0.0
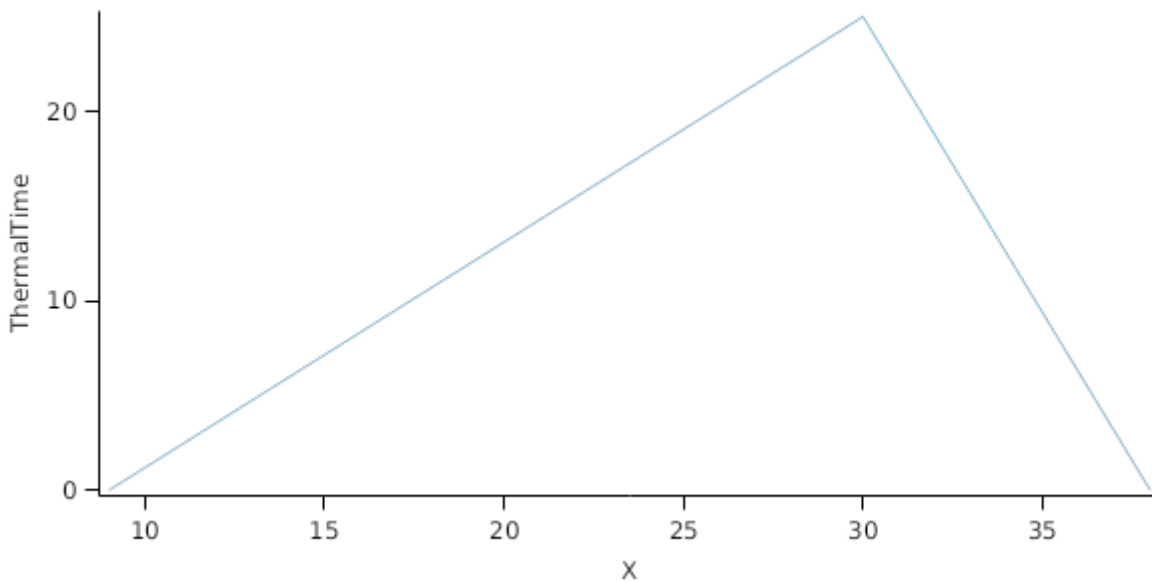
List of stages and phases used in the simulation of crop phenological development

Phase Number	Phase Name	Initial Stage	Final Stage
1	Germinating	Sowing	Germination
2	Emerging	Germination	Emergence
3	Vegetative	Emergence	Flowering
4	Reproductive	Flowering	Ripening
5	GotoPhase	Ripening	Emergence

1.7.2 Germinating

The phase goes from sowing to germination and assumes germination will be reached on the day after sowing or the first day thereafter when the extractable soil water at sowing depth is greater than zero.

Germination will occur one day after sowing, provided that the amount of soil extractable water is greater than zero. Germination rates in plantain typically vary between 75 and 95% when sown close to the surface (<10mm), in moist warm soil (Reed, 2008; Douglas, 2013; Lee, 2015). The plantain model, following convention of PMF, assumes 100% germination, and therefore the user must correct sowing rate when variations between sown and germinated plant density is considered important.

1.7.3 Emerging

This phase goes from germination to emergence and simulates time to emergence as a function of sowing depth. The *ThermalTime Target* for ending this phase is given by:

Target = SowingDepth x *ShootRate + ShootLag*

Where:

ShootRate = 10 (deg day/mm),

ShootLag = 15 (deg day),

SowingDepth (mm) is sent from the manager with the sowing event.

Plantain has small seeds and emergence is best when seeds are sown at depth <10mm (Peri et al., 2000; Sanderson et al., 2000), deeper seed may stay dormant for years in the soil (Blom, 1978; Roberts et al., 1984). Variations in germination rate due to depth are not explicitly simulated by the plantain model in the current version, however the sowing depth does affect timing of emergence. This is controlled by the parameter ShootRate, which is the shoot elongation rate as function of thermal time (mm/oCd).

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

ThermalTime = [Phenology].ThermalTime

1.7.4 Vegetative

This phase goes from emergence to flowering.

During this phase the plant only partitions biomass to leaf and root+taproot organs. The phase starts when plants emerge from the ground, but it is also triggered after the end of the reproductive phase (phenology reset). It ends when the reproductive phase starts, which is triggered by the accumulation of days with long sunlight (Sussex, 1956; Rowarth, 1990; Case et al., 1996; Lacey et al., 2003; González-Parrado, 2015). Stalk development have been recorded to start in October in NZ and in May in the USA (Rowarth, 1990; Lacey et al., 2003; Sanderson, 2003), with data suggesting a minimum of 25-30 days (non consecutive) with long daylight periods (Sussex, 1956; Fajer, 1991; Case et al., 1996). The literature does not provide an indication of how long the sunlight period should be to trigger the reproductive phase, but it is clear that daylight should be grater that the period in darkness (14-16 hours been used to induce flowering in growth chambers). The base plantain model uses the accumulation of days greater than 12hrs to trigger the end of the vegetative phase.

The *Target* for completion is calculated as:

Target = 30 (days)

Progression through phase is calculated daily and accumulated until the *Target* is reached.

Progression is calculated using linear interpolation

X	Progression
10.0	0.0
11.5	0.0
12.0	1.0
13.0	1.0
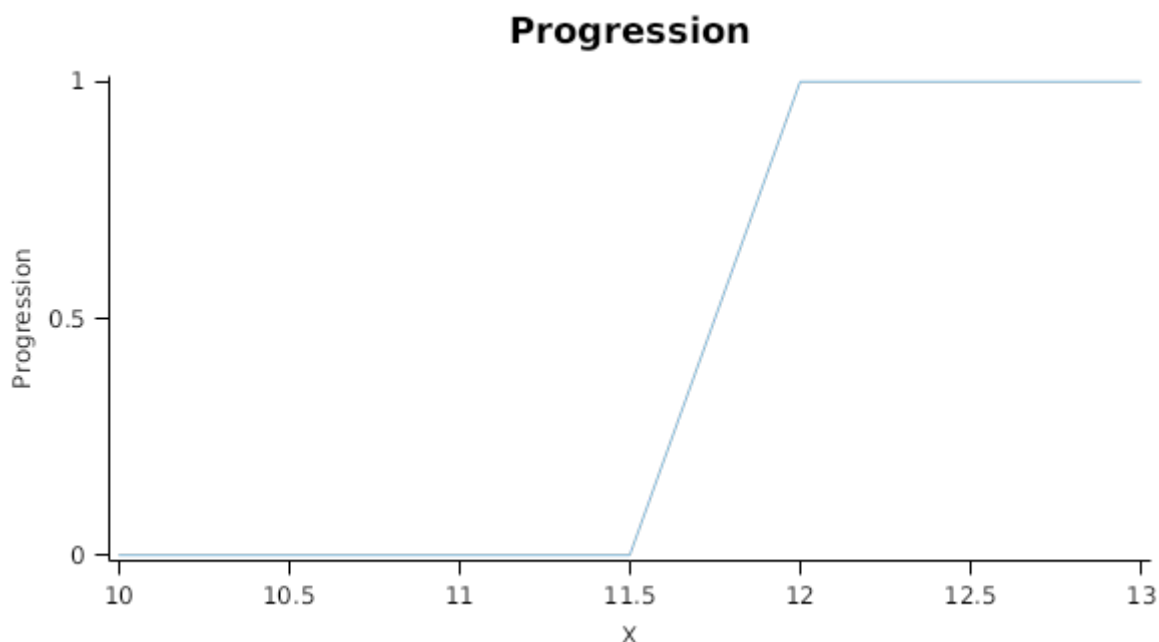
1.7.5 Reproductive

This phase goes from flowering to ripening.

During this phase the plant is partitioning biomass to all organs, including reproductive organs (stems, flowers, and seeds). Flower stages and seeds development are not explicitly described in the current model, only a generic organ refered to as *inflorescence* is defined. This was done partly due to lack of data and partly because of the variability and complex phenology of plantain. There is a lot of variation among plantain plants regarding when flowering occurs and how long it lasts, plus even the same plant can have flowering stalks, stalks with young seeds, as well as stalks with ripen

seed at the same time (Rowarth, 1990; Rumball, 1997; Lacey et al., 2003; González-Parrado, 2015). Seed ripenning is reached some 8-10 weeks after flowering, with commercial cultivars closer to the low end of the range. The available data suggest an accumulation of 450oCd for the flowering period, with base temperature between 5 and 9oC (Rowarth, 1990; Rumball, 1997; González-Parrado, 2015). Howerver flowering continues throughout the summer into autumn and seem to be curtailed only by frosts (Rowarth, 1990) and/or short days (Sanderson, 2003). In the plantain model the photoperiod is used to define the end of reproductive phase, following the same approach used to start it. And correspondelly, the accumulation of days shorter than 12 hours is used as the trigger the end of the phase (this approach also ensures phenology reset even in warmer climates). Note that the DM partition functions also use photoperiod to change priority allocation into reproductive organs, with maximum allocation only when daylight length is greater than 14hours. This was done to limit the allocation to reproductive organs on the sason shoulders when only few plants are actively in the reproductive phase (e.g. Sanderson, 2003).

The *Target* for completion is calculated as:

Target = 30 (days)

Progression through phase is calculated daily and accumulated until the *Target* is reached.

Progression is calculated using linear interpolation

X	Progression
10.0	1.0
11.0	1.0
12.5	0.0
13.0	0.0
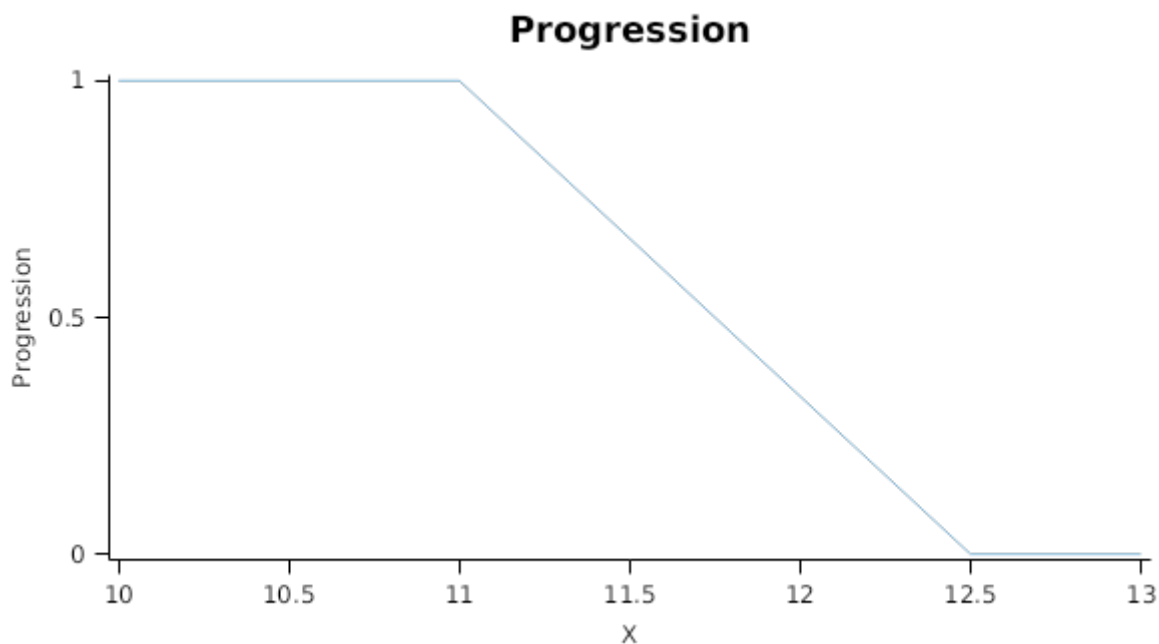
1.7.6 GotoPhase

When the Ripening phase is reached, phenology is rewound to the Vegetative phase.

1.7.7 Photoperiod

Returns the duration of the day, or photoperiod, in hours. This is calculated using the specified latitude (given in the weather file) and twilight sun angle threshold. If a variable called ClimateControl.PhotoPeriod is found in the simulation, it will be used instead.

The day length is calculated with \ref MathUtilities.DayLength.

Twilight = -6 (degrees)

1.8 Arbitrator

1.8.1 Arbitrator

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 different pools of biomass:

* **Structural biomass** which is essential for growth and remains within the organ once it is allocated there.
* **Metabolic biomass** which generally remains within an organ but is able to be re-allocated when the organ senesces and may be retranslocated 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 retranslocation to other organs whenever supply from uptake, fixation, or re-allocation is lower than demand.

The process followed for biomass arbitration is shown in the figure below. Arbitration calculations are triggered by a series of events (shown below) that are raised every day. For these calculations, at each step the Arbitrator exchange information with each organ, so the basic computations of demand and supply are done at the organ level, using their specific parameters.

1. **doPotentialPlantGrowth**. When this event occurs, 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:

* **Fixation supply**. From photosynthesis (DM) or symbiotic fixation (N)
* **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).
* **Retranslocation supply**. Storage biomass that may be moved from organs to meet demands of other organs.
* **Reallocation supply**. Biomass that can be moved from senescing organs to meet the demands of other organs.

1. **doPotentialPlantPartitioning.** On this event the Arbitrator first executes the DoDMSetup() method to gather the DM supplies and demands from each organ, these values are computed at the organ level. 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 gather the N supplies and demands from each organ 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).
2. **doNutrientArbitration.** When this event occurs, 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.
3. **doActualPlantPartitioning.** On this event the arbitrator call DoNRetranslocation() and DoNFixation() to satisfy 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 concentration and final allocations are sent to organs.
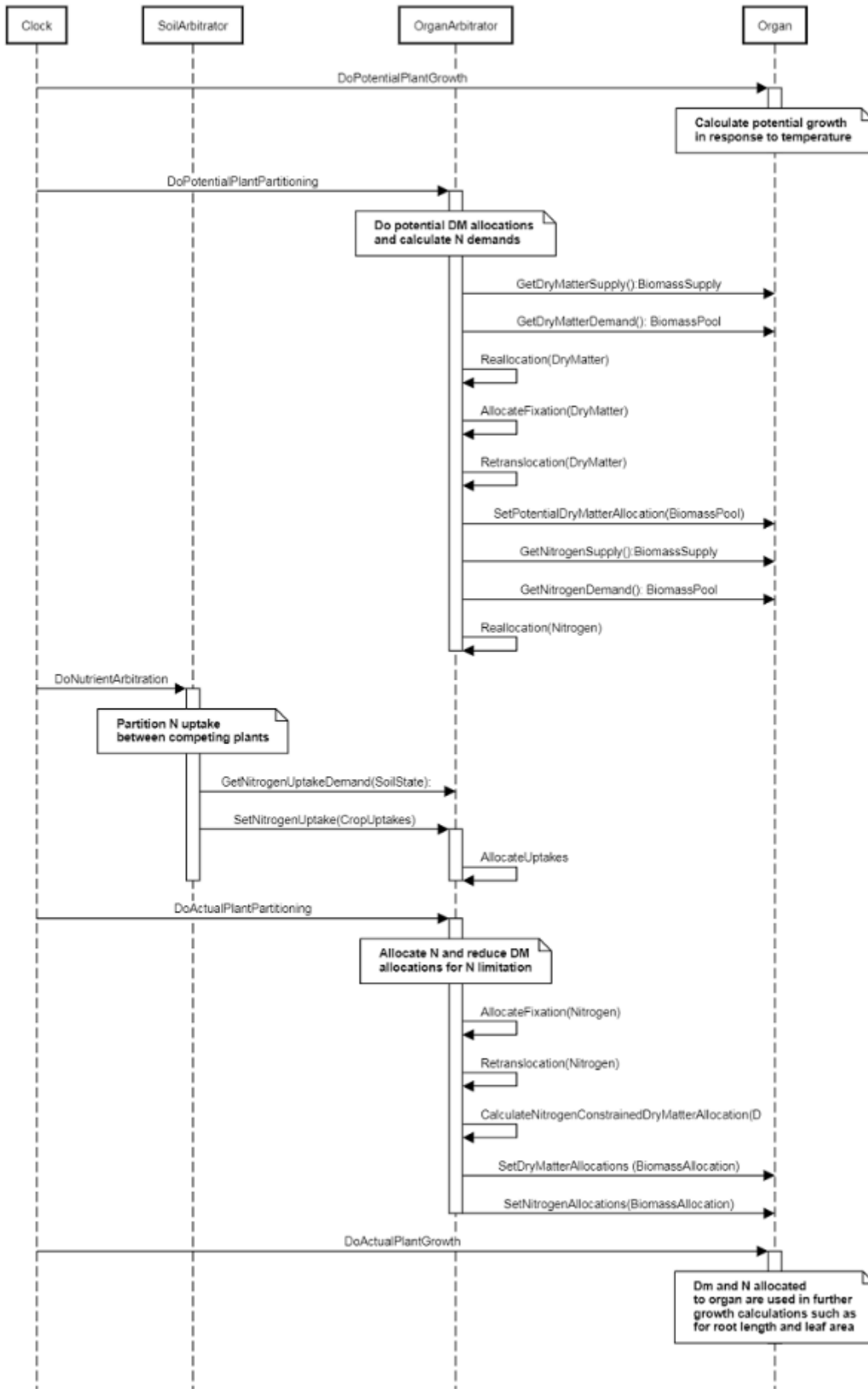
Figure 1: Schematic showing the procedure for arbitration of biomass partitioning. Pink boxes represent events that occur every day and their numbering shows the order of calculations. Blue boxes represent the methods that are called when these events occur. Orange boxes contain properties that make up the organ/arbitrator interface. Green boxes are organ specific properties.

1.9 Leaf

This organ is simulated using a SimpleLeaf organ type. It provides the core functions of intercepting radiation, producing biomass through photosynthesis, and determining the plant's transpiration demand. The model also calculates the growth, senescence, and detachment of leaves. SimpleLeaf does not distinguish leaf cohorts by age or position in the canopy.

Radiation interception and transpiration demand are computed by the MicroClimate model. This model takes into account competition between different plants when more than one is present in the simulation. The values of canopy Cover, LAI, and plant Height (as defined below) are passed daily by SimpleLeaf to the MicroClimate model. MicroClimate uses an implementation of the Beer-Lambert equation to compute light interception and the Penman-Monteith equation to calculate potential evapotranspiration.
These values are then given back to SimpleLeaf which uses them to calculate photosynthesis and soil water demand.

NOTE: the summary above is used in the Apsim's autodoc.

SimpleLeaf has two options to define the canopy: the user can either supply a function describing LAI or a function describing canopy cover directly. From either of these functions SimpleLeaf can obtain the other property using the Beer-Lambert equation with the specified value of extinction coefficient. The effect of growth rate on transpiration is captured by the Fractional Growth Rate (FRGR) function, which is passed to the MicroClimate model.

Note: this organ represents all the leaves in the plant, without distinction between ages or placement in the canopy.

1.9.1 Initial Dry Matter

InitialWt = InitialPlantWt x [Plant].Population

InitialPlantWt = 0.001 (g/plant)

1.9.2 Dry Matter Demand

The dry matter demand for the organ is calculated as defined in DMDemands, based on the DMDemandFunction and partition fractions for each biomass pool.

1.9.2.1 DMDemands

This class holds the functions for calculating the absolute demands and priorities for each biomass fraction.

Structural = DMDemandFunction x *StructuralFraction*

Returns the product of its PartitionFraction and the total DM supplied to the arbitrator by all organs.

DMDemandFunction = PartitionFraction x *[Arbitrator].DM.TotalFixationSupply*

In the plantain model, the DM demand function attempts to keep the shoot to root ratio and then the stem to leaf ratio close to a target value (defined by the [TargetShootRootRatio].Value and [TargetStemsLeafRatio].Value), which may vary according to the phenolgical stage. This approach ensures that the plantain plants will recovery after being cut or grazed. In this case, biomass will be allocated to leaves preferably, even during reproductive phase.

PartitionFraction is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

Vegetative has a value between Emergence and Flowering calculated as:

LeafFraction = Numerator / Denominator

Numerator = [TargetShootRootRatio] x [TargetShootRootRatio]

Denominator = TargetSRs + [ShootRootRatio]

TargetSRs = [TargetShootRootRatio] x [TargetShootRootRatio]

Reproductive has a value between Flowering and Ripening calculated as:

LeafFraction = Numerator / Denominator

Numerator = [TargetShootRootRatio] x [TargetShootRootRatio] x [StemsLeafRatio]

Denominator = SRs x *SLs*

SRs = TargetSRs + [ShootRootRatio]

TargetSRs = [TargetShootRootRatio] x [TargetShootRootRatio]

SLs = *TargetSLs* + [StemsLeafRatio]

TargetSLs = [TargetStemsLeafRatio] x [TargetStemsLeafRatio]

StructuralFraction = 1 (g/g)

Metabolic = 0

The partitioning of daily growth to storage biomass is based on a storage fraction.

StorageFraction = 1 - [Leaf].DMDemands.Structural.StructuralFraction

QStructuralPriority = 1

QMetabolicPriority = 1

QStoragePriority = 1

1.9.3 Nitrogen Demand

The N demand is calculated as defined in NDemands, based on DM demand the N concentration of each biomass pool.

1.9.3.1 NDemands

This class holds the functions for calculating the absolute demands and priorities for each biomass fraction.

Structural = [Leaf].minimumNconc x [Leaf].potentialDMAllocation.Structural

Metabolic = *MetabolicNconc* x [Leaf].potentialDMAllocation.Structural

MetabolicNconc = [Leaf].criticalNConc - [Leaf].minimumNconc

The partitioning of daily N supply to storage N attempts to bring the organ's N content to the maximum concentration.

Storage = [Leaf].maximumNconc × ([Leaf].Live.Wt + potentialAllocationWt) - [Leaf].Live.N

The demand for storage N is further reduced by a factor specified by the [Leaf].NitrogenDemandSwitch.

NitrogenDemandSwitch = [Leaf].nitrogenDemandSwitch

MaxNconc = [Leaf].maximumNconc

QStructuralPriority = 1

QMetabolicPriority = 1

QStoragePriority = 1

1.9.4 Nitrogen Concentration Thresholds

The N demand is calculated as defined in NDemands, based on DM demand the N concentration of each biomass pool.

1.9.4.1 NDemands

This class holds the functions for calculating the absolute demands and priorities for each biomass fraction.

Structural = [Leaf].minimumNconc x [Leaf].potentialDMAllocation.Structural

Metabolic = *MetabolicNconc* x [Leaf].potentialDMAllocation.Structural

MetabolicNconc = [Leaf].criticalNConc - [Leaf].minimumNconc

The partitioning of daily N supply to storage N attempts to bring the organ's N content to the maximum concentration.

Storage = [Leaf].maximumNconc × ([Leaf].Live.Wt + potentialAllocationWt) - [Leaf].Live.N

The demand for storage N is further reduced by a factor specified by the [Leaf].NitrogenDemandSwitch.

NitrogenDemandSwitch = [Leaf].nitrogenDemandSwitch

MaxNconc = [Leaf].maximumNconc

QStructuralPriority = 1

QMetabolicPriority = 1

QStoragePriority = 1

1.9.5 Dry Matter Supply

DMReallocationFactor = 0

DMRetranslocationFactor = 0 (/day)

1.9.6 Photosynthesis

Biomass fixation is modelled as the product of intercepted radiation and its conversion efficiency, the radiation use efficiency (RUE) (Monteith et al., 1977).
This approach simulates net photosynthesis rather than providing separate estimates of growth and respiration.
The potential photosynthesis calculated using RUE is then adjusted according to stress factors, these account for plant nutrition (FN), air temperature (FT), vapour pressure deficit (FVPD), water supply (FW) and atmospheric CO_2 concentration (FCO2).
NOTE: RUE in this model is expressed as g/MJ for a whole plant basis, including both above and below ground growth.

