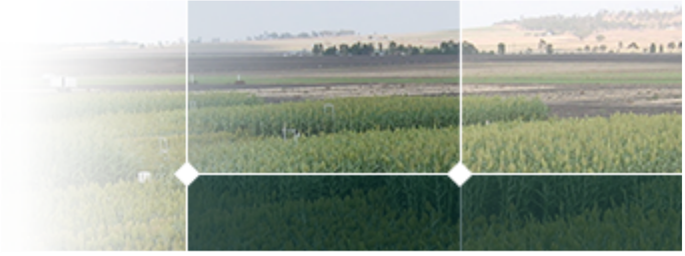

Version 0.0.0.0, built 2018-06-18

1 DataStore

A storage service for reading and writing to/from a SQLITE database.

2 Plantain

A simulation model

The clock model

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

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

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

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

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

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

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

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

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

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

$U_1 = f(Y_t)$,

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

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

$U_4 = f(Y_t - U_3)$.

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

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

The design has been chosen to provide the following benefits:

1) The approach is numerically simple and pure.

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

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

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

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

2.1 Field

A generic system that can have children

2.1.1 Management

This class encapsulates an operations schedule.

This class encapsulates an operations schedule.

The manager model

The manager model

2.1.2 MicroClimate

The module MICROMET, described here, has been developed to allow the calculation of potential transpiration for multiple competing canopies that can be either layered or intermingled.

This model controls the irrigation events, which can be triggered using the Apply() method.

The fertiliser model

Manages access to solutes.

2.1.3 SurfaceOrganicMatter

The surface organic matter model, ported by Ben Jolley from the Fortran version. Tidied up (somewhat) for ApsimX by Eric Zurcher, August 2014.

The soil class encapsulates a soil characterisation and 0 or more soil samples. the methods in this class that return double[] always return using the "Standard layer structure" i.e. the layer structure as defined by the Water child object. method. Mapping will occur to achieve this if necessary. To obtain the "raw", unmapped, values use the child classes e.g. SoilWater, Analysis and Sample.

This class captures data from a soil analysis

A model for capturing water parameters

A soil crop parameterization class.

.NET port of the Fortran SoilWat model Ported by Shaun Verrall Mar 2011 Extended by Eric Zurcher Mar 2012

Computes the soil C and N processes

A model for capturing soil organic matter properties

Represents the simulation initial water status. There are multiple ways of specifying the starting water; 1) by a fraction of a full profile, 2) by depth of wet soil or 3) a single value of plant available water.

The class represents a soil sample.

Calculates the average soil temperature at the centre of each layer, based on the soil temperature model of EPIC (Williams et al 1984) This code was separated from old SoilN - tidied up but not updated (RCichota, sep/2012)

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

List of Plant Model Components.

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

2.1.3.1 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.

2.1.3.2 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.

2.1.3.3 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.

2.1.3.4 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.

2.1.3.5 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.

2.1.3.6 Phenology

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

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

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

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

2.1.3.6.1 Phenological Phases

2.1.3.6.1.1 Germinating Phase

This phase goes from Sowing to Germination.

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.

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

2.1.3.6.1.2 Emerging Phase

This phase goes from Germination to Emergence.

This phase simulates time to emergence as a function of sowing depth. The *ThermalTime Target* from Sowing to Emergence is given by:
 Target = SowingDepth x ShootRate + ShootLag
Where:
 ShootRate = 10 (deg day/mm),
 ShootLag = 15 (deg day),
and *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

2.1.3.6.1.3 Vegetative Phase

This phase goes from Emergence to Flowering.

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

During this phase the 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.

Target = 30 (days)

2.1.3.6.1.4 Reproductive Phase

This phase goes from Flowering to Ripening.

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

During this phase the plant is partitioning biomass to all organs, 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).

Target = 30 (days)

2.1.3.6.1.5 GotoPhase Phase

This phase goes from Ripening to Ripening.

At the end of reproductive phase, plantain phenology is reset to 'Vegetative'.

A special phase that jumps to another phase.

2.1.3.6.2 ThermalTime

The thermal time is calculated from the daily average temperature using three cardinal temperatures: minimum, maximum, and optimum. Crop development acelerates as temperature increases from minimum to optimum and slows down after that, stopping completely when maximum temperature is reached. 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.

2.1.3.7 Photoperiod

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

Twilight = -6 (degrees)

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

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

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

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