Data for photosynthesys in plantain is very sparse and so some of the data used here are from studies that employed wild varieties. Values for CO2 assimilation rates are generally consistent (Poot et al., 1997; Labreveux, 2002; van den Berge, 2014; Cranston, 2015) and follow a classic relationhip with light intensity (directly proportional) as well with N concentration in the leaves (inversely proportional). Reported values of photosynthetic rate indicate that these are similar or slightly higher in plantain when compared to Chicory (Labreveux, 2002; Cranston, 2015). No reported values for RUE were found in the literature, but they can be infered as to be just under 2.0 g DM/MJ for wild vareties (Poot et al., 1997). The current model assumes generic responses to enviromental factors, such as temperature and water availability. Wild plantain is ubiquitous in meadows in subtropical climates around the world, and it is generally assumed to be tollerant to high temperatures but not to cold (Sagar et al., 1964; Stewart, 1996). Forage plantain shows large differences between cultivars, but generally can grow more over winter compared to wild varieties and still outperform temperate grasses in summer (Stewart, 1996; Moorhead, 2009, Douglas, 2013), although survivability in harsh winters in the USA was found to be low (Sanderson, 2003, Skinner, 2005). Forage plantain is also often mentioned as a drought tollerant species (Stewart, 1996; Douglas, 2013; Quijada, 2015), although less so than deep rooted species such as chicory or lucerne. The use of reserves from the taproots seem to be mechanism used to confer drought resistance in plantain as is the case for many herbs (Cranston, 2015; Quijada, 2015).

RUE = 2 (g/MJ)

This model calculates the CO_2 impact on RUE using the approach of Reyenga et al., 1999.

For C3 plants,

F_{CO2} = (CO$_2$ - CP) x (350 + 2 x CP)/(CO$_2$ + 2 x CP) x (350 - CP)

where CP, is the compensation point calculated from daily average temperature (T) as

*CP = (163.0 - T) / (5.0 - 0.1 * T)*

For C4 plants,

*F_{CO2} = 0.000143 * CO$_2$ + 0.95*

FN is calculated using linear interpolation

X	FN
0.0	0.0
0.4	0.5
0.8	1.0
1.5	1.0

FN
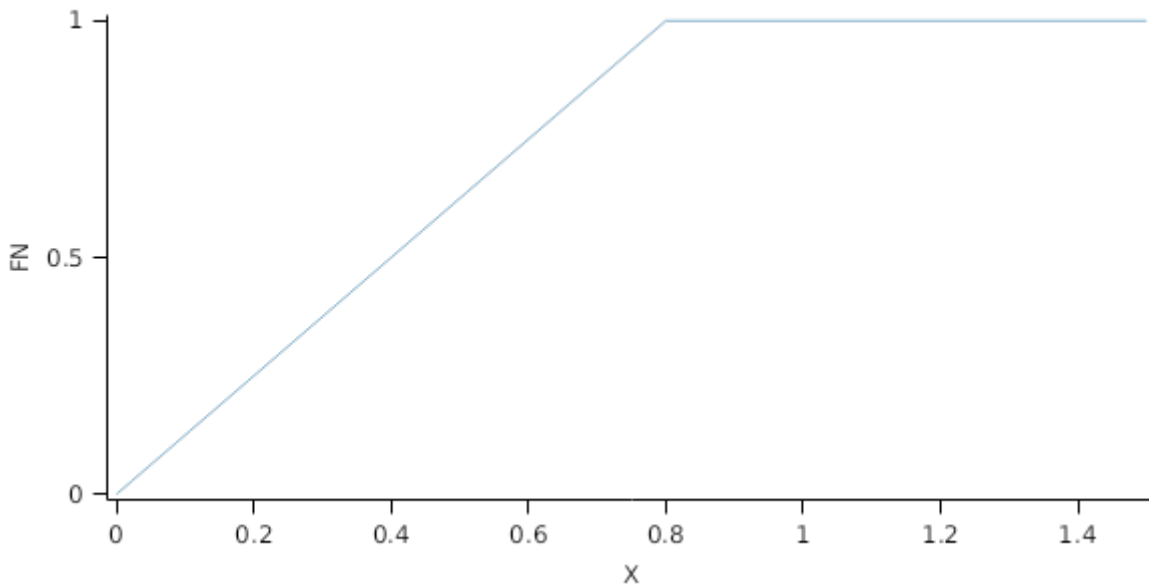
FT is calculated as a function of daily min and max temperatures, these are weighted toward max temperature according to the specified MaximumTemperatureWeighting factor. A value equal to 1.0 means it will use max temperature, a value of 0.5 means average temperature.

MaximumTemperatureWeighting = 0.75

X	FT
4.0	0.0
10.0	0.1
15.0	0.3
21.0	1.0
27.0	1.0
35.0	0.0

FT

FT
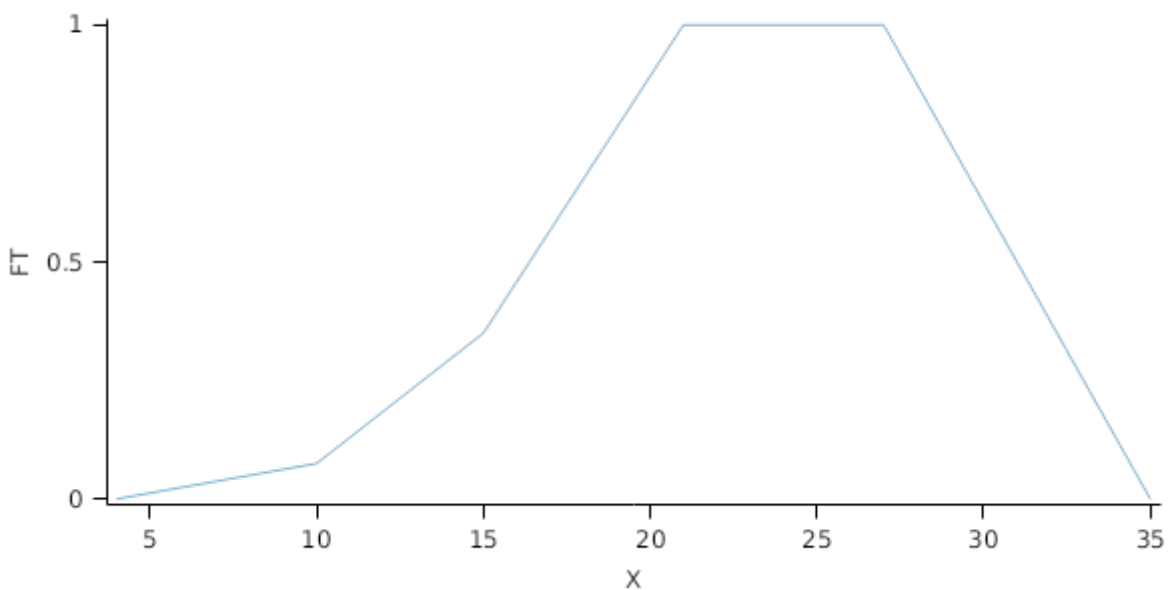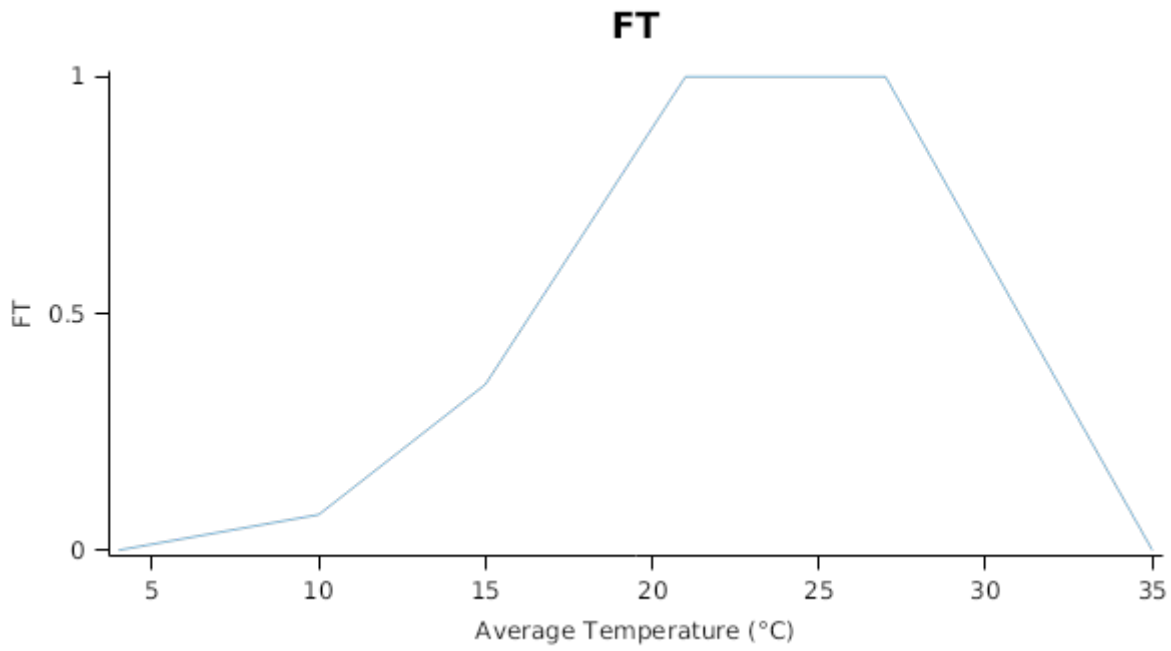
FW is calculated using linear interpolation

X	FW
0.0	0.0
0.8	1.0
1.0	1.0
1.5	1.0

FW
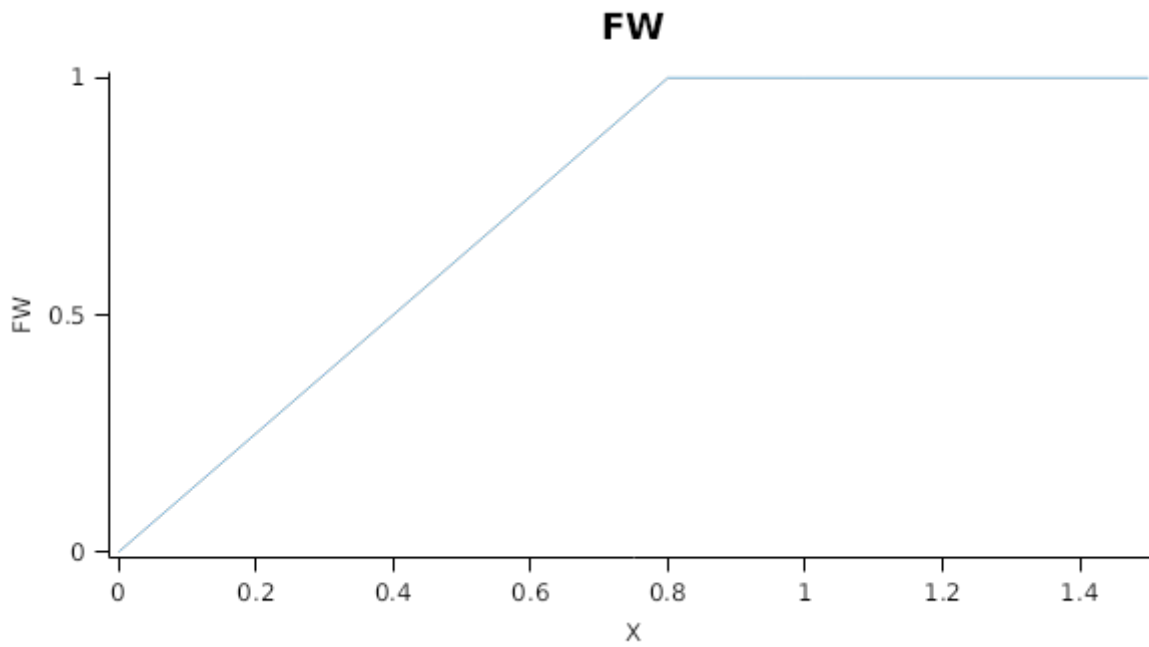
FVPD is calculated using linear interpolation

X	FVPD
0.0	1.0
10.0	1.0
50.0	1.0

FVPD
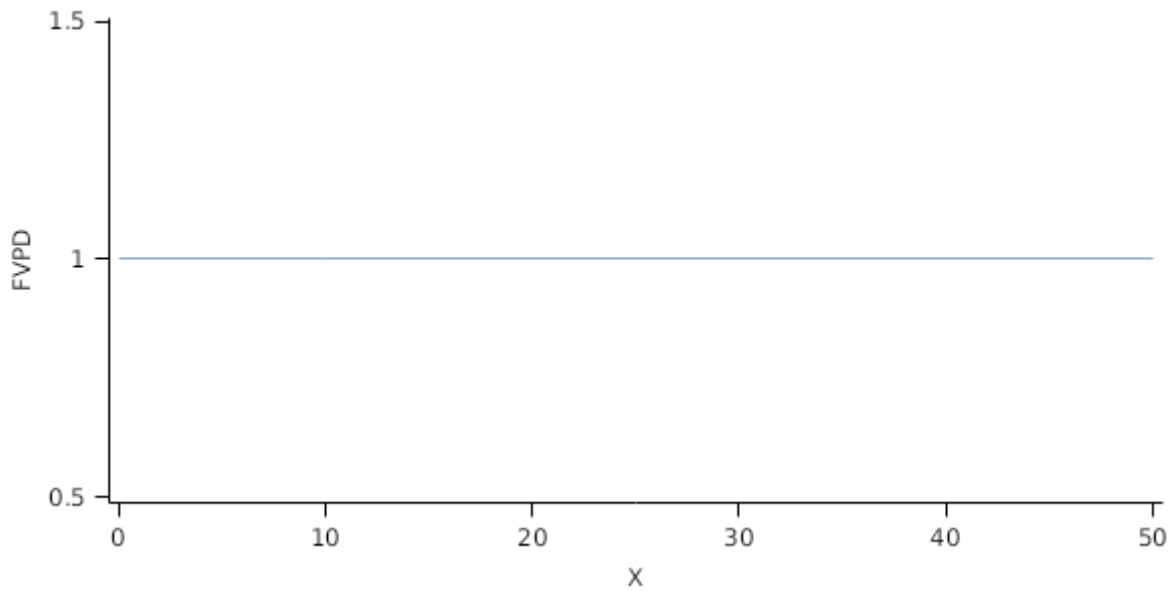
RadnInt = [Leaf].RadiationIntercepted

1.9.7 Nitrogen Supply

NReallocationFactor = 1 (/day)

NRetranslocationFactor = 0 (/day)

1.9.8 Canopy Properties

Leaf has been defined with a LAIFunction, cover is calculated using the Beer-Lambert equation.

Area = SpecificLeafArea x [Leaf].Live.Wt

SpecificLeafArea = 0.022 (m^2/g)

ExtinctionCoefficient = 0.6 (0-1)

Tallness is calculated using linear interpolation

X	Tallness
10.0	100.0
100.0	350.0
500.0	500.0

Tallness
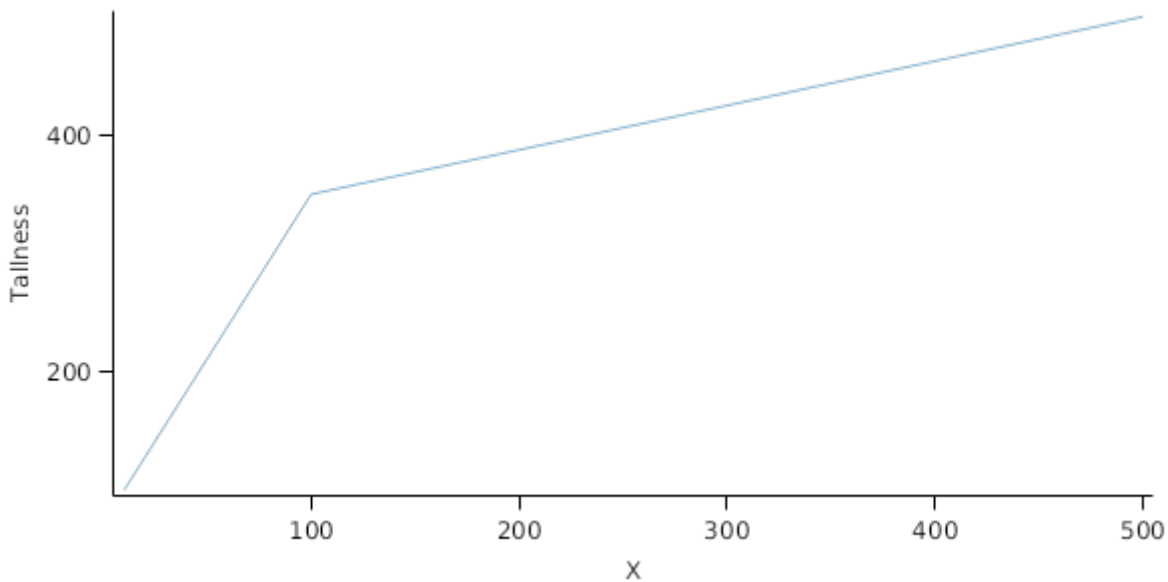
1.9.9 StomatalConductance

Stomatal Conductance (gs) is calculated for use within the micromet model by adjusting a value provided for an atmospheric CO2 concentration of 350 ppm. The impact of other stresses (e.g. Temperature, N) are captured through the modifier, Frgr.

gs = Gsmax350 x FRGR x stomatalConductanceCO2Modifier

StomatalConductanceCO2Modifier = 1

1.9.10 Senescence and Detachment

The proportion of live biomass that senesces and moves into the dead pool each day is quantified by the SenescenceRate.

The sparse availabe data suggests that plantain has a relatively slow senescence rate compared to other medow herbs (Calviere et al., 1995; Schippers et al., 2000). Generic relationships to enviromental factors, such as temperature and soil moisture, are assumed based on other plant models.

SenescenceRate = ReferenceRate x StageFactor x CoverFactor x TemperatureFactor x SoilMoistureFactor

ReferenceRate = 0.005 (/day)

StageFactor is calculated using linear interpolation

X	StageFactor
3.0	0.5
4.0	1.0
5.0	1.0

StageFactor
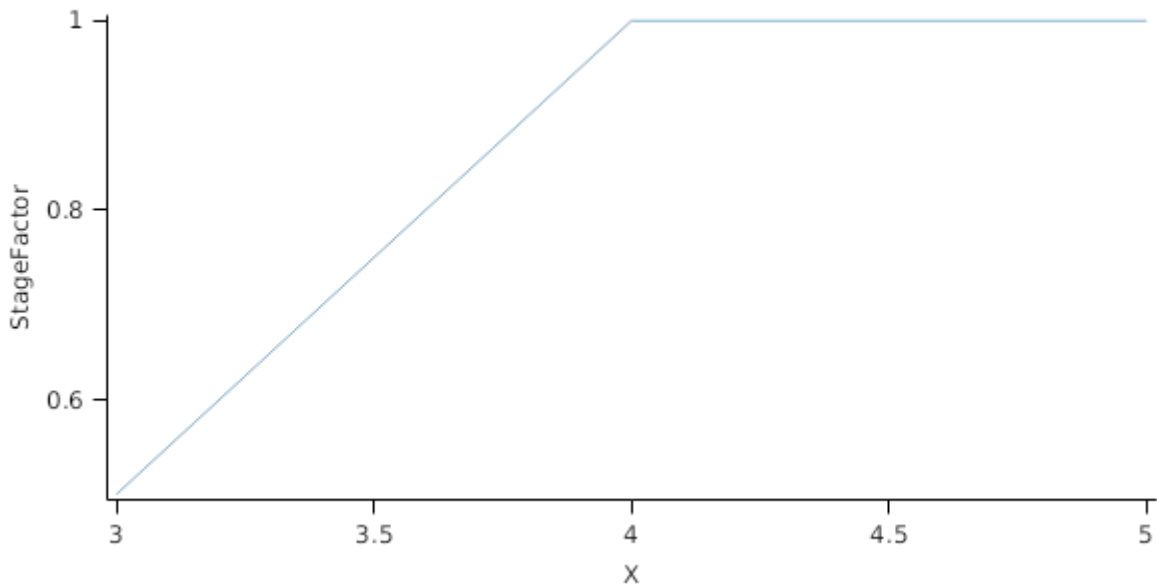
CoverFactor is calculated using linear interpolation

X	CoverFactor
0.0	1.0
0.5	1.0
0.9	1.0
0.9	1.1
1.0	2.0
1.0	3.0

CoverFactor
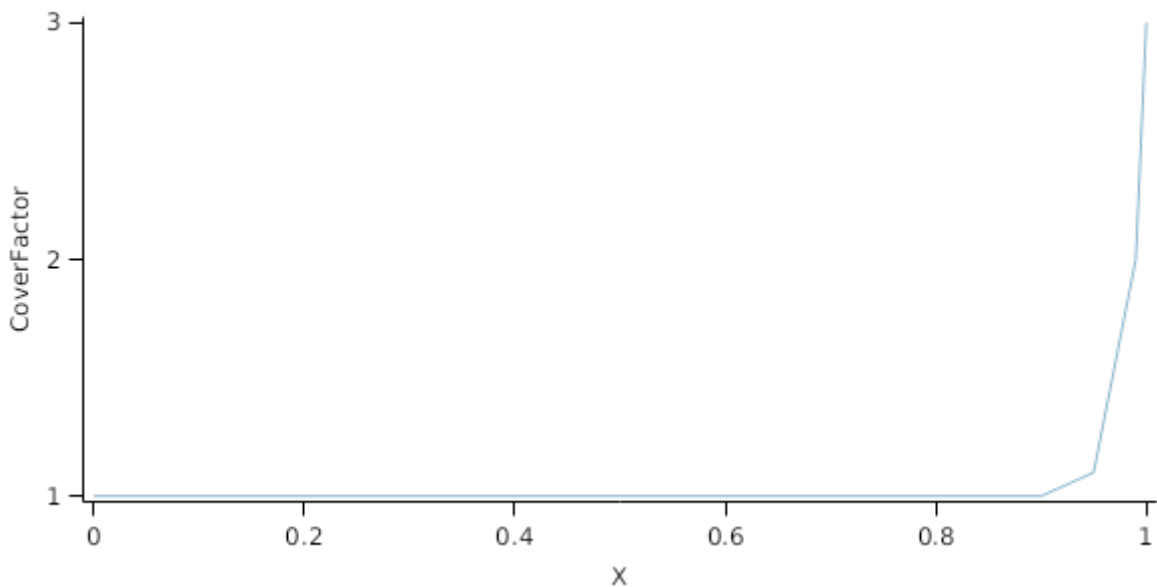
TemperatureFactor is calculated as a function of daily min and max temperatures, these are weighted toward max temperature according to the specified MaximumTemperatureWeighting factor. A value equal to 1.0 means it will use max temperature, a value of 0.5 means average temperature.

MaximumTemperatureWeighting = 0.5

X	TemperatureFactor
-15.0	1.5
-2.0	0.2
2.0	0.0
10.0	0.0
20.0	1.0
30.0	1.0
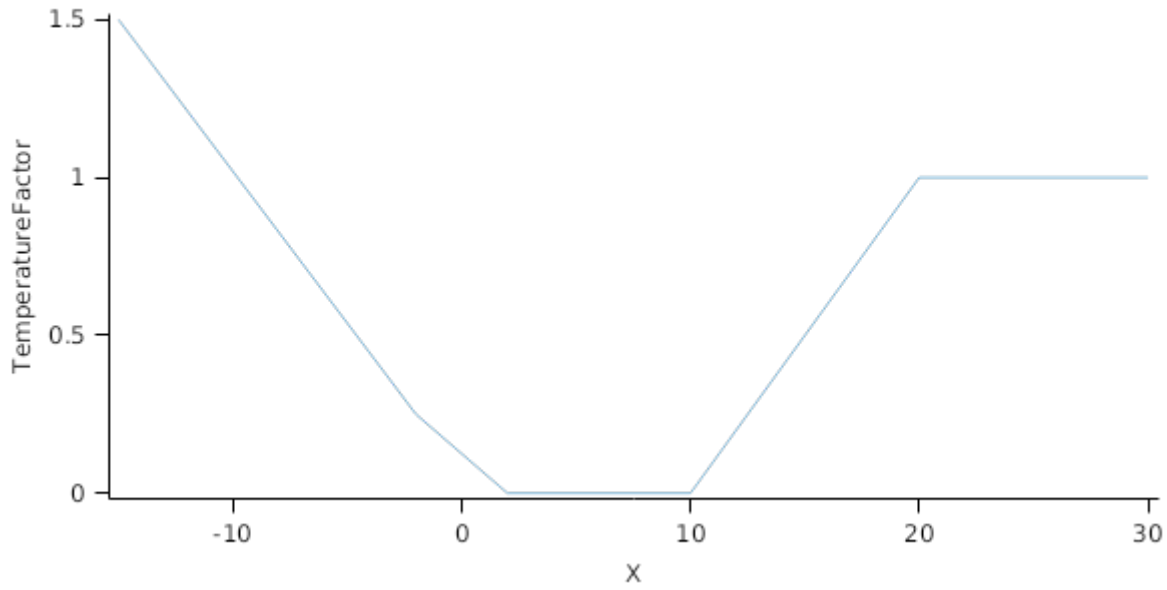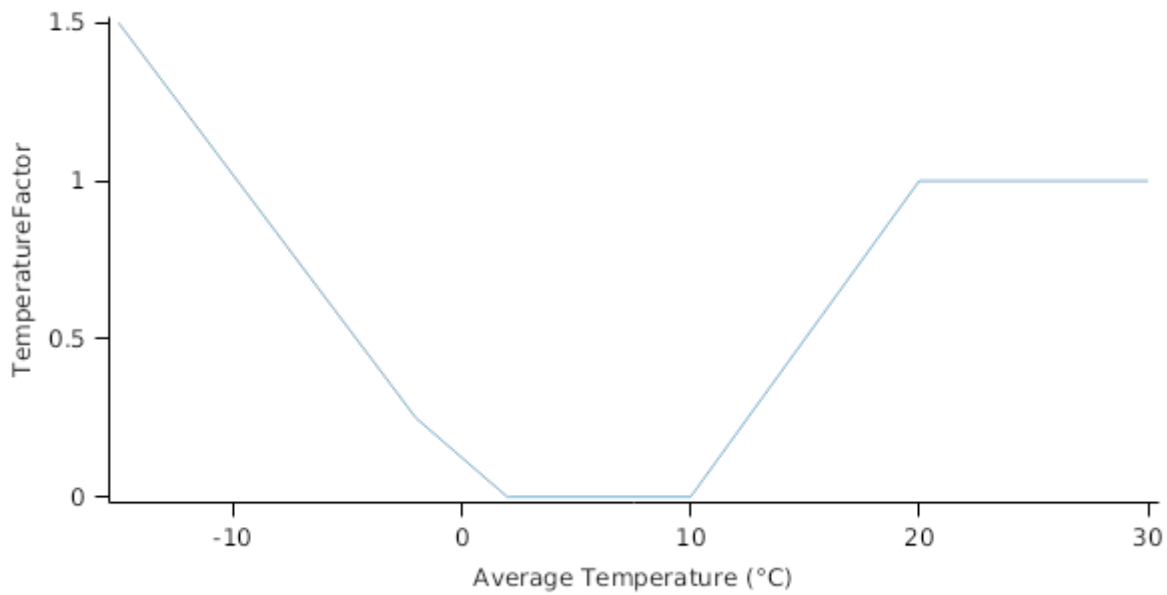
TemperatureFactor

TemperatureFactor

SoilMoistureFactor is calculated using linear interpolation

X	SoilMoistureFactor
0.0	2.0
0.5	1.0

X	SoilMoistureFactor
1.0	1.0

SoilMoistureFactor
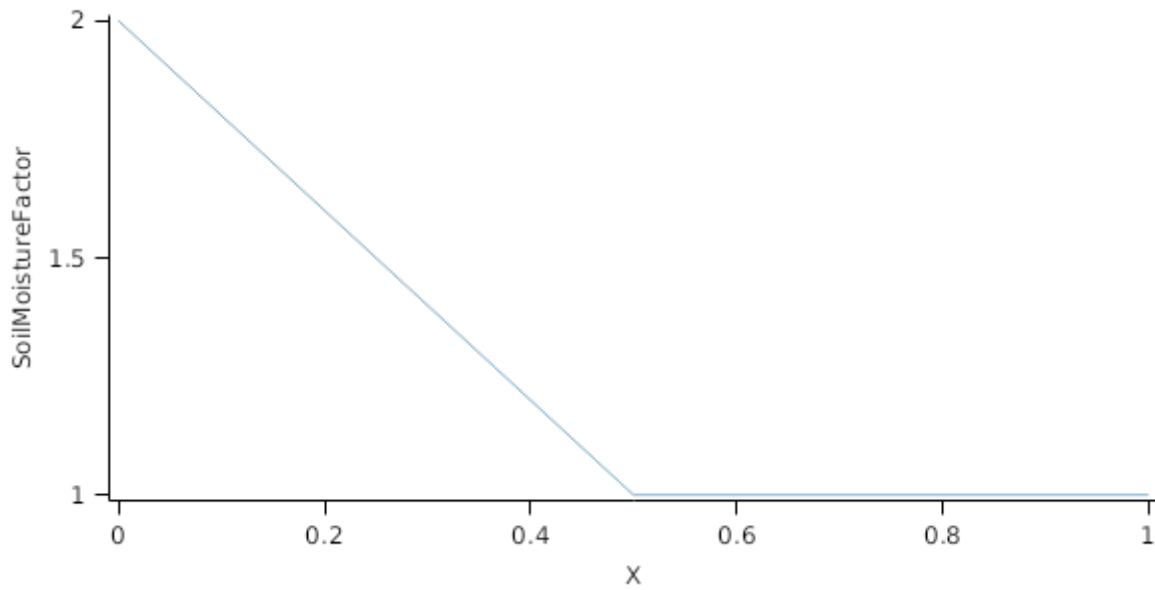
The proportion of Biomass that detaches and is passed to the surface organic matter model for decomposition is quantified by the DetachmentRateFunction.

A generic relationship between detachment and soil moisture is assumed. It implies that under dry conditions the detachment rate decreases due to the lower level of activity of decomposing microorganisms.

DetachmentRate = ReferenceRate x SoilMoistureFactor

ReferenceRate = 0.1 (/day)

SoilMoistureFactor is calculated using linear interpolation

X	SoilMoistureFactor
0.0	0.5
0.5	0.5
1.0	1.0

SoilMoistureFactor
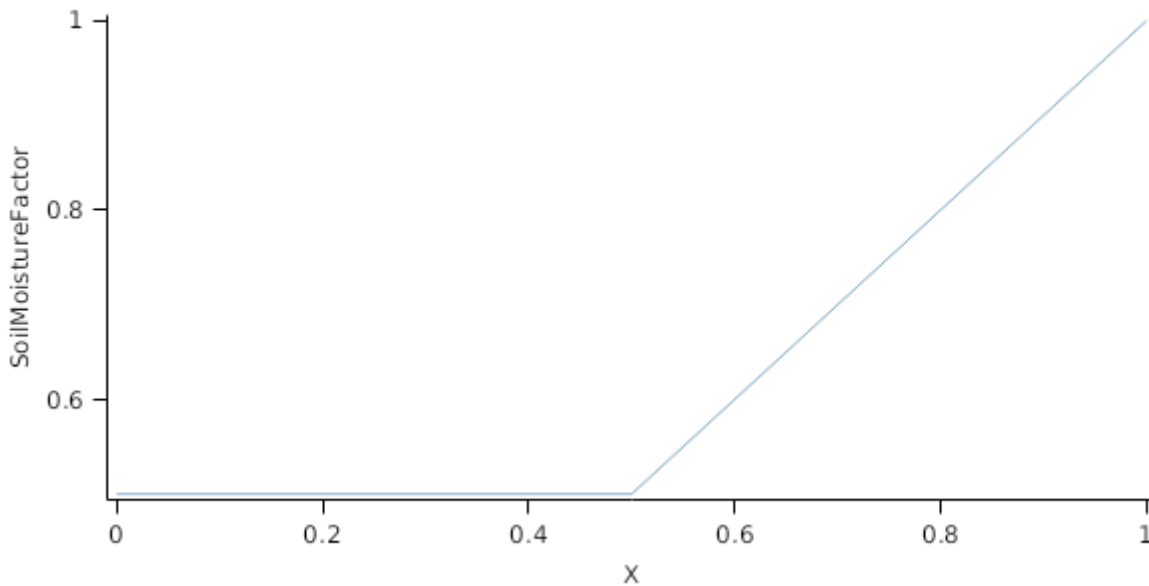
1.9.11 Biomass removal

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 surface residues. The following table describes the default proportions of live and dead biomass that are transferred out of the simulation using "Removed" or to soil surface residue using "To Residue" for a range of management actions. The total percentage removed for live or dead must not exceed 100%. The difference between the total and 100% gives the biomass remaining on the plant. These can be changed during a simulation using a manager script.

Method	% Live Removed	% Dead Removed	% Live To Residue	% Dead To Residue
Cut	70	50	0	0
Graze	70	10	10	10
Harvest	0	0	10	10
Prune	0	0	10	10

1.10 Stem

1.10.1 Stem

This organ is simulated using a GenericOrgan type. It is parameterised to calculate the growth, senescence, and detachment of any organ that does not have specific functions.

1.10.2 Dry Matter Demand

The dry matter demand for the organ is calculated as defined in DMDemands, based on the DMDemandFunction and partition fractions for each biomass pool.

1.10.2.1 DMDemands

This class holds the functions for calculating the absolute demands and priorities for each biomass fraction.

Structural = DMDemandFunction x StructuralFraction

Returns the product of its PartitionFraction and the total DM supplied to the arbitrator by all organs.

DMDemandFunction = PartitionFraction x [Arbitrator].DM.TotalFixationSupply

A simple approach is used in the plantain model to define the allocation of biomass to various organs. The proportion of the above ground biomass allocated to stems is determined based on the current state and two target ratios, the [TargetStemsLeafRatio].Value and [FlowerStemRatio].Value). Allocation of biomass to stems can only occur during the reproductive phase.

PartitionFraction is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

Reproductive has a value between Flowering and Ripening calculated as:

StemFraction = Numerator / Denominator

Numerator = [TargetShootRootRatio] x [TargetShootRootRatio] x [TargetStemsLeafRatio] x [TargetStemsLeafRatio] x [FlowerStemRatio]

Denominator = SRs x *SLs* x *FSs*

SRs = TargetSRs + [ShootRootRatio]

TargetSRs = [TargetShootRootRatio] x [TargetShootRootRatio]

SLs = TargetSLs + [StemsLeafRatio]

TargetSLs = [TargetStemsLeafRatio] x [TargetStemsLeafRatio]

FSs = TargetFSs + [FlowerStemRatio]

TargetFSs = [TargetFlowerStemRatio] x [TargetFlowerStemRatio]

StructuralFraction = 1 (g/g)

Metabolic = 0

The partitioning of daily growth to storage biomass is based on a storage fraction.

StorageFraction = 1 - [Stem].DMDemands.Structural.StructuralFraction

QStructuralPriority = 1

QMetabolicPriority = 1

QStoragePriority = 1

1.10.3 Nitrogen Demand

The N demand is calculated as defined in NDemands, based on DM demand the N concentration of each biomass pool.

1.10.3.1 NDemands

This class holds the functions for calculating the absolute demands and priorities for each biomass fraction.

Structural = [Stem].minimumNconc x [Stem].potentialDMAllocation.Structural

Metabolic = MetabolicNconc x [Stem].potentialDMAllocation.Structural

MetabolicNconc = [Stem].criticalNConc - [Stem].minimumNconc

The partitioning of daily N supply to storage N attempts to bring the organ's N content to the maximum concentration.

Storage = [Stem].maximumNconc × ([Stem].Live.Wt + potentialAllocationWt) - [Stem].Live.N

The demand for storage N is further reduced by a factor specified by the [Stem].NitrogenDemandSwitch.

NitrogenDemandSwitch = [Stem].nitrogenDemandSwitch

MaxNconc = [Stem].maximumNconc

QStructuralPriority = 1

QMetabolicPriority = 1

QStoragePriority = 1

1.10.4 N Concentration Thresholds

MinimumNConc = 0.005 (gN/gDM)

CriticalNConc = [Stem].MinimumNConc

MaximumNConc = 0.02 (gN/gDM)

1.10.5 Dry Matter Supply

Stem does not reallocate DM when senescence of the organ occurs.

Stem does not retranslocate non-structural DM.

1.10.6 Nitrogen Supply

Stem can reallocate up to 100% of N that senesces each day if required by the plant arbitrator to meet N demands.

Stem does not retranslocate non-structural N.

1.10.7 Senescence and Detachment

The proportion of live biomass that senesces and moves into the dead pool each day is quantified by the SenescenceRate.

The reference senescence rate is adjusted using generic relationships to enviromental factors, such as temperature and soil moisture. These are based on general knowledge from other plant models.

SenescenceRate = ReferenceRate x *StageFactor* x *TemperatureFactor* x *SoilMoistureFactor*

ReferenceRate = 0.2 (/day)

StageFactor is calculated using linear interpolation

X	StageFactor
3.0	1.0
4.0	1.0
4.0	0.5
4.5	0.6
4.8	0.8
5.0	1.0
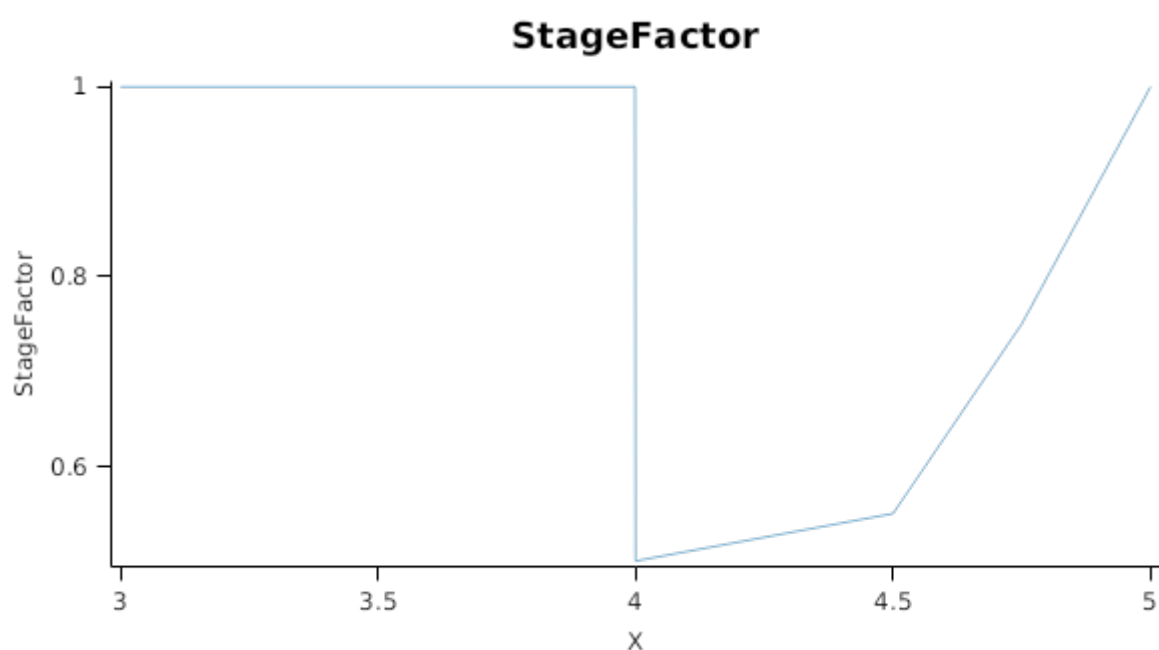
StageFactor

TemperatureFactor is calculated as a function of daily min and max temperatures, these are weighted toward max temperature according to the specified MaximumTemperatureWeighting factor. A value equal to 1.0 means it will use max temperature, a value of 0.5 means average temperature.

MaximumTemperatureWeighting = 0.5

X	TemperatureFactor
-15.0	2.0
0.0	0.2
2.0	0.0
10.0	0.0
20.0	1.0
30.0	1.0
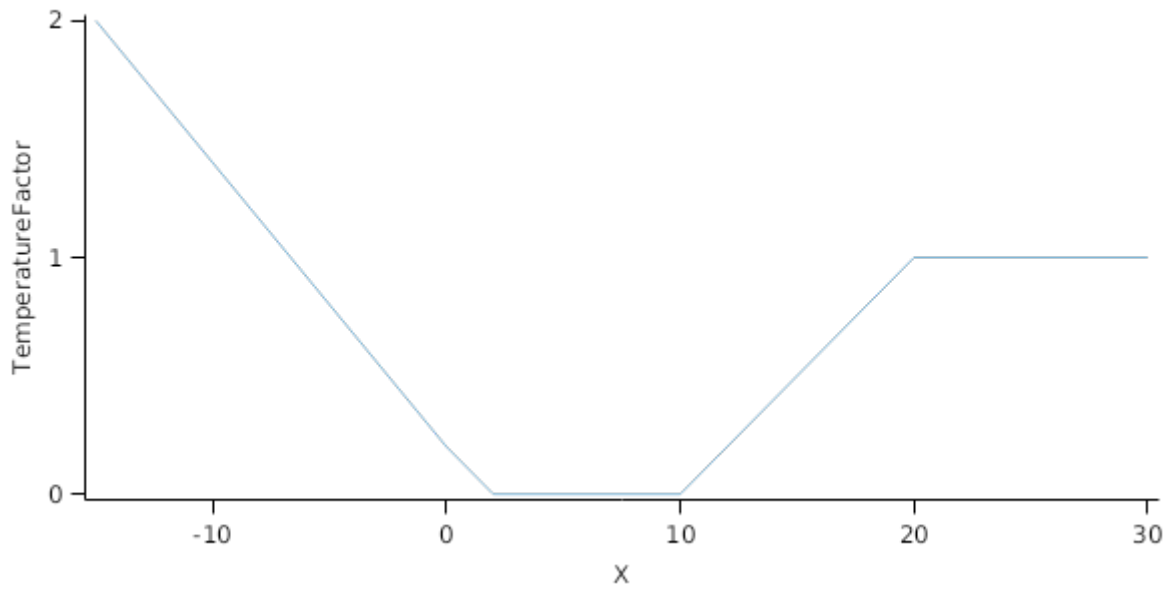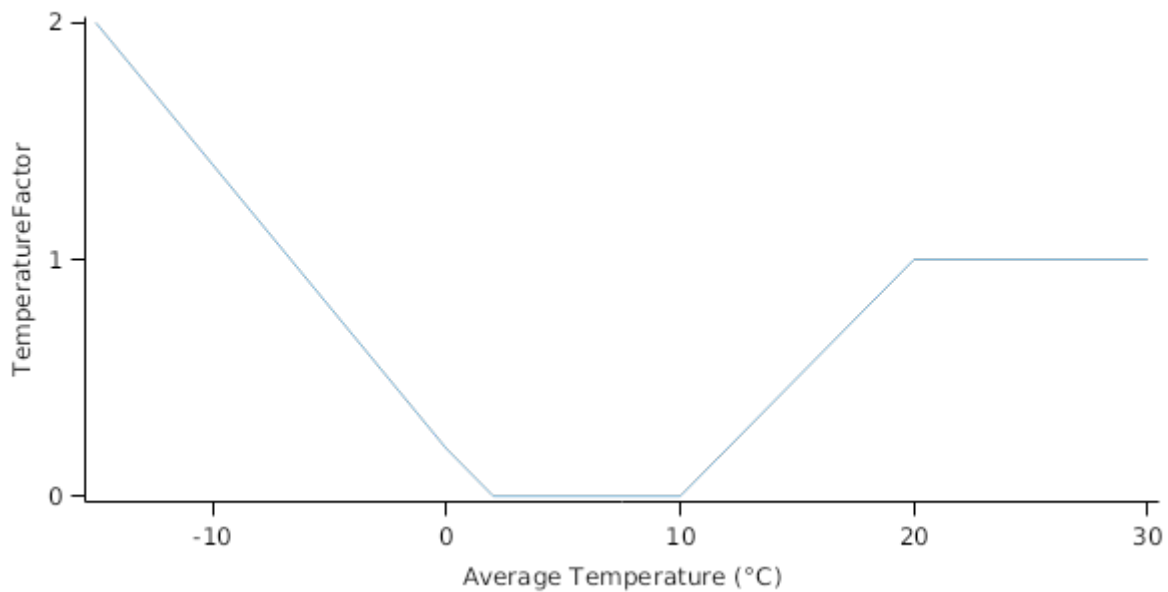
TemperatureFactor

TemperatureFactor

SoilMoistureFactor is calculated using linear interpolation

X	SoilMoistureFactor
0.0	2.0

X	SoilMoistureFactor
0.5	1.0
1.0	1.0
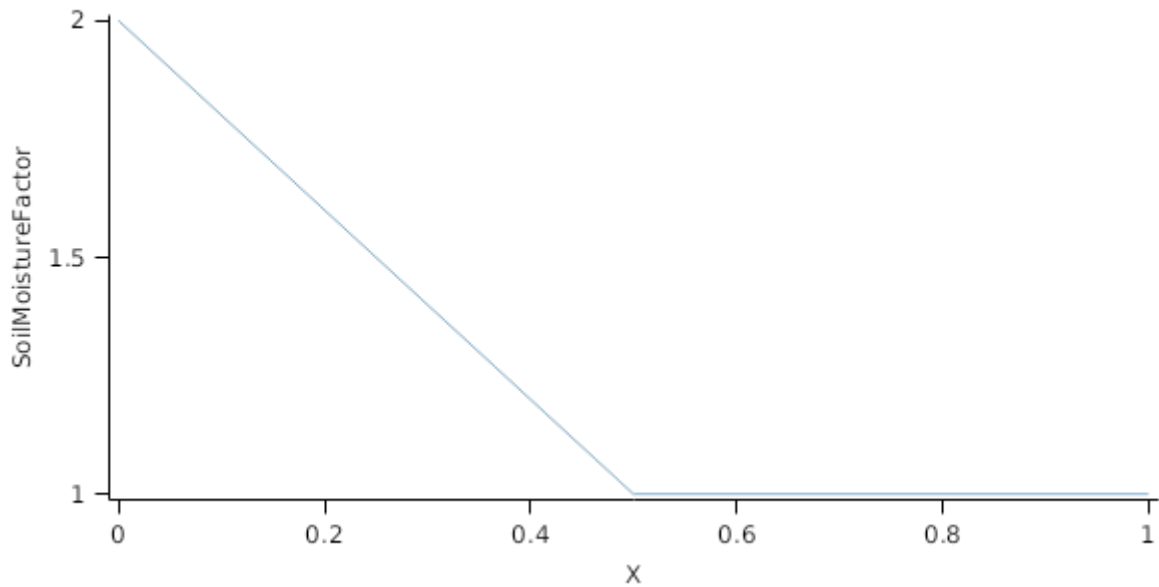
The proportion of Biomass that detaches and is passed to the surface organic matter model for decomposition is quantified by the DetachmentRateFunction.

A generic relationship between detachment and soil moisture is assumed. It implies that under dry conditions the detachment rate decreases due to the lower level of activity of decomposing microorganisms.

DetachmentRateFunction = ReferenceRate x SoilMoistureFactor

ReferenceRate = 0.1 (/day)

SoilMoistureFactor is calculated using linear interpolation

X	SoilMoistureFactor
0.0	0.1
0.5	0.1
0.8	0.2
1.0	1.0

SoilMoistureFactor

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 surface residues. The following table describes the default proportions of live and dead biomass that are transferred out of the simulation using "Removed" or to soil surface residue using "To Residue" for a range of management actions. The total percentage removed for live or dead must not exceed 100%. The difference between the total and 100% gives the biomass remaining on the plant. These can be changed during a simulation using a manager script.

Method	% Live Removed	% Dead Removed	% Live To Residue	% Dead To Residue
Cut	80	65	0	0
Graze	80	25	10	20
Harvest	0	0	10	10
Prune	0	0	50	20

1.11 Inflorescence

1.11.1 Inflorescence

This organ is simulated using a GenericOrgan type. It is parameterised to calculate the growth, senescence, and detachment of any organ that does not have specific functions.

1.11.2 Dry Matter Demand

The dry matter demand for the organ is calculated as defined in DMDemands, based on the DMDemandFunction and partition fractions for each biomass pool.

1.11.2.1 DMDemands

This class holds the functions for calculating the absolute demands and priorities for each biomass fraction.

Structural = DMDemandFunction x StructuralFraction

Returns the product of its PartitionFraction and the total DM supplied to the arbitrator by all organs.

DMDemandFunction = PartitionFraction x [Arbitrator].DM.TotalFixationSupply

The plantain model uses a simple approach to define the allocation of biomass to various organs. The fraction of the above ground biomass allocated to inflorescence is determined based on the current proprotion and two target ratios, the [TargetStemsLeafRatio].Value and [FlowerStemRatio].Value). Allocation to inflorescence can only occur during the reproductive phase.

PartitionFraction is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

Reproductive has a value between Flowering and Ripening calculated as:

FlowerFraction = Numerator / Denominator

Numerator = [TargetShootRootRatio] x [TargetShootRootRatio] x [TargetStemsLeafRatio] x [TargetStemsLeafRatio] x [TargetFlowerStemRatio] x [TargetFlowerStemRatio]

Denominator = SRs x SLs x FSs

SRs = TargetSRs + [ShootRootRatio]

TargetSRs = [TargetShootRootRatio] x [TargetShootRootRatio]

SLs = TargetSLs + [StemsLeafRatio]

TargetSLs = [TargetStemsLeafRatio] x [TargetStemsLeafRatio]

FSs = TargetFSs + [FlowerStemRatio]

TargetFSs = [TargetFlowerStemRatio] x [TargetFlowerStemRatio]

StructuralFraction = 1 (g/g)

Metabolic = 0

The partitioning of daily growth to storage biomass is based on a storage fraction.

StorageFraction = 1 - [Inflorescence].DMDemands.Structural.StructuralFraction

QStructuralPriority = 1

QMetabolicPriority = 1

QStoragePriority = 1

1.11.3 Nitrogen Demand

The N demand is calculated as defined in NDemands, based on DM demand the N concentration of each biomass pool.

1.11.3.1 NDemands

This class holds the functions for calculating the absolute demands and priorities for each biomass fraction.

Structural = [Inflorescence].minimumNconc x [Inflorescence].potentialDMAllocation.Structural

Metabolic = *MetabolicNconc* x [Inflorescence].potentialDMAllocation.Structural

MetabolicNconc = [Inflorescence].criticalNConc - [Inflorescence].minimumNconc

The partitioning of daily N supply to storage N attempts to bring the organ's N content to the maximum concentration.

Storage = [Inflorescence].maximumNconc × ([Inflorescence].Live.Wt + potentialAllocationWt) - [Inflorescence].Live.N

The demand for storage N is further reduced by a factor specified by the [Inflorescence].NitrogenDemandSwitch.

NitrogenDemandSwitch = [Inflorescence].nitrogenDemandSwitch

MaxNconc = [Inflorescence].maximumNconc

QStructuralPriority = 1

QMetabolicPriority = 1

QStoragePriority = 1

1.11.4 N Concentration Thresholds

MinimumNConc = 0.02 (gN/gDM)

CriticalNConc = [Inflorescence].MinimumNConc

MaximumNConc = 0.06 (gN/gDM)

1.11.5 Dry Matter Supply

Inflorescence does not reallocate DM when senescence of the organ occurs.

Inflorescence does not retranslocate non-structural DM.

1.11.6 Nitrogen Supply

Inflorescence can reallocate up to 100% of N that senesces each day if required by the plant arbitrator to meet N demands.

Inflorescence does not retranslocate non-structural N.

1.11.7 Senescence and Detachment

The proportion of live biomass that senesces and moves into the dead pool each day is quantified by the SenescenceRate.

The sparse availabe data suggests that plantain has a relatively slow senescence rate compared to other medow herbs (Calviere et al., 1995; Schippers et al., 2000). Generic relationships to enviromental factors, such as temperature and soil moisture, are assumed based on other plant models.

SenescenceRate = ReferenceRate x *StageFactor* x *TemperatureFactor* x *SoilMoistureFactor*

ReferenceRate = 0.25 (/day)

StageFactor is calculated using linear interpolation

X	StageFactor
3.0	1.0
4.0	1.0
4.0	0.5
4.5	0.7
5.0	1.0

TemperatureFactor is calculated as a function of daily min and max temperatures, these are weighted toward max temperature according to the specified MaximumTemperatureWeighting factor. A value equal to 1.0 means it will use max temperature, a value of 0.5 means average temperature.

MaximumTemperatureWeighting = 0.5

X	TemperatureFactor
0.0	0.0
5.0	0.0
20.0	1.0
30.0	1.0

TemperatureFactor

TemperatureFactor

SoilMoistureFactor is calculated using linear interpolation

X	SoilMoistureFactor
0.0	2.0
0.5	1.0
1.0	1.0

SoilMoistureFactor
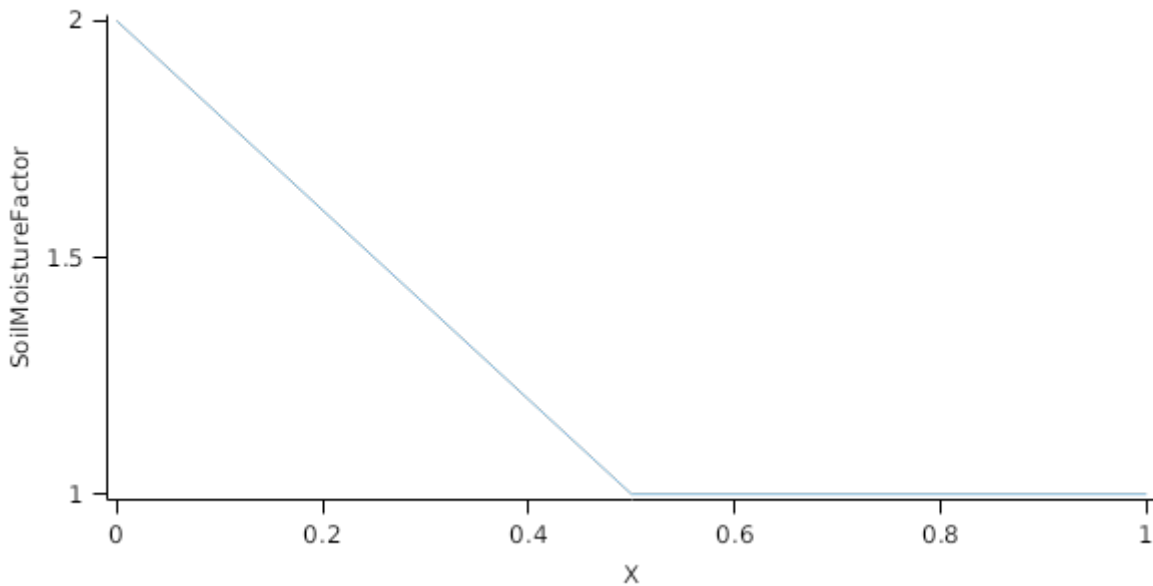
The proportion of Biomass that detaches and is passed to the surface organic matter model for decomposition is quantified by the DetachmentRateFunction.

A generic relationship between detachment and soil moisture is assumed. It implies that under dry conditions the detachment rate decreases due to the lower level of activity of decomposing microorganisms.

DetachmentRateFunction = ReferenceRate x SoilMoistureFactor

ReferenceRate = 0.25 (/day)

SoilMoistureFactor is calculated using linear interpolation

X	SoilMoistureFactor
0.0	0.0
0.5	0.5
1.0	1.0

SoilMoistureFactor

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 surface residues. The following table describes the default proportions of live

and dead biomass that are transferred out of the simulation using "Removed" or to soil surface residue using "To Residue" for a range of management actions. The total percentage removed for live or dead must not exceed 100%. The difference between the total and 100% gives the biomass remaining on the plant. These can be changed during a simulation using a manager script.

Method	% Live Removed	% Dead Removed	% Live To Residue	% Dead To Residue
Cut	80	25	0	0
Graze	80	25	10	10
Harvest	80	80	10	10
Prune	0	0	50	25

1.12 Taproot

1.12.1 Taproot

This organ is simulated using a GenericOrgan type. It is parameterised to calculate the growth, senescence, and detachment of any organ that does not have specific functions.

1.12.2 Dry Matter Demand

The dry matter demand for the organ is calculated as defined in DMDemands, based on the DMDemandFunction and partition fractions for each biomass pool.

1.12.2.1 DMDemands

This class holds the functions for calculating the absolute demands and priorities for each biomass fraction.

Structural = DMDemandFunction x StructuralFraction

Returns the product of its PartitionFraction and the total DM supplied to the arbitrator by all organs.

DMDemandFunction = PartitionFraction x [Arbitrator].DM.TotalFixationSupply

The plantain model computes the allocation of biomass to taproots assuming that there is a target ratio the biomass of root and taproot (defined by [TaprootRootRatio].Value). The existing literature does not provide values for this parameter, and based on other herbs, such as chicory, a simple value which is further modified by plant specific biomass is assumed in the model. This should be update when more data becomes available.

PartitionFraction is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

AllPhases has a value between Emergence and Ripening calculated as:

TaprootFraction = Numerator / Denominator

Numerator = [ShootRootRatio] x [TargetTaprootRootRatio] x [TargetTaprootRootRatio]

Denominator = SRs x TRs

SRs = TargetSRs + [ShootRootRatio]

TargetSRs = [TargetShootRootRatio] x [TargetShootRootRatio]

TRs = TargetTRs + [TaprootRootRatio]

TargetTRs = [TargetTaprootRootRatio] x [TargetTaprootRootRatio]

StructuralFraction = 0.1 (g/g)

Metabolic = 0

The partitioning of daily growth to storage biomass is based on a storage fraction.

StorageFraction = 1 - [Taproot].DMDemands.Structural.StructuralFraction

QStructuralPriority = 1

QMetabolicPriority = 1

QStoragePriority = 1

1.12.3 Nitrogen Demand

The N demand is calculated as defined in NDemands, based on DM demand the N concentration of each biomass pool.

1.12.3.1 NDemands

This class holds the functions for calculating the absolute demands and priorities for each biomass fraction.

Structural = [Taproot].minimumNconc x [Taproot].potentialDMAllocation.Structural

Metabolic = *MetabolicNconc* x [Taproot].potentialDMAllocation.Structural

MetabolicNconc = [Taproot].criticalNConc - [Taproot].minimumNconc

The partitioning of daily N supply to storage N attempts to bring the organ's N content to the maximum concentration.

Storage = [Taproot].maximumNconc × ([Taproot].Live.Wt + potentialAllocationWt) - [Taproot].Live.N

The demand for storage N is further reduced by a factor specified by the [Taproot].NitrogenDemandSwitch.

NitrogenDemandSwitch = [Taproot].nitrogenDemandSwitch

MaxNconc = [Taproot].maximumNconc

QStructuralPriority = 1

QMetabolicPriority = 1

QStoragePriority = 1

1.12.4 N Concentration Thresholds

MinimumNConc = 0.007 (gN/gDM)

CriticalNConc = [Taproot].MinimumNConc

MaximumNConc = 0.02 (gN/gDM)

1.12.5 Dry Matter Supply

Taproot does not reallocate DM when senescence of the organ occurs.

Taproot will retranslocate 15% of non-structural DM each day.

1.12.6 Nitrogen Supply

Taproot can reallocate up to 100% of N that senesces each day if required by the plant arbitrator to meet N demands.

Taproot can retranslocate up to 20% of non-structural N each day if required by the plant arbitrator to meet N demands.

1.12.7 Senescence and Detachment

The proportion of live biomass that senesces and moves into the dead pool each day is quantified by the SenescenceRate.

The reference senescence rate is adjusted according to enviromental factors, temperature and soil moisture. Currently only sensitivity to temperature is considered, based on general knowledge from other plant models. The sensitivity of plantain roots to low moisture or water logging is not clear , so this will have to be upgrade in the future when more data is available. According to Sagar et al., 1964, *P. major*, a similar species, is more tolerant to water logging than *P. lanceolata*, which rarely occurs in water logged sites (van Tiederen, 1992).

SenescenceRate = *ReferenceRate* x *TemperatureFactor* x *SoilMoistureFactor* x *SoilAerationFactor*

ReferenceRate = 0.001 (/day)

TemperatureFactor is calculated as a function of daily min and max temperatures, these are weighted toward max

temperature according to the specified MaximumTemperatureWeighting factor. A value equal to 1.0 means it will use max temperature, a value of 0.5 means average temperature.

MaximumTemperatureWeighting = 0.5

X	TemperatureFactor
0.0	0.0
5.0	0.0
22.0	1.0
30.0	1.0

TemperatureFactor
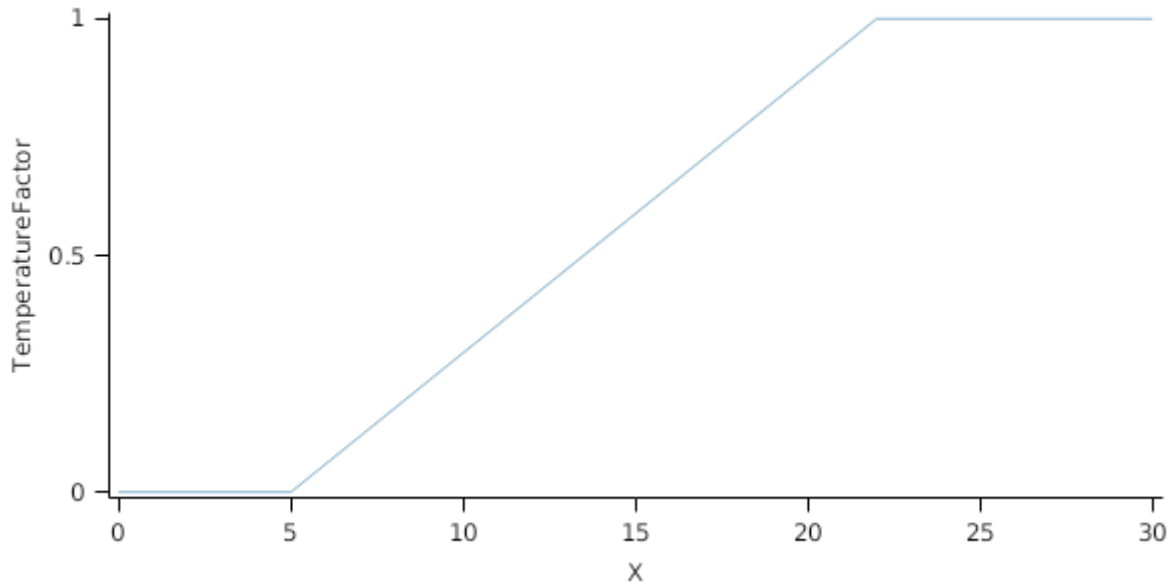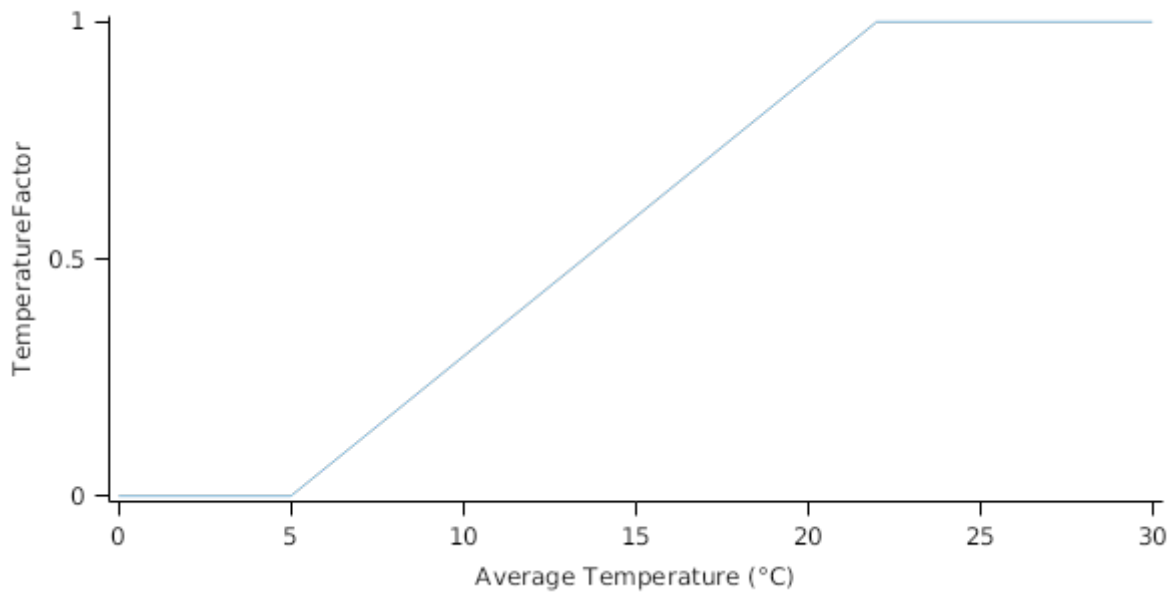
TemperatureFactor

SoilMoistureFactor is calculated using linear interpolation

X	SoilMoistureFactor
0.0	1.0

X	SoilMoistureFactor
0.5	1.0
1.0	1.0

SoilMoistureFactor
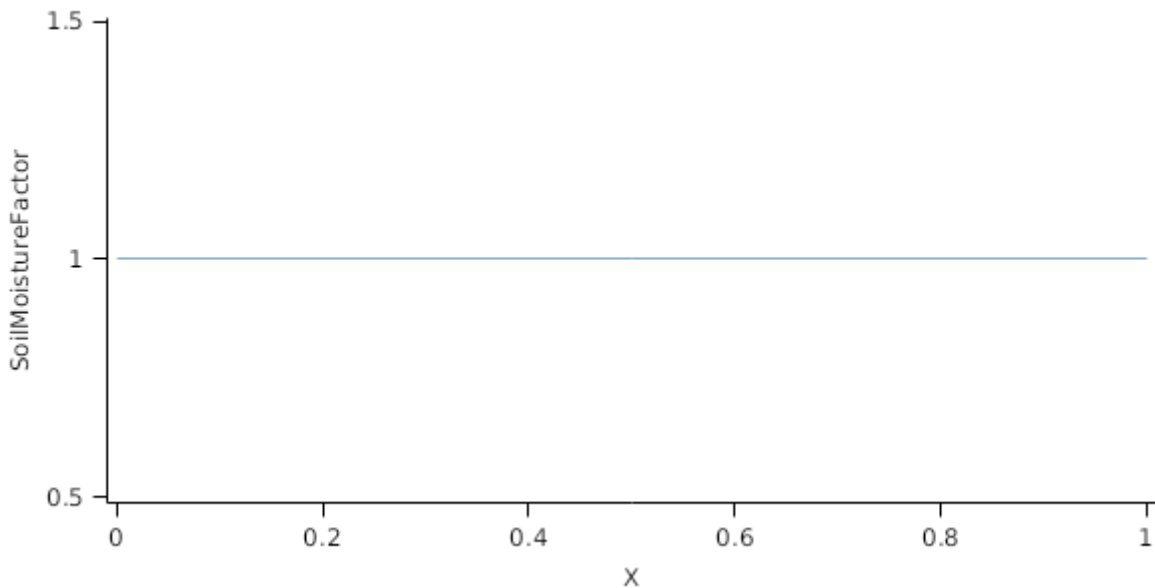
SoilAerationFactor = 1 (0-1)

Taproot detaches 100% of its live biomass each day, passing it to the surface organic matter model for decomposition.

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 surface residues. The following table describes the default proportions of live and dead biomass that are transferred out of the simulation using "Removed" or to soil surface residue using "To Residue" for a range of management actions. The total percentage removed for live or dead must not exceed 100%. The difference between the total and 100% gives the biomass remaining on the plant. These can be changed during a simulation using a manager script.

Method	% Live Removed	% Dead Removed	% Live To Residue	% Dead To Residue
Cut	0	0	10	0
Graze	0	0	10	0
Harvest	0	0	10	0
Prune	0	0	10	0

1.13 Root

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

1.13.1 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 Increase = RootFrontVelocity x XF_i x RootDepthStressFactor

where i is the index of the soil layer at the rooting front.

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'. For example, the Root Activity for water is calculated as

$RAw_i = -WaterUptake_i / LiveRootWt_i \times LayerThickness_i \times ProportionThroughLayer$

The amount of root mass partitioned to a layer is then proportional to root activity

$DMAllocated_i = TotalDMAllocated \times RAw_i / TotalRAw$

1.13.2 Dry Matter Demands

A daily DM demand is provided to the organ arbitrator 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.

1.13.3 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.

1.13.4 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$_As can be seen from the above equations, the values of kNO3 and kNH4 equate to the potential fraction of each mineral N pool which can be taken up per day for wet soil when that pool has a concentration of 1 ppm.Nitrogen uptake demand is limited to the maximum daily potential uptake (MaxDailyNUptake) and the plant's N demand. The former provides a means to constrain N uptake to a maximum value observed in the field for the crop as a whole.The demand for soil N is then passed to the soil arbitrator which determines how much of the N uptake demandeach plant instance will be allowed to take up.

1.13.5 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. $SW\ uptake = (SW_i - LL_i) \times KL_i \times KLModifier$

1.13.6 Constants

MinimumNConc = 0.005 (gN/gDM)

MaximumNConc = 0.015 (gN/gDM)

MaximumRootDepth = 1000 (mm)

No effect of temperature on root growth is currently captured in the model.

TemperatureEffect = 1

No effect of soil water content on root growth is currently captured in the model.

SoilWaterEffect = 1

SpecificRootLength = 100 (m/g)

DMRetranslocationFactor = 0 (/day)

NRetranslocationFactor = 0 (/day)

NReallocationFactor = 0 (/day)

MaxDailyNUptake = 10 (kgN/ha)

DMConversionEfficiency = 1

MaintenanceRespirationFunction = 1

RemobilisationCost = 0

CarbonConcentration = 0.4

RootDepthStressFactor = 1

1.13.7 RootShape

This model calculates the proportion of each soil layer occupided by roots.

1.13.8 Description

Note: this represents all the fine roots of the plant. The root organ demands and is partitioned N and DM and its depth increases through time to provide a water uptake supply

1.13.9 NitrogenDemandSwitch

NitrogenDemandSwitch has a value between Germination and Ripening calculated as:

Constant = 1

1.13.10 RootFrontVelocity

RootFrontVelocity is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

PreEmergence has a value between Germination and Emergence calculated as:

ReferenceVelocity = 5 (mm/day)

Vegetative has a value between Emergence and Flowering calculated as:

ReferenceVelocity = 10 (mm/day)

Reproductive has a value between Flowering and Ripening calculated as:

ReferenceVelocity = 7.5 (mm/day)

1.13.11 SenescenceRate

The reference senescence rate is adjusted according to enviromental factors, temperature and soil moisture. Currently only sensitivity to temperature is considered, based on general knowledge from other plant models. The sensitivity of plantain roots to low moisture or water logging is not clear (according to Sagar et al., 1964, *P. major* is more tolerant to water logging than *P. lanceolata*) , so this will have to be upgrade in the future when more data is available.

SenescenceRate = ReferenceRate x *TemperatureFactor* x *SoilMoistureFactor* x *SoilAerationFactor*

ReferenceRate = 0.005 (/day)

TemperatureFactor is calculated as a function of daily min and max temperatures, these are weighted toward max temperature according to the specified MaximumTemperatureWeighting factor. A value equal to 1.0 means it will use max temperature, a value of 0.5 means average temperature.

MaximumTemperatureWeighting = 0.5

X	TemperatureFactor
0.0	0.0
5.0	0.0
20.0	1.0
30.0	1.0

TemperatureFactor

TemperatureFactor

SoilMoistureFactor is calculated using linear interpolation

X	SoilMoistureFactor
0.0	1.0
0.5	1.0
1.0	1.0

SoilMoistureFactor
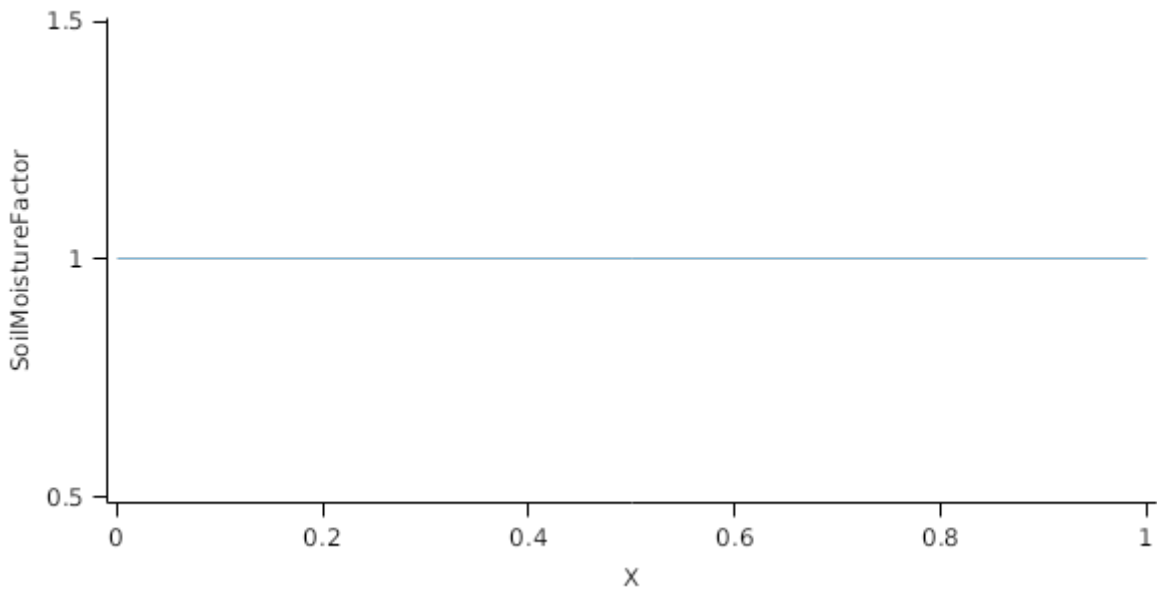
SoilAerationFactor = 1

1.13.12 KLModifier

KLModifier is calculated using linear interpolation

X	KLModifier
0.0	1.0
1.0	1.0

KLModifier
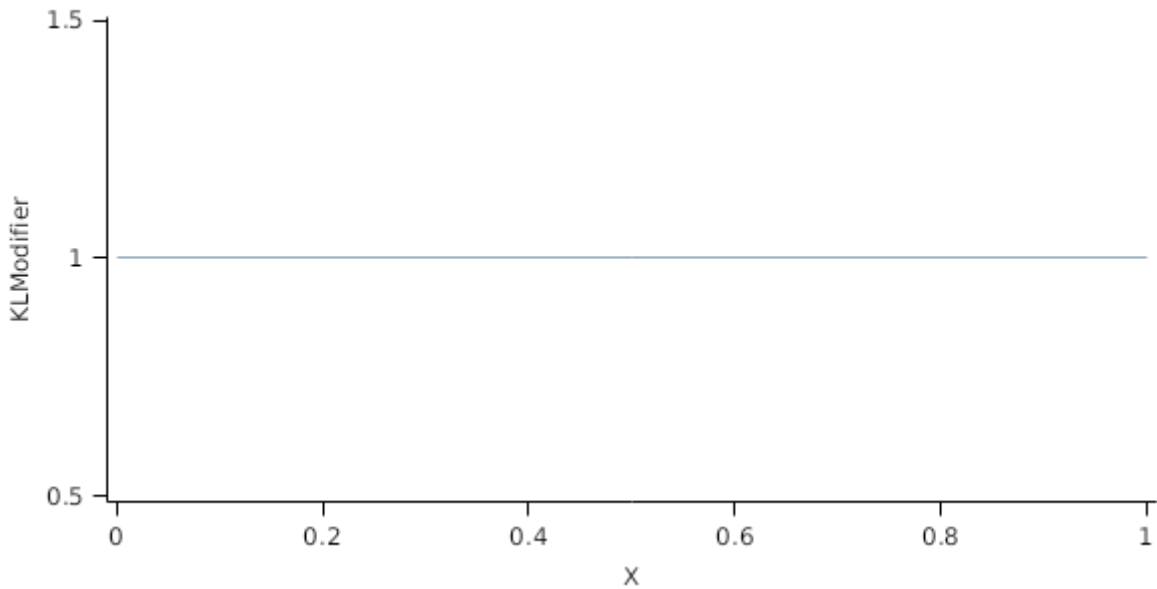
1.13.13 KNH4

KNH4 is calculated using linear interpolation

X	KNH4
0.0	0.0
0.0	0.0
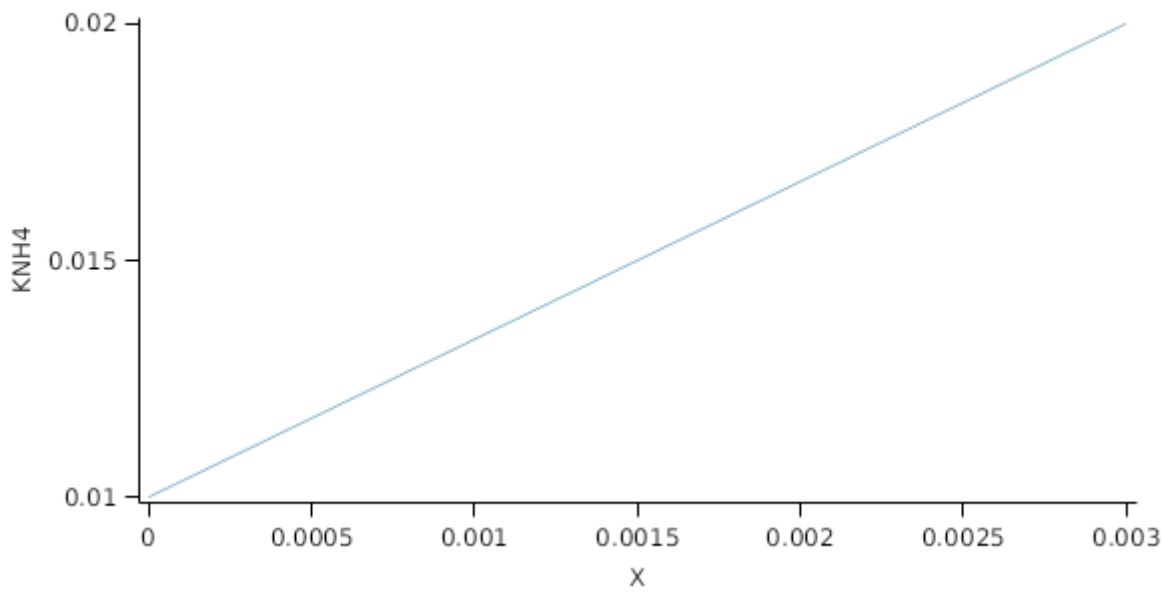
1.13.14 KNO3

KNO3 is calculated using linear interpolation

X	KNO3
0.0	0.0
0.0	0.0
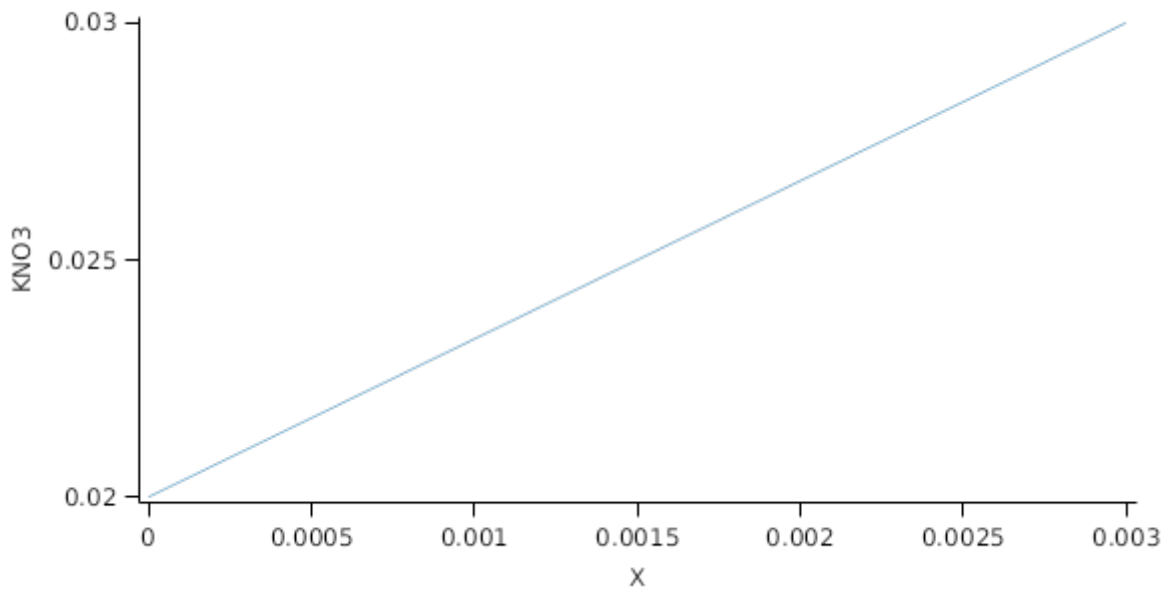
1.13.15 NUptakeSWFactor

NUptakeSWFactor is calculated using linear interpolation

X	NUptakeSWFactor
0.0	0.0
0.5	1.0
1.0	1.0

NUptakeSWFactor
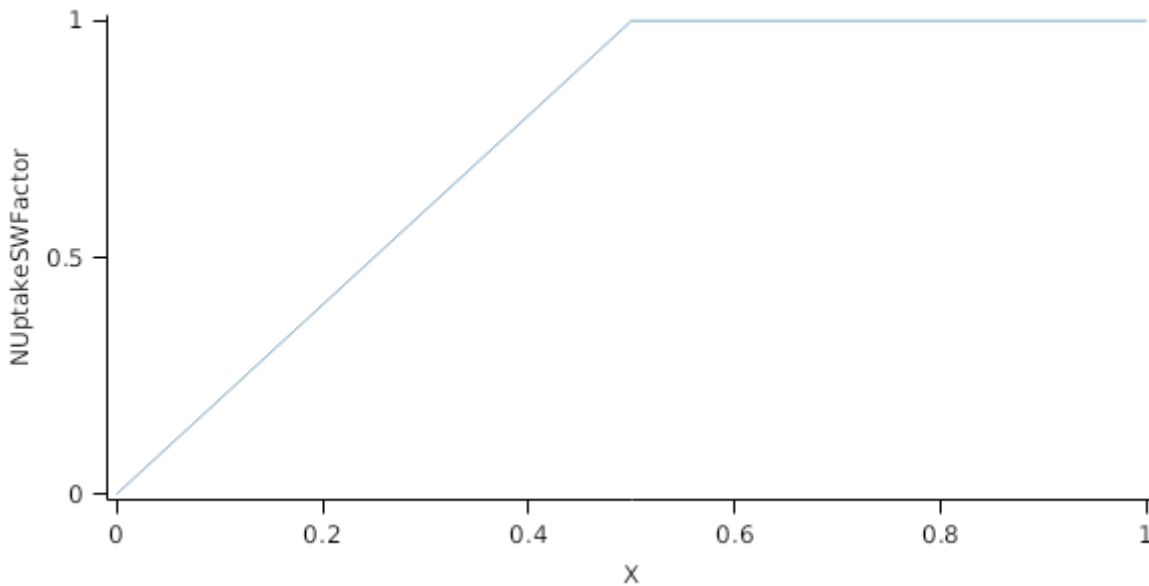
1.13.16 BiomassRemovalDefaults

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 surface residues. The following table describes the default proportions of live and dead biomass that are transferred out of the simulation using "Removed" or to soil surface residue using "To Residue" for a range of management actions. The total percentage removed for live or dead must not exceed 100%. The difference between the total and 100% gives the biomass remaining on the plant. These can be changed during a simulation using a manager script.

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

1.13.17 DMDemands

1.13.17.1 DMDemands

This class holds the functions for calculating the absolute demands and priorities for each biomass fraction.

Structural = DMDemandFunction x StructuralFraction

Returns the product of its PartitionFraction and the total DM supplied to the arbitrator by all organs.

DMDemandFunction = PartitionFraction x [Arbitrator].DM.TotalFixationSupply

PartitionFraction is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

The allocation of biomass below ground follows a simple approach in the plantain model. The amount allocated to roots is computed based on current proportion and two target ratios (the [TargetShootRootRatio].Value and [TaprootRootRatio] .Value). There is little information in the literature about these parameters and they should vary with cultivar. Currently the model will attempt to keep a given proportion in ach organ, ho these porportions vary should be update when more data becomes available.

AllPhases has a value between Emergence and Ripening calculated as:

RootFraction = Numerator / Denominator

Numerator = [ShootRootRatio] x [TaprootRootRatio]

Denominator = SRs x *TRs*

SRs = TargetSRs + [ShootRootRatio]

TargetSRs = [TargetShootRootRatio] x [TargetShootRootRatio]

TRs = TargetTRs + [TaprootRootRatio]

TargetTRs = [TargetTaprootRootRatio] x [TargetTaprootRootRatio]

StructuralFraction = 1 (g/g)

Metabolic = 0

The partitioning of daily growth to storage biomass is based on a storage fraction.

StorageFraction = 1 - [Root].DMDemands.Structural.StructuralFraction

QStructuralPriority = 1

QMetabolicPriority = 1

QStoragePriority = 1

1.13.18 NDemands

1.13.18.1 NDemands

This class holds the functions for calculating the absolute demands and priorities for each biomass fraction.

Structural = [Root].minimumNconc x [Root].potentialDMAllocation.Structural

Metabolic = MetabolicNconc x [Root].potentialDMAllocation.Structural

MetabolicNconc = [Root].criticalNConc - [Root].minimumNconc

The partitioning of daily N supply to storage N attempts to bring the organ's N content to the maximum concentration.

Storage = [Root].maximumNconc × ([Root].Live.Wt + potentialAllocationWt) - [Root].Live.N

The demand for storage N is further reduced by a factor specified by the [Root].NitrogenDemandSwitch.

NitrogenDemandSwitch = [Root].nitrogenDemandSwitch

MaxNconc = [Root].maximumNconc

QStructuralPriority = 1

QMetabolicPriority = 1

QStoragePriority = 1

1.13.19 CriticalNConc

CriticalNConc = [Root].MinimumNConc

1.13.20 InitialWt

This class holds the functions for calculating the absolute demands for each biomass fraction.

Structural = InitialRootWt x [Plant].Population

InitialRootWt = 0.001 (g/plant)

Metabolic = 0

Storage = 0

1.14 AboveGround

1.14.1 AboveGround

This is a composite biomass class, representing the sum of 1 or more biomass objects from one or more organs.

AboveGround summarises the following biomass objects:

* Leaf
* Stem
* Inflorescence

1.15 AboveGroundLive

1.15.1 AboveGroundLive

This is a composite biomass class, representing the sum of 1 or more biomass objects from one or more organs.

AboveGroundLive summarises the following biomass objects:

* Leaf
* Stem
* Inflorescence

1.16 BelowGround

1.16.1 BelowGround

This is a composite biomass class, representing the sum of 1 or more biomass objects from one or more organs.

BelowGround summarises the following biomass objects:

* Root
* Taproot

1.17 BelowGroundLive

1.17.1 BelowGroundLive

This is a composite biomass class, representing the sum of 1 or more biomass objects from one or more organs.

BelowGroundLive summarises the following biomass objects:

* Root
* Taproot

1.18 Total

1.18.1 Total

This is a composite biomass class, representing the sum of 1 or more biomass objects from one or more organs.

Total summarises the following biomass objects:

* Leaf
* Stem
* Inflorescence
* Root
* Taproot

1.19 PerPlantBelowGroundWt

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

PerPlantBelowGroundWt = [BelowGroundLive].Wt / [Plantain].Population

1.20 ShootRootRatio

ShootRootRatio is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

AllPhases has a value between Emergence and Ripening calculated as:

CurrentSR = [AboveGroundLive].Wt / [BelowGroundLive].Wt

1.21 TargetShootRootRatio

TargetShootRootRatio is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

To ensure prompt regrowth of forage plantain after a defoliation, the model will adjust the allocation of new growth following any defoliation event. This is a simplified approach to biomass allocation plasticity (e.g. Wilson, 1988; Levang-Brilz et al., 2002), it assumes that the plant switches allocation of towards leaves whenever the current shoot:root ratio differs from the target value.
Published data for the shoot:root ratio in plantain is highly variable, with values as low as 1.0 for wild varieties and as high as 6.0 for seedlings of commercial cultivars with no water of nutrient limitations (Schippers et al., 2000; Labreveux, 2002; Cranston, 2015; Pankoke, 2015). The data suggests mean values to be around 1.75-2.0 for adult plants. This value is likely to be affected by environmental conditions, with water or nutrient deficit favouring root growth, while low light conditions leading to higher allocation above ground. However, these relationships can vary considerably in different plants and there is little data for plantain, so the model current ignores the influence of environmental factors on the shoot:root partition, this should be upgraded when data becomes available.

Vegetative has a value between Emergence and Flowering calculated as:

TargetSR = 1.75 (g/g)

Reproductive has a value between Flowering and Ripening calculated as:

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

PlusTarget = DeltaTarget x *PhotoperiodEffect*

DeltaTarget = MaxTargetSR - [TargetShootRootRatio].Vegetative.TargetSR

MaxTargetSR = 2 (g/g)

PhotoperiodEffect is calculated using linear interpolation

X	PhotoperiodEffect
11.0	0.0
12.0	0.0
13.0	0.2
13.8	0.8
14.0	1.0
15.0	1.0

PhotoperiodEffect
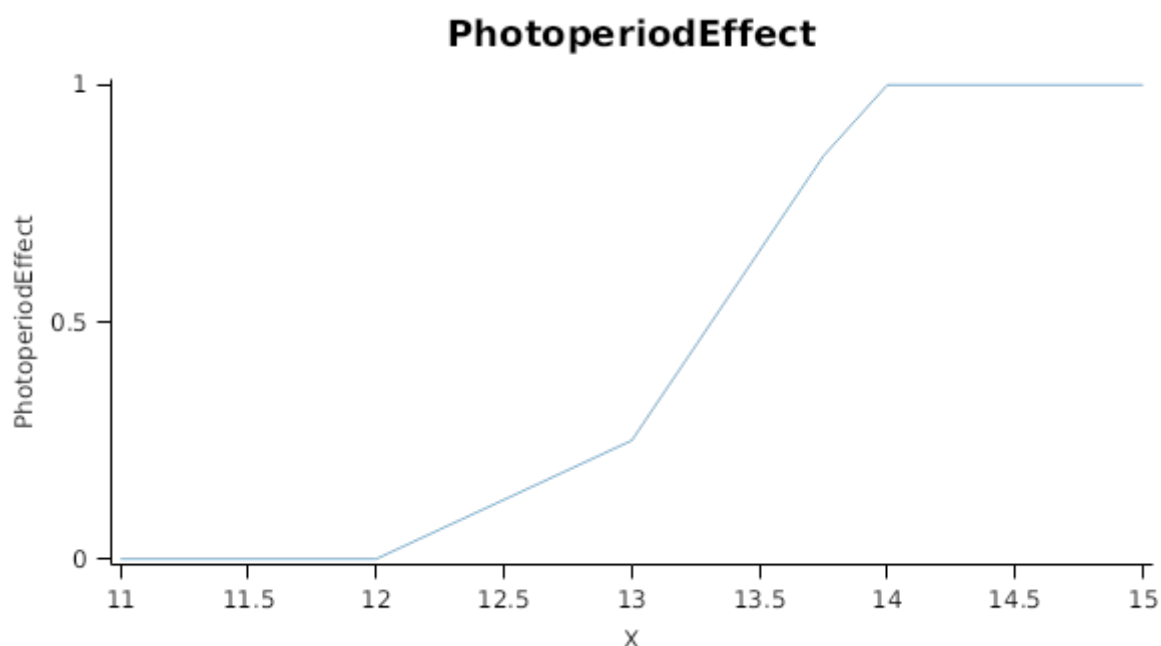
1.22 StemsLeafRatio

StemsLeafRatio is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

Reproductive has a value between Flowering and Ripening calculated as:

CurrentSL = StemFlowerDM / [Leaf].Live.Wt

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

1.23 TargetStemsLeafRatio

TargetStemsLeafRatio is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

The plantain model defines allocation of biomass above ground following a simple approach, it attempts 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 reproductive phase, the partition is further modified based on the ratio of stems+inflorescence to leaves. This ratio may be affected by defoliation (Ayala et al., 2011; Quijada, 2015) and is probably affected by enviromental factors too. There is not enough data to describe these interactions.
Published results suggest that reproductive parts represent a relatively small proportion of the biomass, about 10-25% in grazed swards, and about 40% if not grazed (Schippers et al., 2000; Labreveux, 2002; Moorhead, 2009; Ayala et al., 2011).

Reproductive has a value between Flowering and Ripening calculated as:

TargetSL = MaximumSL x *PhotoperiodEffect*

MaximumSL = 0.25 (g/g)

PhotoperiodEffect is calculated using linear interpolation

X	PhotoperiodEffect
11.0	0.0
12.5	0.0
13.2	0.2
13.8	0.8
14.0	1.0
15.0	1.0

1.24 FlowerStemRatio

FlowerStemRatio is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

Reproductive has a value between Flowering and Ripening calculated as:

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

1.25 TargetFlowerStemRatio

TargetFlowerStemRatio is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

The allocation of biomass follows a simple approach in the plantain model. Allocation during the reproductive phase will attempt to keep a ratio between stem and inflorescence biomass. This ratio is probably affected by enviromental factors, but there is not data to determine how these would interact. Because of the short period between stem elongation, flowering and seed maturity, and a relatively long reproductive phase, plantain plants will have ripe seeds as well as young stalks at the same time. This makes quite difficult to define variation in biomass allocation to inflorescence. Inference from published values suggest that the ratio of flower biomass to stems varies from around 0.1 to nearly 0.4 (Schippers et al., 2000).

Reproductive has a value between Flowering and Ripening calculated as:

TargetFS = MaximumFS x PhotoperiodEffect

MaximumFS = 0.25 (g/g)

PhotoperiodEffect is calculated using linear interpolation

X	PhotoperiodEffect
11.0	0.0
12.8	0.0
13.2	0.1
13.8	0.8
14.0	1.0
15.0	1.0
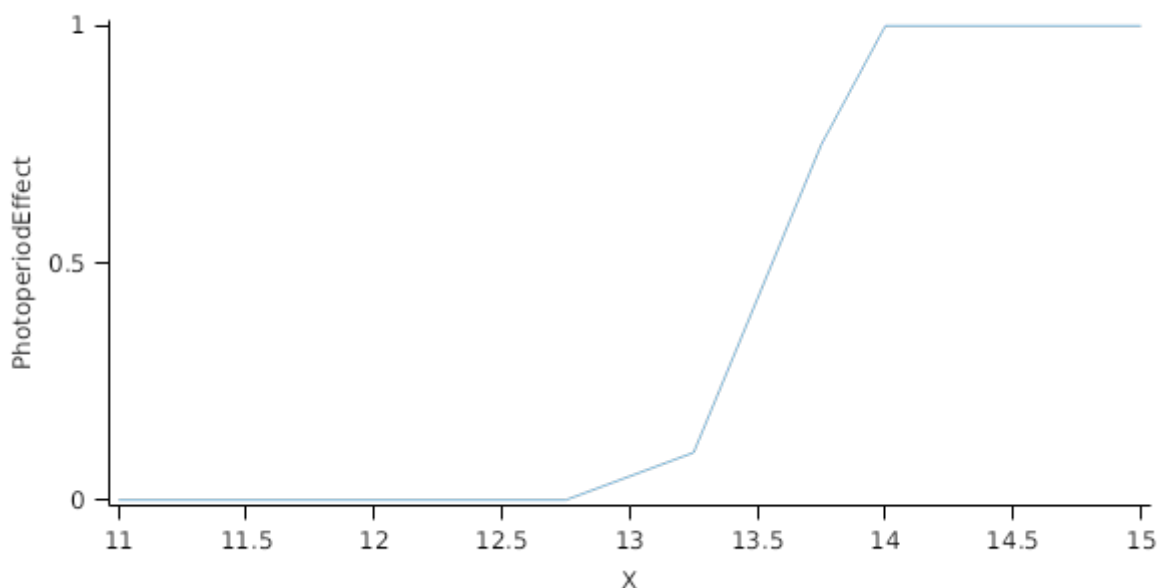
1.26 TaprootRootRatio

TaprootRootRatio is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

AllPhases has a value between Emergence and Ripening calculated as:

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

1.27 TargetTaprootRootRatio

TargetTaprootRootRatio is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

The plantain model assumes that biomass is allocated so to mantain a given proportion of among the various organs (varying with phenological phase and other factors). The ratio between taproot and root biomass is assumed to vary, increasing with the biomass below ground per plant, approaching a maximum target. This is a simple approach and can describe the general behaviour of plantain plants, it may be upgraded if deemed necessary when more data becomes available.

AllPhases has a value between Emergence and Ripening calculated as:

TargetTR = *MaximumTR* x *BiomassFactor*

MaximumTR = 1 (g/g)

BiomassFactor is calculated using linear interpolation

X	BiomassFactor
0.0	0.0
0.0	0.0
0.1	0.4
0.2	0.8
0.5	0.9
1.0	1.0
1.5	1.0

BiomassFactor
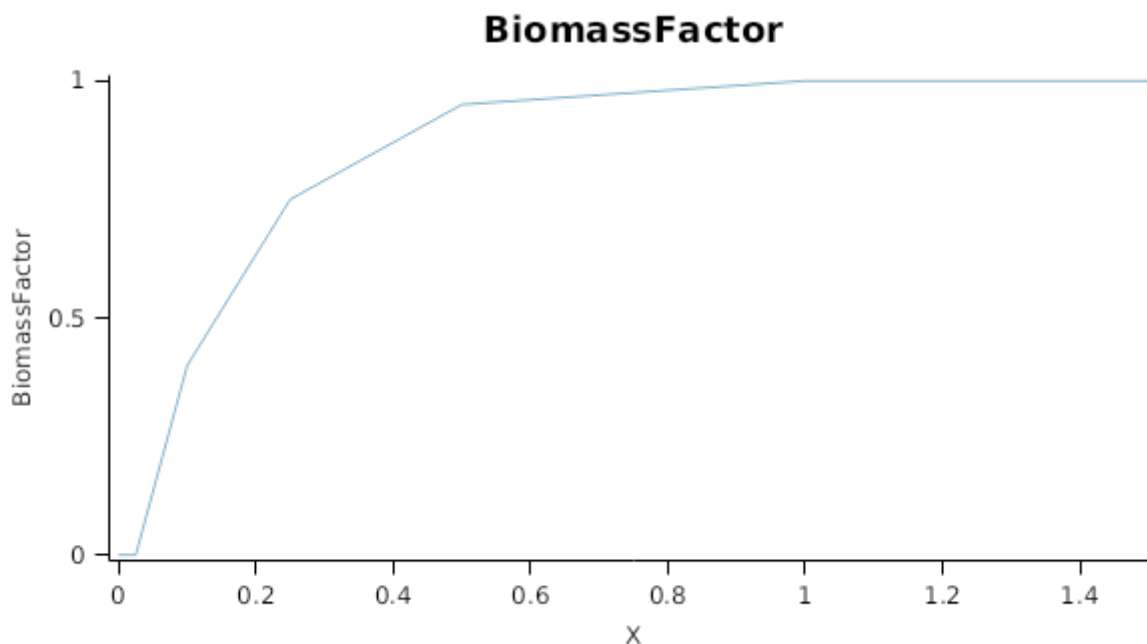
1.28 Cultivars

1.28.1 Lancelot

Lancelot overrides the following properties:

[Leaf].Photosynthesis.FT.XYPairs.X = 5, 10, 15, 21, 27, 35

[Leaf].Photosynthesis.FT.XYPairs.Y = 0.0, 0.04, 0.3, 1.0, 1.0, 0.0

[Leaf].Tallness.XYPairs.X = 10, 100, 500

[Leaf].Tallness.XYPairs.Y = 100, 300, 400

1.29 MortalityRate

MortalityRate = 0

2 Validation

The performance of the plantain model is evaluated in simulations based on experiments conducted primarily in New Zealand. Datasets from USA have been added, but they should be taken with caution as there was limited information about the experiments and published results corresponded to annual or seasonal aggregates only. Note that population is not explicitly simulated by the model, only a decrease in plant numbers as function of cuts or grazings is considered. The literature suggest that severe defoliation may reduce population by increasing death rate, but mostly is infered from other species and even then the variation is high. Plantain persistency has been shown to be low, usually restricted to 2-4 years, but very little actuall data is available.

The model describes N content in the above ground tissues reasonably well only for treatments where N deficit was not high (See results for the FRNL datasets with annual fertiliser rates of 200 kgN/ha and above). The measured data showed little effect on plant N concentration for the treatment with nil or low N rates, wehreas the model predicts differences between them. The variability among replicates is high and there wer only three or four replicates, this may blur some of the differences. Also, there was no information from which potential sources of nitrogen, such as soil mineralisation or N fixation from 'weeds' (the present of white clover was noted), could be identified and used to adjust the simulations. Besides these isses, some of the underlying PMF code may need to be upgraded in order to describe some processes under plant cut/grazing and re-growth conditions. Processes for computing N demand and supply (especially regarding remobilisation within living tissues) are still under developement and this needs especific detailed datasets. The SimpleLeaf module was employed to simulate the plant canopy in the plantain model, this was done because there was not enough data to parameterise the more complex PMF approach. This means that the model has only one leaf cohort with simple N thresholds (only maximum and minimum), this may be too simplistic to capture the nuances of the re-growth processes especially when sustained by the remobilisation from storage organs (taproot and old tissue). The model will be upgraded in the near future as the work on the code to improve the description of those specific processes is ongoing.

2.1 New Zealand

2.1.1 All data from New Zealand

List of experiments.

Experiment Name	Design (Number of Treatments)
FRNLLincoln	NRate (6)
FRNLRuakura	NRate (6)

2.1.2 FRNLLincoln

###FRNL Lincoln###

Simulation setup based on field trial performed at Lincoln University Research Dairy Farm, New Zealand, between 2014 and 2016. The experiment was part of the FRNL (Forages for Reduced Nitrogen Leaching) program and the data is basically unpublished (references will be added when this come about). Here only plots with pure plantain are used. The experiment consisted of six fertiliser treatments (N rates of 0, 50, 100, 200, 350 and 500 kg/ha/yr) in four replicates, and measurements comprised yield and quality indicators (here N content is used).
Data supplied by Grant Edwards, Lincoln University.

The soil at the experimental site was a Templeton fine sandy loam (an Immature Pallic soil, USDA: Udic Haplustept), the required parameters were inferred based on data from the New Zealand National Soils Database (Landcare Research). Weather data was obtained from nearby Broadfields weather station (NIWA).
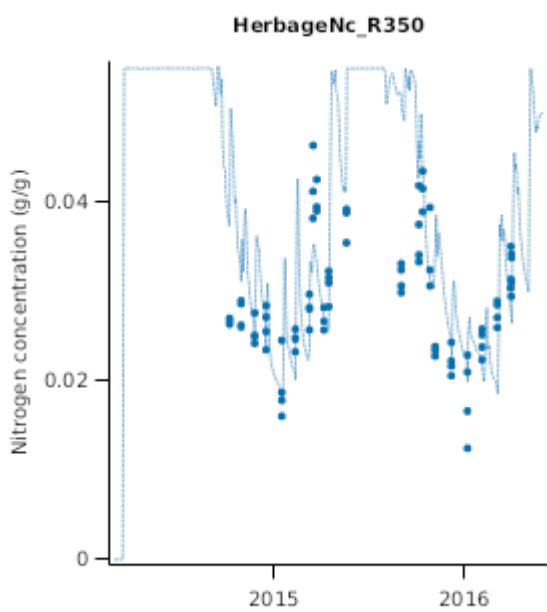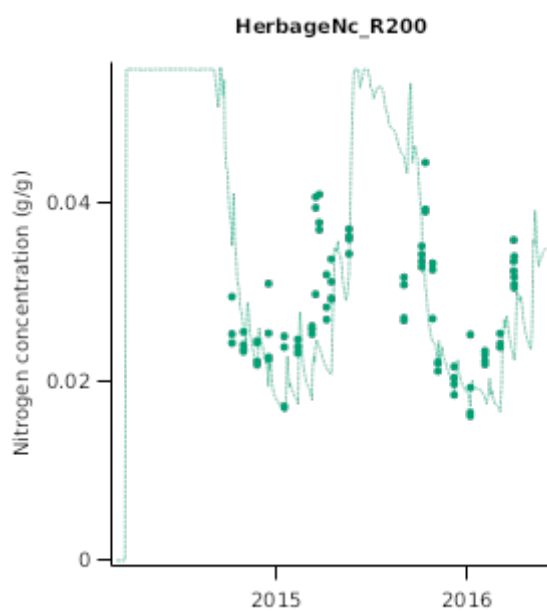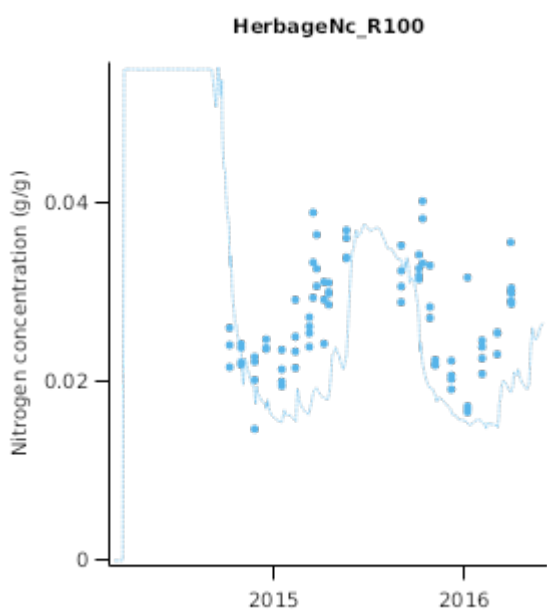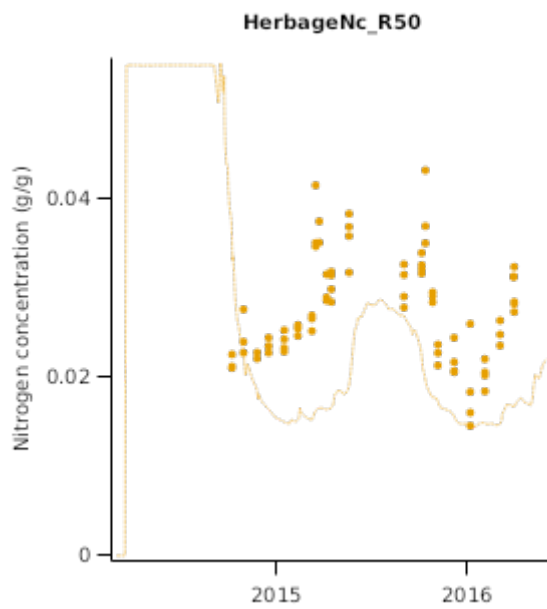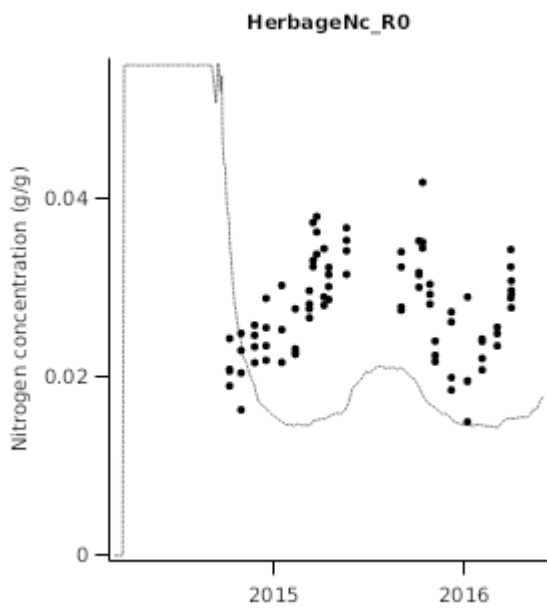
2.1.2.1 Results

2.1.2.1.1 PlantDM
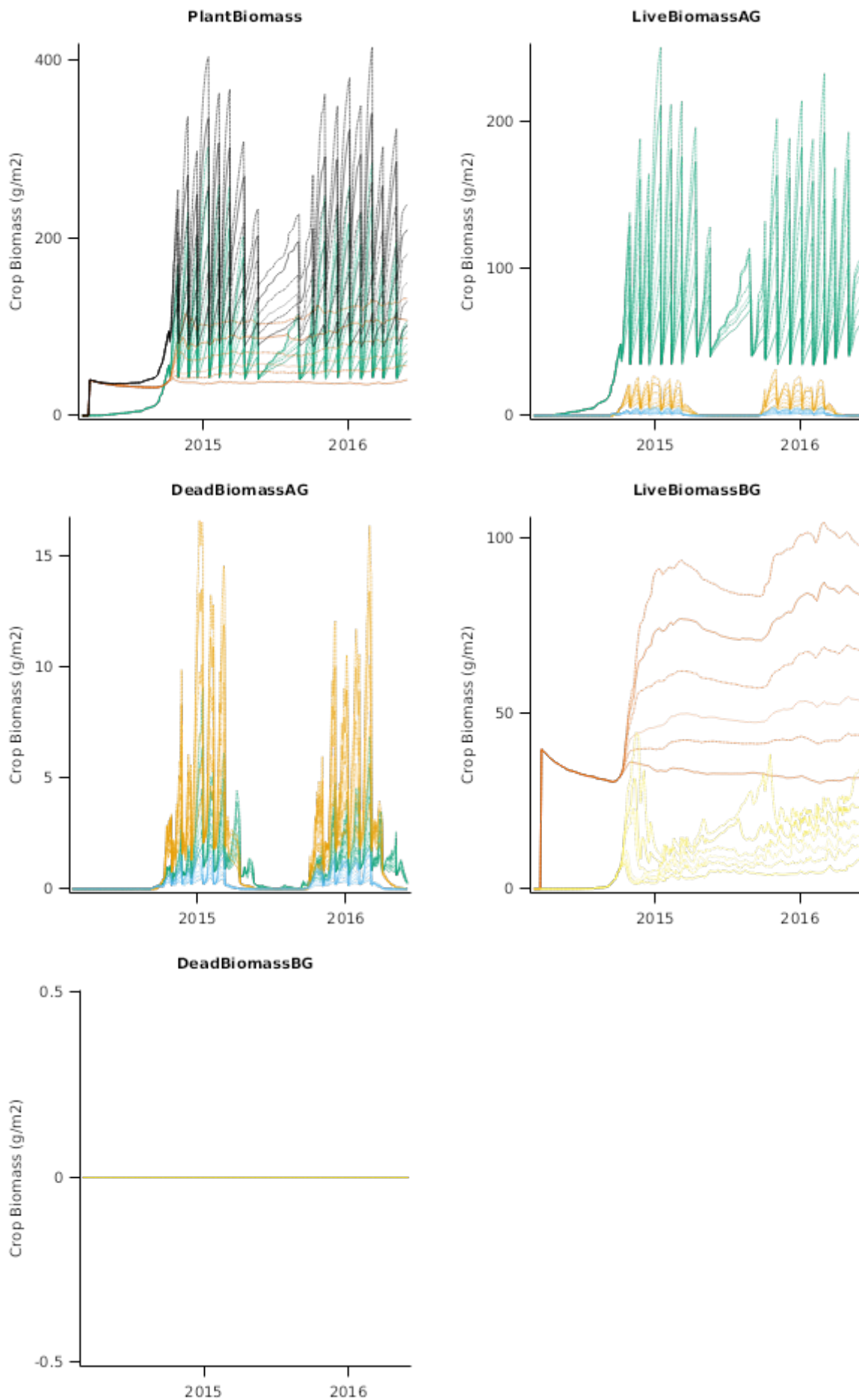
2.1.2.1.2 PlantNc
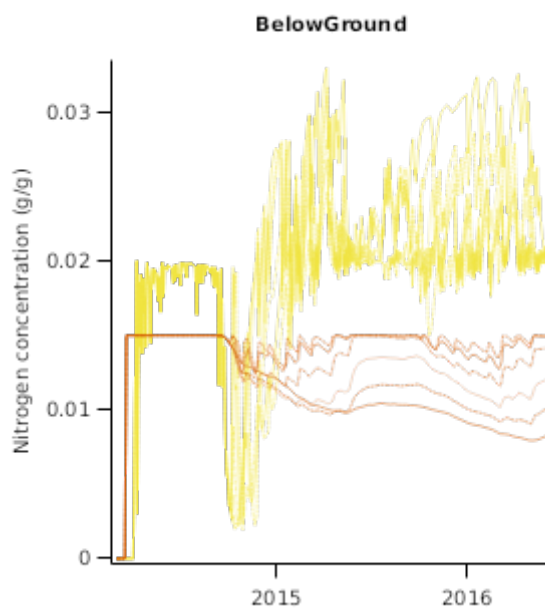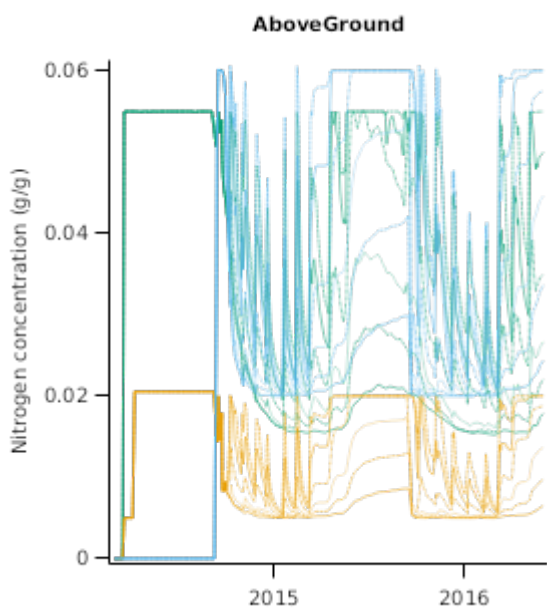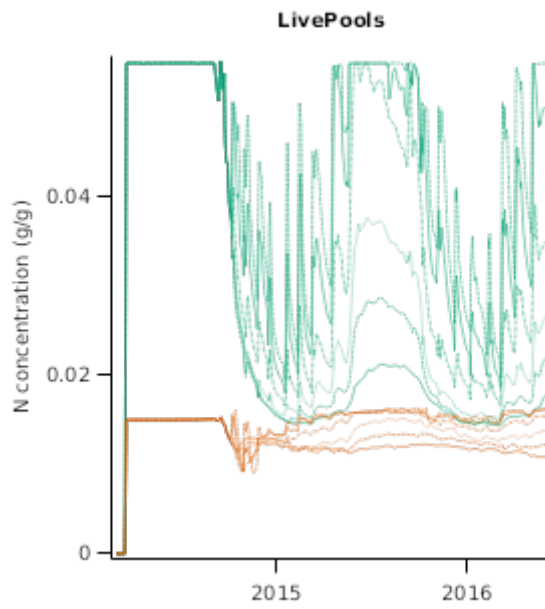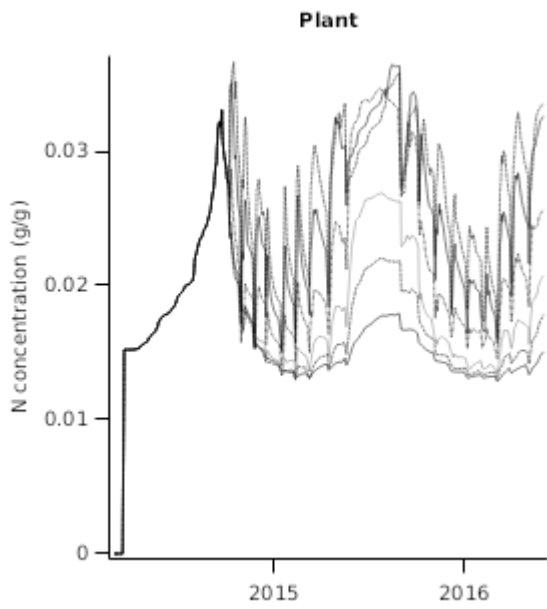
2.1.2.2 ObservedResults
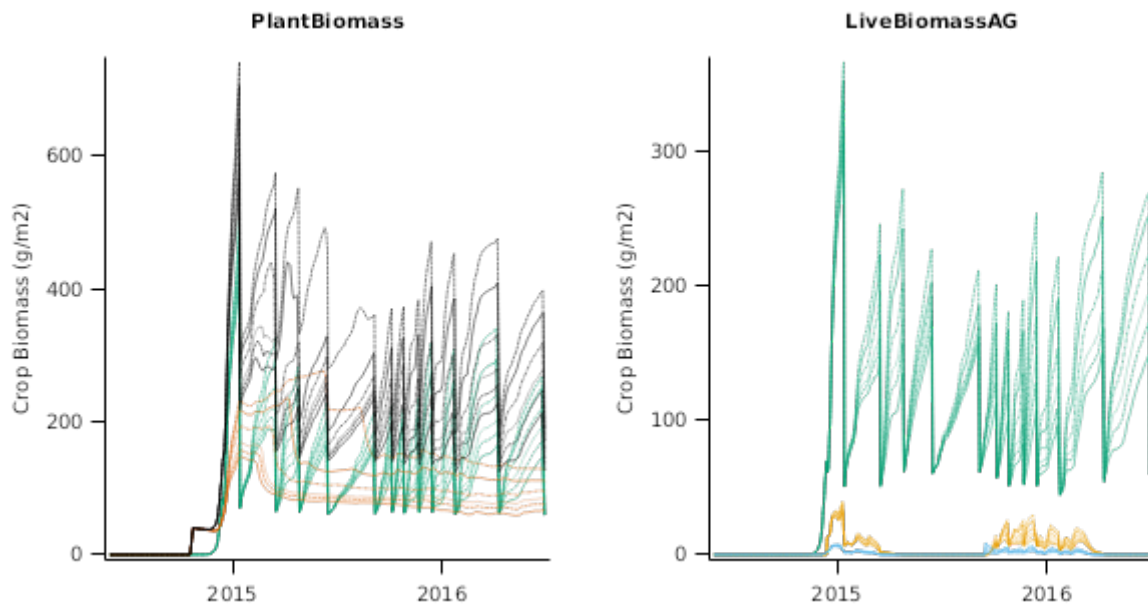
2.1.2.2.1 Nconcentration
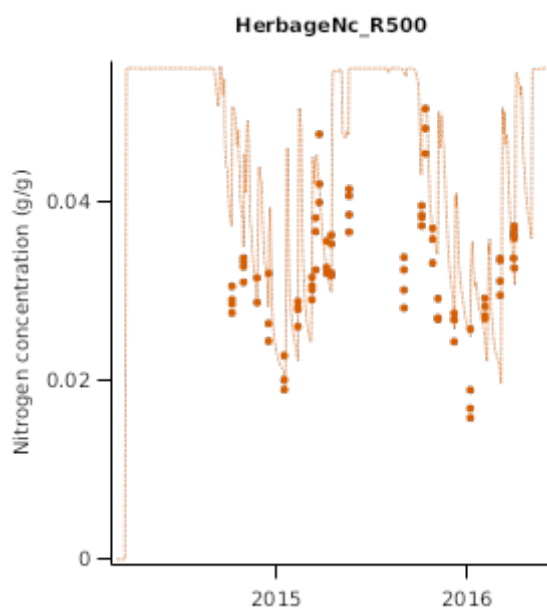
2.1.3 FRNLRuakura

###FRNL Ruakura###

This simulation setup was based on field trials performed at DairyNZ's Scott Farm, in Ruakura, New Zealand, between 2014 and 2016. The experiment was part of the FRNL (Forages for Reduced Nitrogen Leaching) program and the data is basically unpublished (references will be added when this come about). Here only plots with pure plantain are used.
The experiment consisted of six fertiliser treatments (N rates of 0, 50, 100, 200, 350 and 500 kg/ha/yr) in three replicates, and measurements comprised yield and quality indicators (here N content is used).
Observed data supplied by Grant Edwards, Lincoln University.

The soil at the experimental site was a Horotiu silt loam (an Orthic Allophanic soil; USDA: Typic Udivitrand), the parameters required were inferred using data from the New Zealand National Soils Database (Landcare Research).
Weather data was obtained from nearby Ruakura weather station (NIWA).

2.1.3.1 Results

2.1.3.1.1 PlantDM

DeadBiomassAG

LiveBiomassBG

DeadBiomassBG
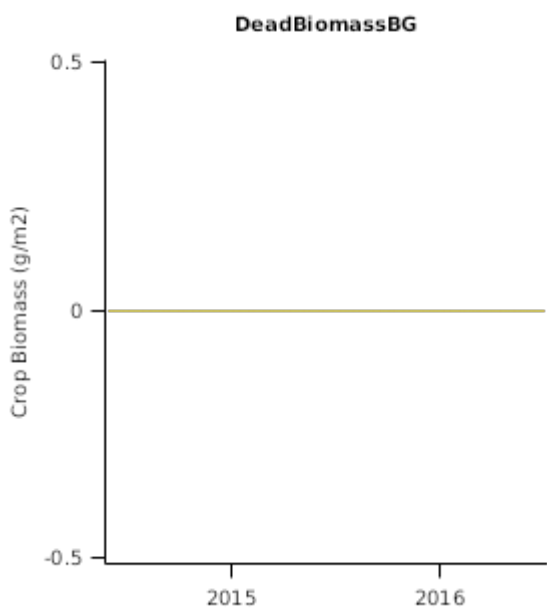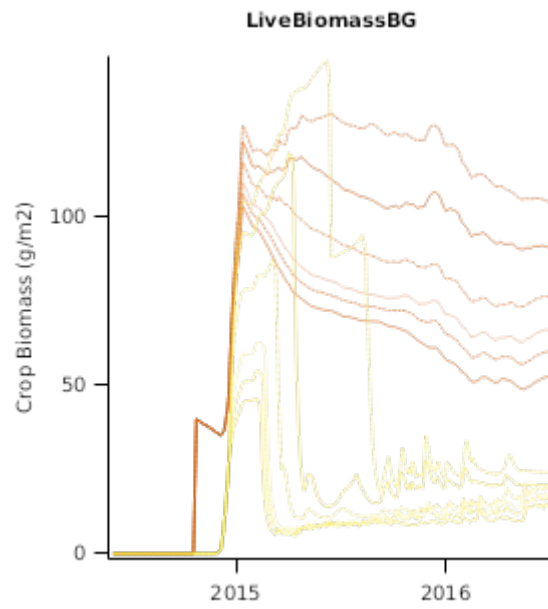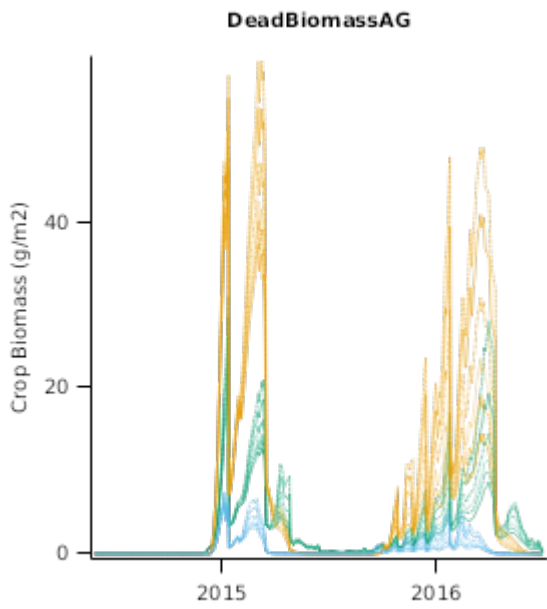
2.1.3.1.2 PlantNc
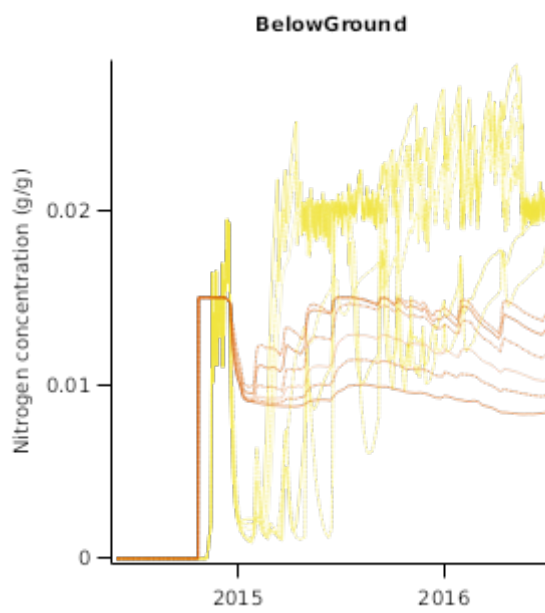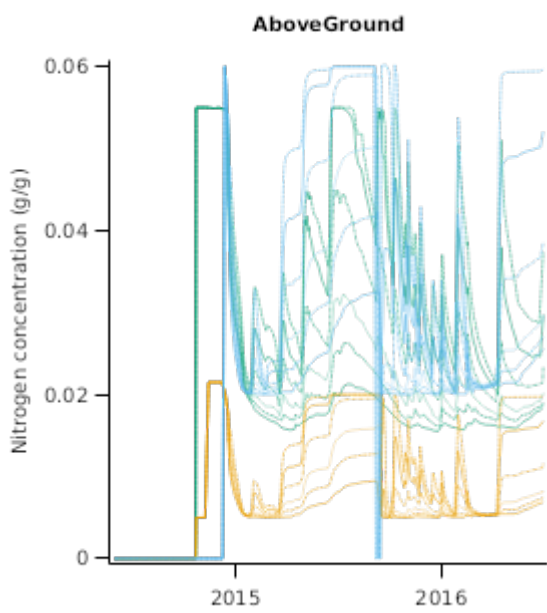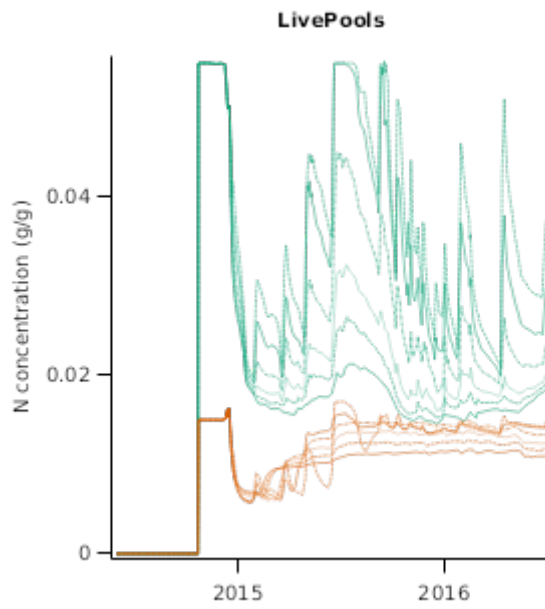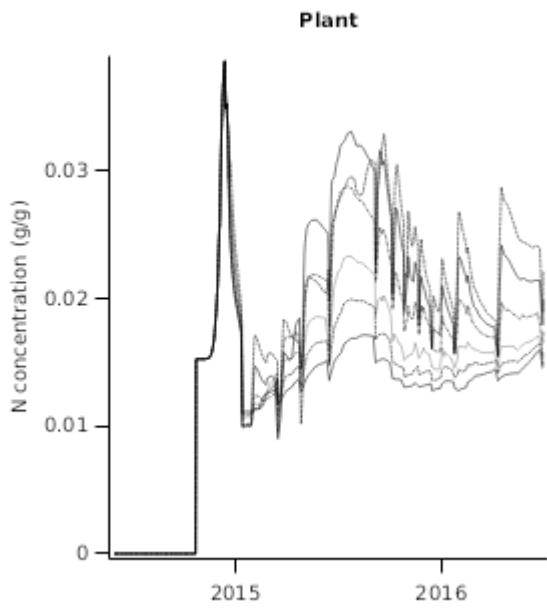
2.1.3.2 ObservedResults

2.1.3.2.1 Nconcentration
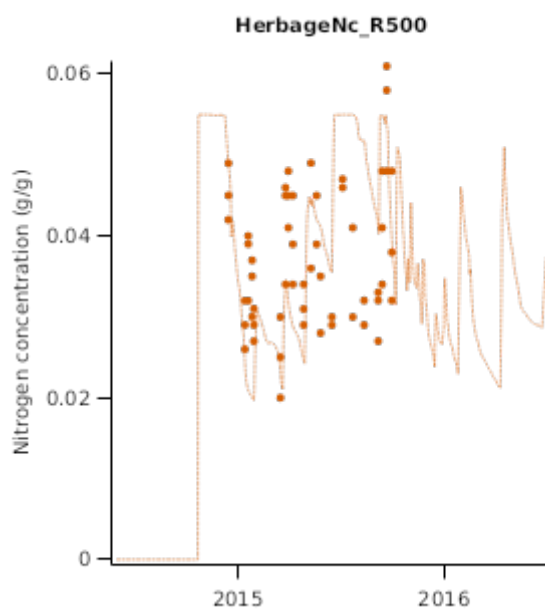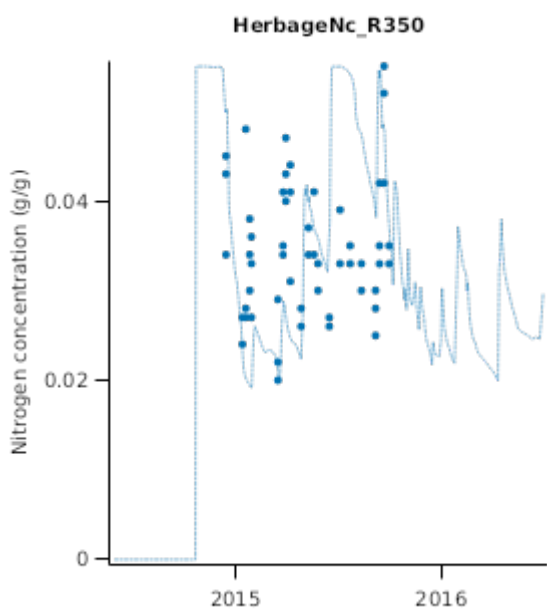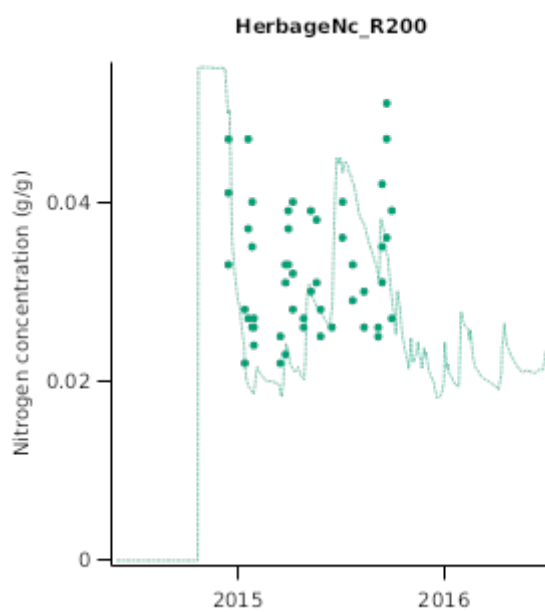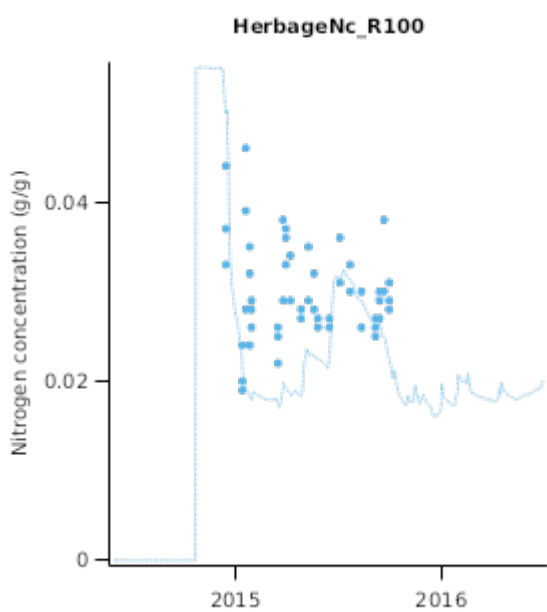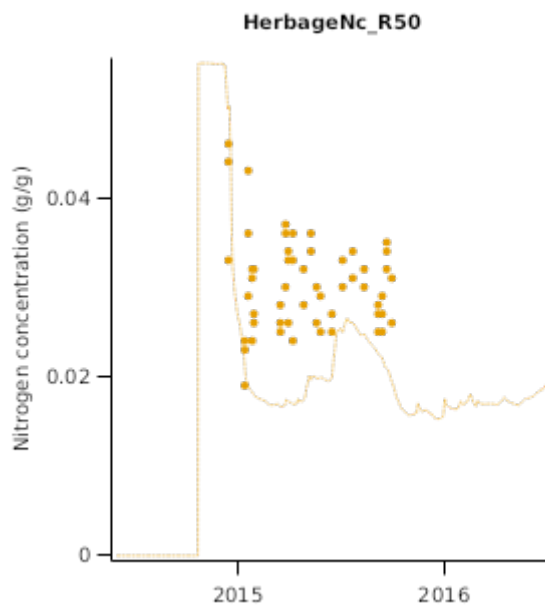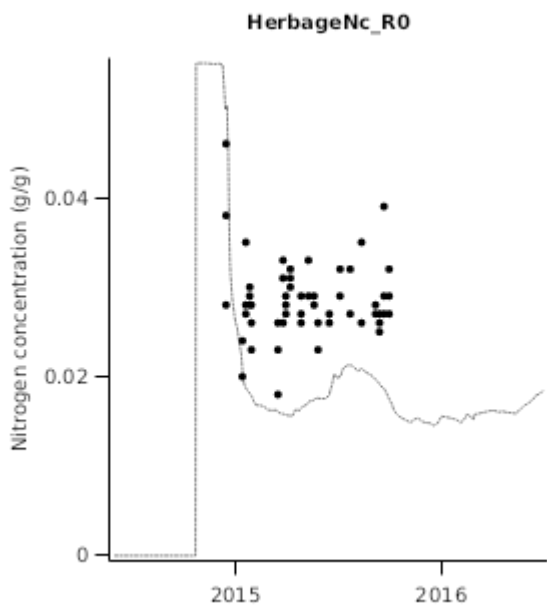
2.2 USA

2.2.1 All data from USA

List of experiments.

Experiment Name	Design (Number of Treatments)
RELARC_01	Cultivar x CutFrequency (4)
RELARC_02	Cultivar (2)

2.2.2 RELARC_01

###RELARC 01###

This simulation was adapted from a defoliation trial conducted in 1998-1999, at Russell E. Larson Agricultural Research Center, Pennsylvania, USA. The trial consisted of small plots where two plantain cultivars ('*Lancelot*' and '*Tonic*') were sown separately in May-1997 (at 11.0 kg seed/ha). Population decreased markedly after the 1998/99 winter and plantain plots were no longer used. Plots were fertilized with 27 kgP and 72 kgK/ha in October 1997. Fertilizer N was applied at 56 kg/ha in June and July of 1998. Treatments were replicated five times and the soil at the site was a Hagerstown silt loam (fine, mixed, semiactive mesic Typic Hapludalfs).
Each plot was divided in two, one-half was harvested every 3 wk and the other half every 5 wk. Each strip was cut to a 7-cm height with a rotary mower. Dates for each cut were given, but only annual and treatment yields are reported; population numbers were provided for few specific dates. Yield for each harvest were arbitrarily inferred, therefore they should be seen as rough indication only.
Met file was built using data obtained from NOAA website. The data set was largely complete except for solar radiation, which was added from an alternative interpolated set for this location, also from NOAA.
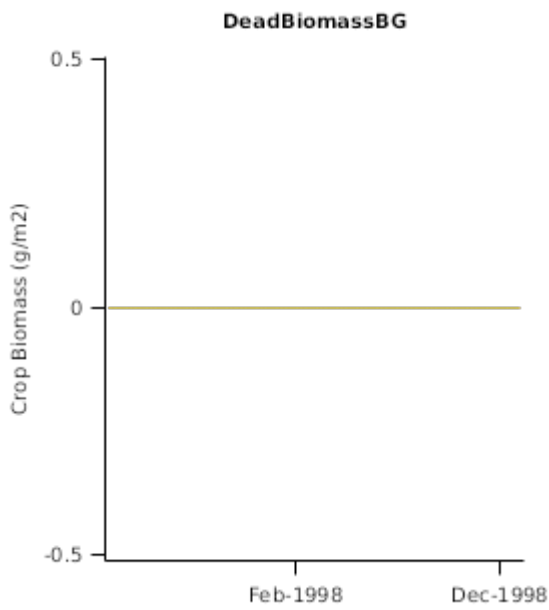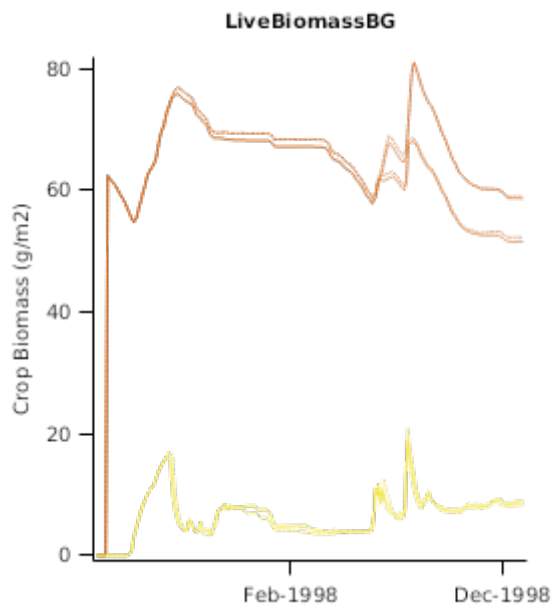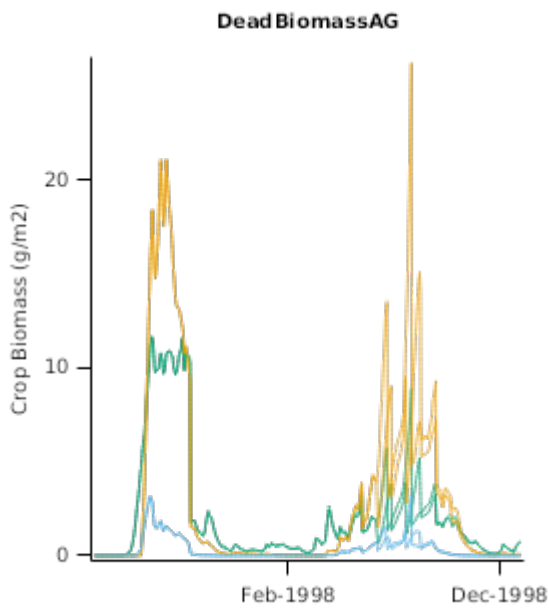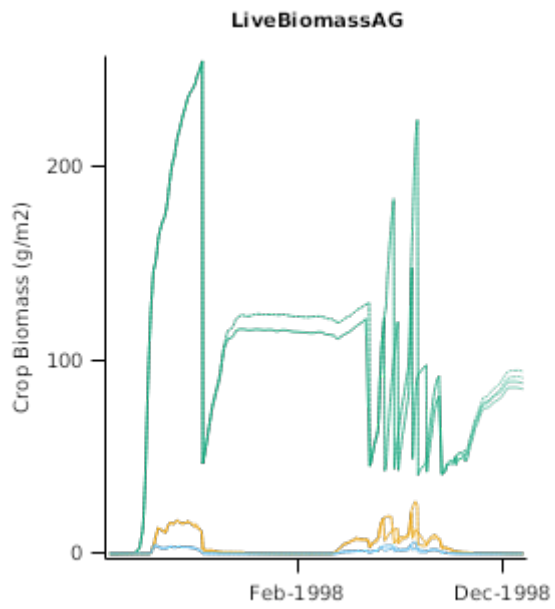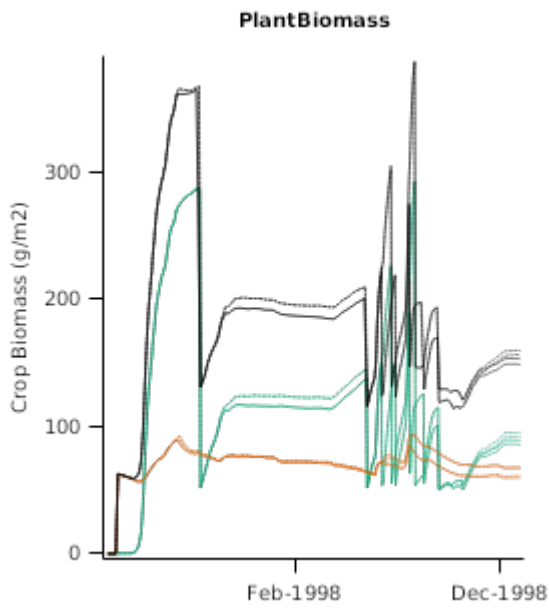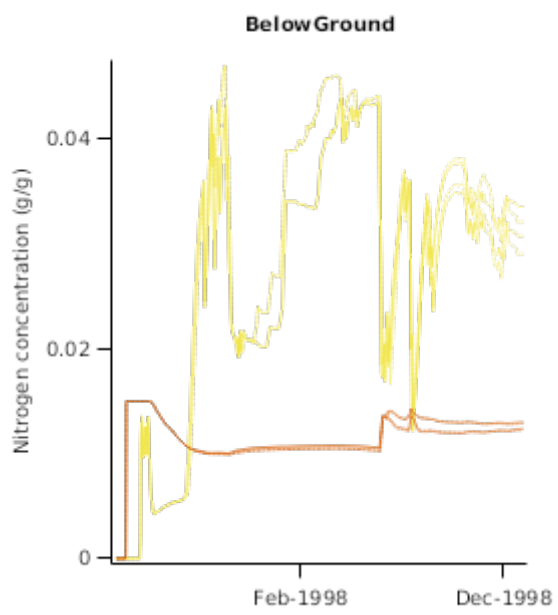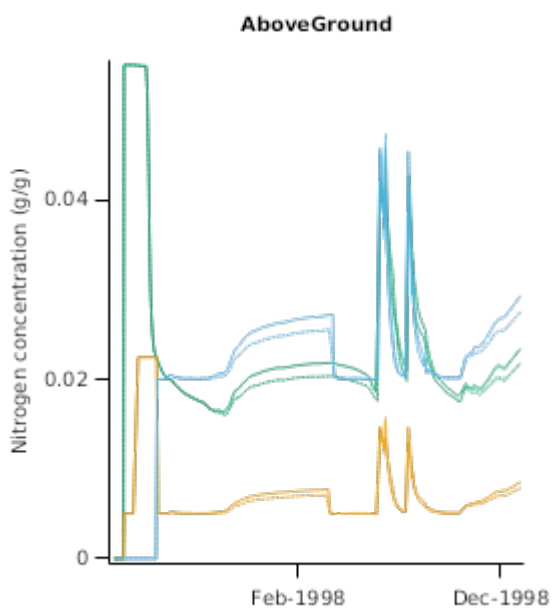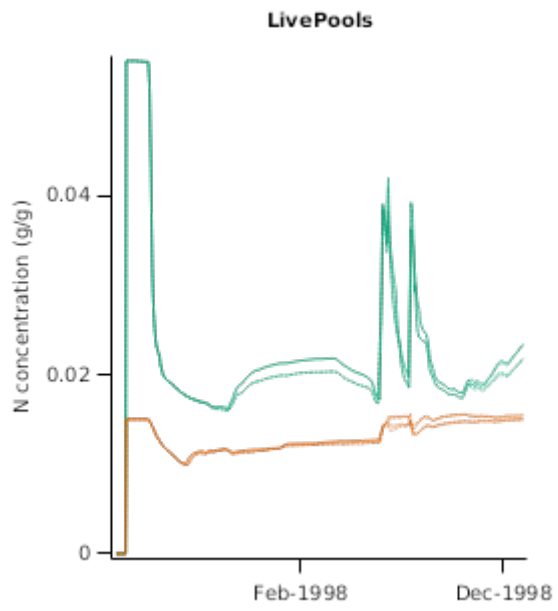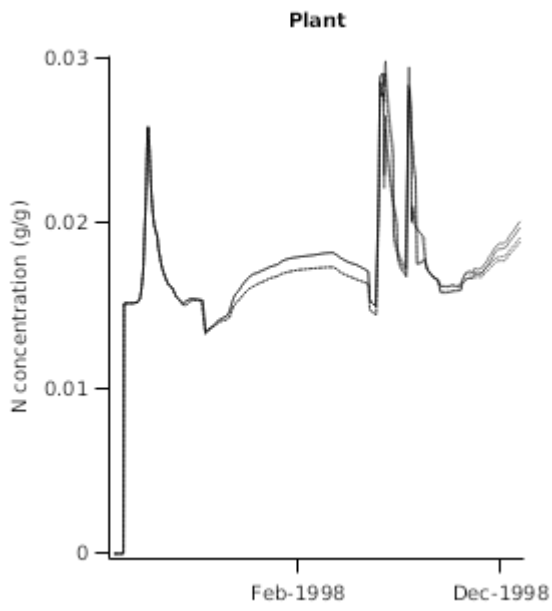Information to assemble the soil data was obtained from USGS.

References:
Sanderson, M.A.; Labreveux, M.; Hall, M.H.; Elwinger, G.F. 2003. Forage yield and persistence of chicory and english plantain. Crop Science, 43: 995-1000.
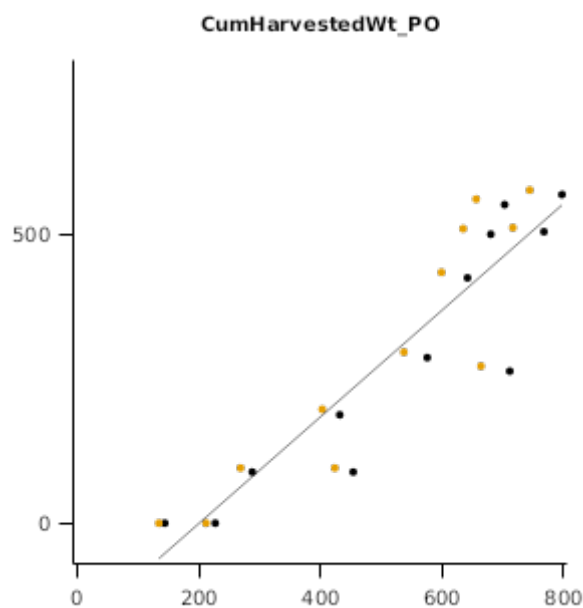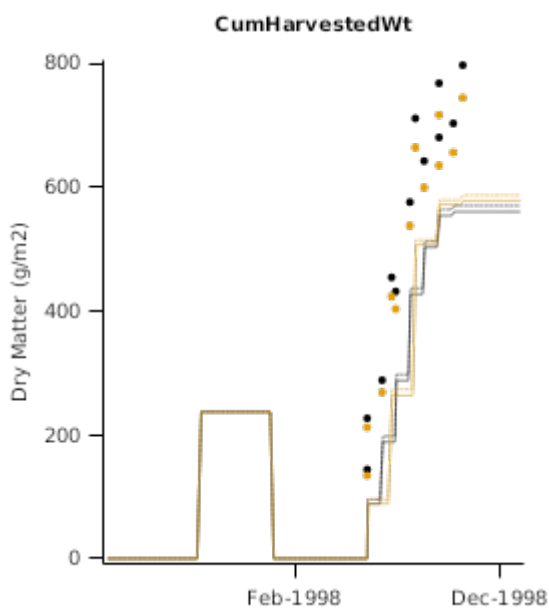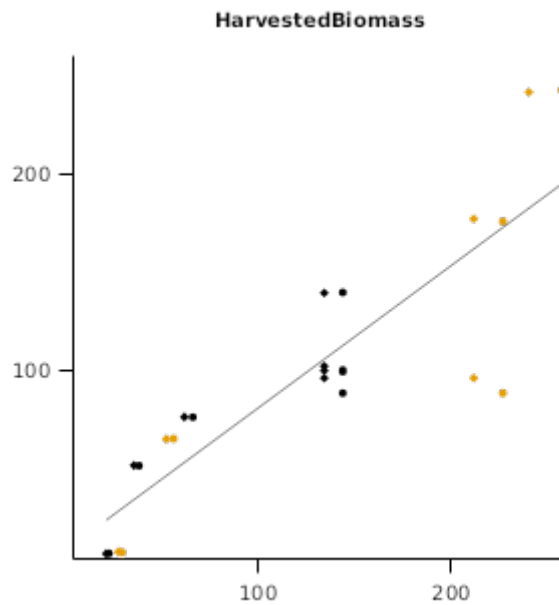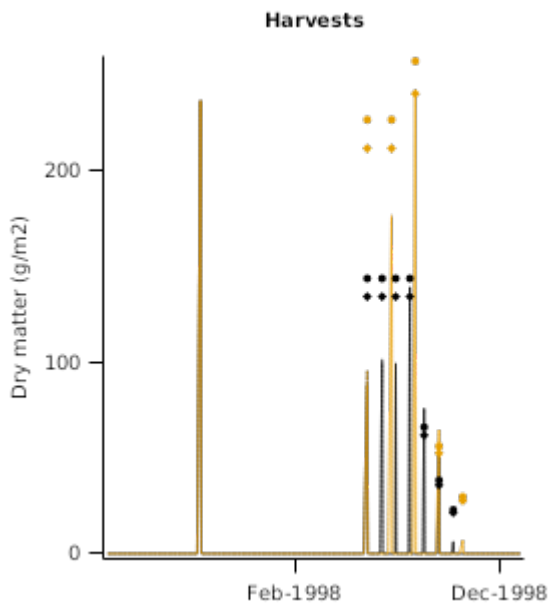
2.2.2.1 Results

2.2.2.1.1 PlantDM

2.2.2.1.2 PlantNc

Plant

LivePools

AboveGround

BelowGround

2.2.2.2 ObservedResults

2.2.3 RELARC_02

###RELARC 02###

This simulation was adapted from a defoliation trial conducted in 2000-2001, at Russell E. Larson Agricultural Research Center, Pennsylvania, USA. The trial was established in small plots, replicated five times, with plantain sown in April-1999 (Cultivars '*Lancelot*' and '*Tonic*'. Only data from the first year is used as the population declined markedly in the second winter. All plots received 4.5 t/ha of limestone and were fertilized with 56 kg N/ha in April, June and July of 2000. The soil at the site was a Hagerstown silt loam (fine, mixed, semiactive mesic Typic Hapludalfs).
Each plot was mechanically mowed to height of 7cm every 4 weeks. Only annual and treatment yields are reported, however population was given for specific dates. Dates for each harvest were reported. From these data, yield was arbitrarily inferred for each harvest, therefore they should be seen as rough approximation only (N variation between cultivars were considered here).
Met file was built using data obtained from NOAA website. The data set was largely complete except for solar radiation, which was added from an alternative interpolated set for this location, also from NOAA.
Information to assemble the soil data was obtained from USGS.

References:
Sanderson, M.A.; Labreveux, M.; Hall, M.H.; Elwinger, G.F. 2003. Forage yield and persistence of chicory and english plantain. Crop Science, 43: 995-1000.

2.2.3.1 ObservedResults

Population

Harvests

HarvestedBiomass

CumHarvestedWt

CumHarvestedWt_PO
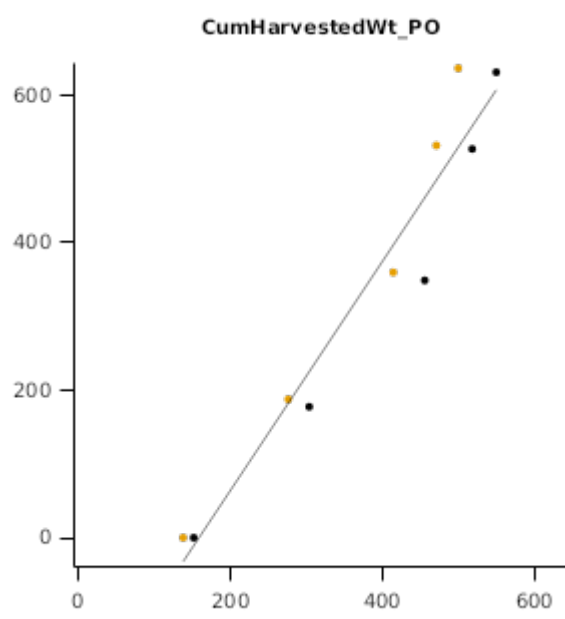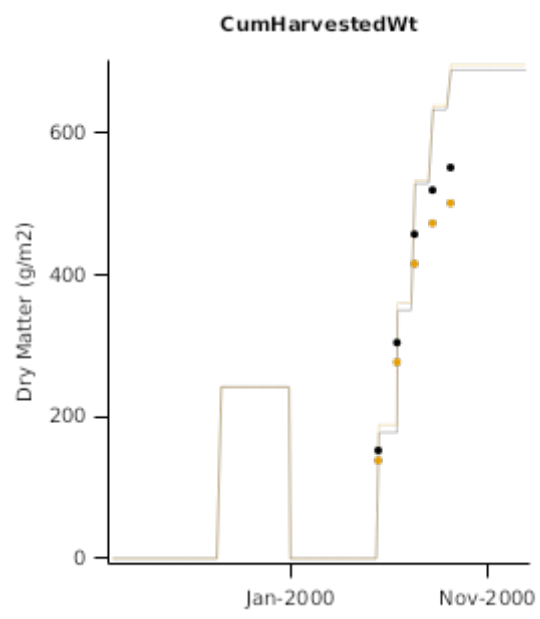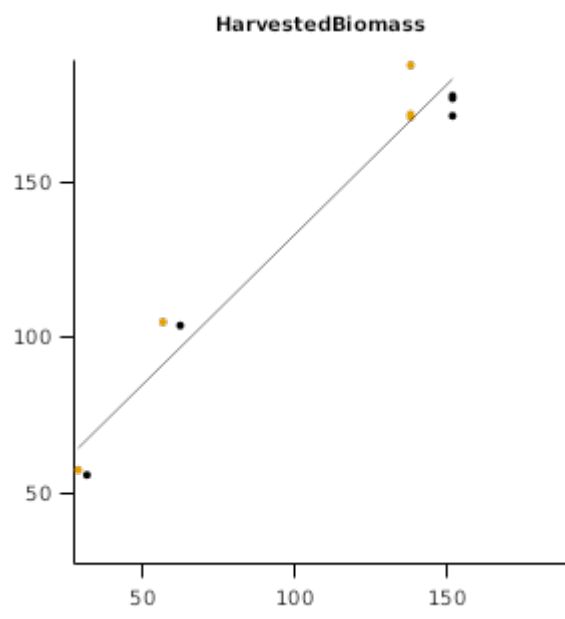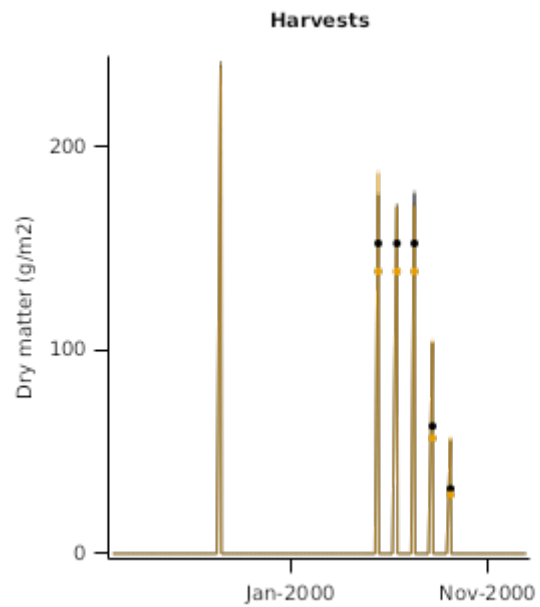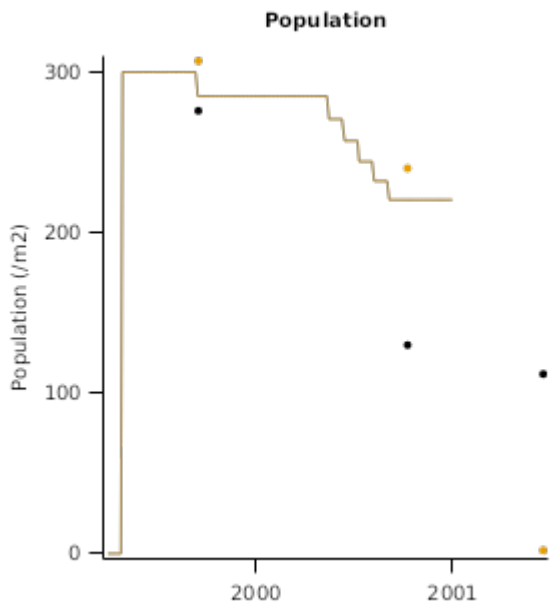
3 References

Ayala, W.; Barrios, E.; Bermudez, R., Serron, N., 2011. Effect of defoliation strategies on the productivity, population and morphology of plantain (Plantago lanceolata). Pasture persistence symposium. Grassland Research and Practice Series 15, 69-72.

Blom, C. W. P. M, 1978. Germination, seedling emergence and establishment of some Plantago species under laboratory and field conditions.. Acta botanica neerlandica 27 (5-6), 257-271.

Brown, Hamish E., Huth, Neil I., Holzworth, Dean P., Teixeira, Edmar I., Zyskowski, Rob F., Hargreaves, John N. G., Moot, Derrick J., 2014. Plant Modelling Framework: Software for building and running crop models on the APSIM platform. Environmental Modelling and Software 62, 385-398.

Calviere, I., Duru, M., 1995. Leaf appearance and senescence patterns of some pasture species. Grass and Forage Science 50 (4), 447-451.

Case, A. L.; Lacey, E. P, Hopkins, G.R., 1996. Parental effects in Plantago lanceolata L. II. Manipulation of grandparental temperature and parental flowering time.. Heredity 76 (3), 287-295.

Cranston, L. M.; Kenyon, P. R.; Morris, S. T.; Lopez-Villalobos, N.; & Kemp, P. D., 2015. Morphological and physiological responses of plantain (Plantago lanceolata) and chicory (Cichorium intybus) to water stress and defoliation frequency. Journal of Agronomy and Crop Science, 1-12.

Douglas, G. B.; Tozer, K. N.; Cameron, C.; Fraser, T. J.; Muir, P. D.; Moss, R. A.; Rennie, G. M.; Knight, T. L., 2013. Successful establishment of oversown chicory and plantain on uncultivatable hill country. Proceeding of the 22nd International Grassland Congress, 523-524.

Elgersma, A; Soegaard, K; Jensen,S.K., 2014. Herbage dry-matter production and forage quality of three legumes and four non-leguminous forbs grown in single-species stands. Grass and Forage Science 69 (4), 705-716.

Fajer, E. D.; Bowers, M. D.; & Bazzaz, F. A., 1991. Performance and allocation patterns of the perennial herb, plantago lanceolata, in response to simulated herbivory and elevated CO2 environments. Oecologia 87 (1), 37-42.

González-Parrado, Z.; Fernández-González, D.; Vega-Maray, A. M.; & Valencia-Barrera, R. M., 2015. Relationship between flowering phenology, pollen production and atmospheric pollen concentration of Plantago lanceolata (L.). Aerobiologia 31 (4), 481-498.

Ishikawa, K.; Onoda, Y., Hikosaka, K., 2007. Intraspecific variation in temperature dependence of gas exchange characteristics among Plantago asiatica ecotypes from different temperature regimes. New Phytologist 176, 356-364.

Jacobs, J. L., G. N. Ward, 2010. Effect of nitrogen application on dry matter yields, nutritive characteristics and mineral content of summer-active forage crops in southern Australia. Animal Production Science 51 (1), 77-86.

Jansma, A. P., 2016. Performance of two plantain cultivars during the first months after establishment., 13.

Jones, C.A., Kiniry, J.R., Dyke, P.T., 1986. CERES-Maize: a simulation model of maize growth and development..

Labreveux, M. E., 2002. Productivity of forage cultivars of chicory and plantain in the Northeast Region of the United States., 112.

Lacey, E. P., D. A. Roach, 2003. Multigenerational effects of flowering and fruiting phenology in Plantago lanceolata. Ecology 84 (9), 2462-2475.

Lee, J. M.; Hemmingson, N. R.; Minnee, E. M. K.; & Clark, C. E. F., 2015. Management strategies for chicory (Cichorium intybus) and plantain (Plantago lanceolata): impact on dry matter yield, nutritive characteristics and plant density. Crop and Pasture Science 66 (2), 168-183.

Levang-Brilz, N., M. E. Biondini, 2002. Growth rate, root development and nutrient uptake of 55 plant species from the Great Plains Grasslands, USA. Plant Ecology 165 (1), 117-114.

Monteith, J. L., Moss, C. J., 1977. Climate and the Efficiency of Crop Production in Britain [and Discussion]. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 281 (980), 277-294.

Moorhead, A.; & Piggot, G., 2009. The performance of pasture mixes containing 'Ceres Tonic'plantain (Plantago lanceolata) in Northland. Proceedings of the New Zealand Grassland Association 71, 195-199.

Nie, Z. N.; Miller, S.; Moore, G. A.; Hackney, B. F.; Boschma, S. P.; Reed, K. F. M.; Mitchell, M.; Albertsen, T. O.; Clark, S.; Craig, A. D.; Kearney, G.; Li, G. D., Dear, B. S., 2008. Field evaluation of perennial grasses and herbs in southern Australia. 2. Persistence, root characteristics and summer activity. Australian Journal of Experimental Agriculture 48 (4), 424-35.

Pankoke, H.; Höpfner, I.; Matuszak, A.; Beyschlag, W.; & Müller, C., 2015. The effects of mineral nitrogen limitation, competition, arbuscular mycorrhiza, and their respective interactions, on morphological and chemical plant traits of Plantago lanceolata. Phytochemistry 118, 149-161.

Poot, P.;, Van Den Broek, T., 1997. A comparison of the vegetative growth of male-sterile and hermaphroditic lines of Plantago lanceolata in relation to N supply. New Phytologist 135 (3), 429-437.

Quijada, S. D. C. N., 2015. Evaluation of herb pastures for New Zealand dairy systems., 237.

Reed, K. F. M.; Nie, Z. N.; Miller, S.; Hackney, B. F.; Boschma, S. P.; Mitchell, M. L.; Albertsen, T. O.; Moore, G. A.; Clark, S. G.; Graig, A. D.; Kearney, G.; Li, G. D.; Dear, B. S., 2008. Field evaluation of perennial grasses and herbs in southern Australia. 1. Establishment and herbage production. Australian Journal of Experimental Agriculture 48 (4), 409-423.

Reyenga, P.J., Howden, S. M., Meinke, H., McKeon, G.M., 1999. Modelling global change impacts on wheat cropping in south-east Queensland, Australia. Environmental Modelling & Software 14, 297-306.

Roberts, H. A., Boddrell,J. E., 1984. Seed survival and seasonal emergence of seedlings of some ruderal plants. Journal of Applied Ecology 21 (2), 617-628.

Rowarth, J. S., 1990. Plantain seed production in a radial trial. Proceedings of the New Zealand Grassland Association 52, 103-106.

Rumball, W.; Keogh, R.G., 1997. Grasslands Lancelot (Plantago lanceolata L.). New Zealand Journal of Agricultural Research 40 (3), 373-377.

Sagar, G. R., Harper, J. L., 1964. Plantago Major L.; P. Media L. and P. Lanceolata L.. Journal of Ecology 52 (1), 189-221.

Sanderson, M.A.; Labreveux, M.; Hall, M.H.; Elwinger, G.F., 2003. Forage yield and persistence of chicory and english plantain. Crop Science 43 (3), 995-1000.

Sanderson, M.A.;Elwinger, G.F., 2000. Seedling development of chicory and plantain. Agronomy Journal 92 (1), 69-74.

Schippers, P., Olff, H., 2000. Biomass partitioning, architecture and turnover of six herbaceous species from habitats with different nutrient supply. Plant Ecology 149 (2), 219-231.

Skinner, R.H, 2005. Cultivar and environmental effects on freezing tolerance of narrow-leaf plantain. Crop Science 45 (6), 2330-2336.

Stewart, A., 1996. Plantain (Plantago lanceolata)-a potential pasture species. Proceedings of the New Zealand Grasslands Association 58, 77-86.

Sussex, I. M., 1956. The causes of flowering. Tuatara 6 (1), 43070.

van den Berge, J.; K. Naudts, de Boeck, H. J.; Ceulemans, R.; Nijs, I., 2014. Do interactions with neighbours modify the above-ground productivity response to drought? A test with two grassland species. Environmental and Experimental Botany 105, 18-24.

van Tiederen, P. H., 1992. Variation in a population of Plantago lanceolata along a topographical gradient. Oikos 64 (3), 560-572.

Wilson, J. B., 1988. A review of evidence on the control of shoot:root ratio, in relation to models. Annals of Botany 61 (4), 433-449.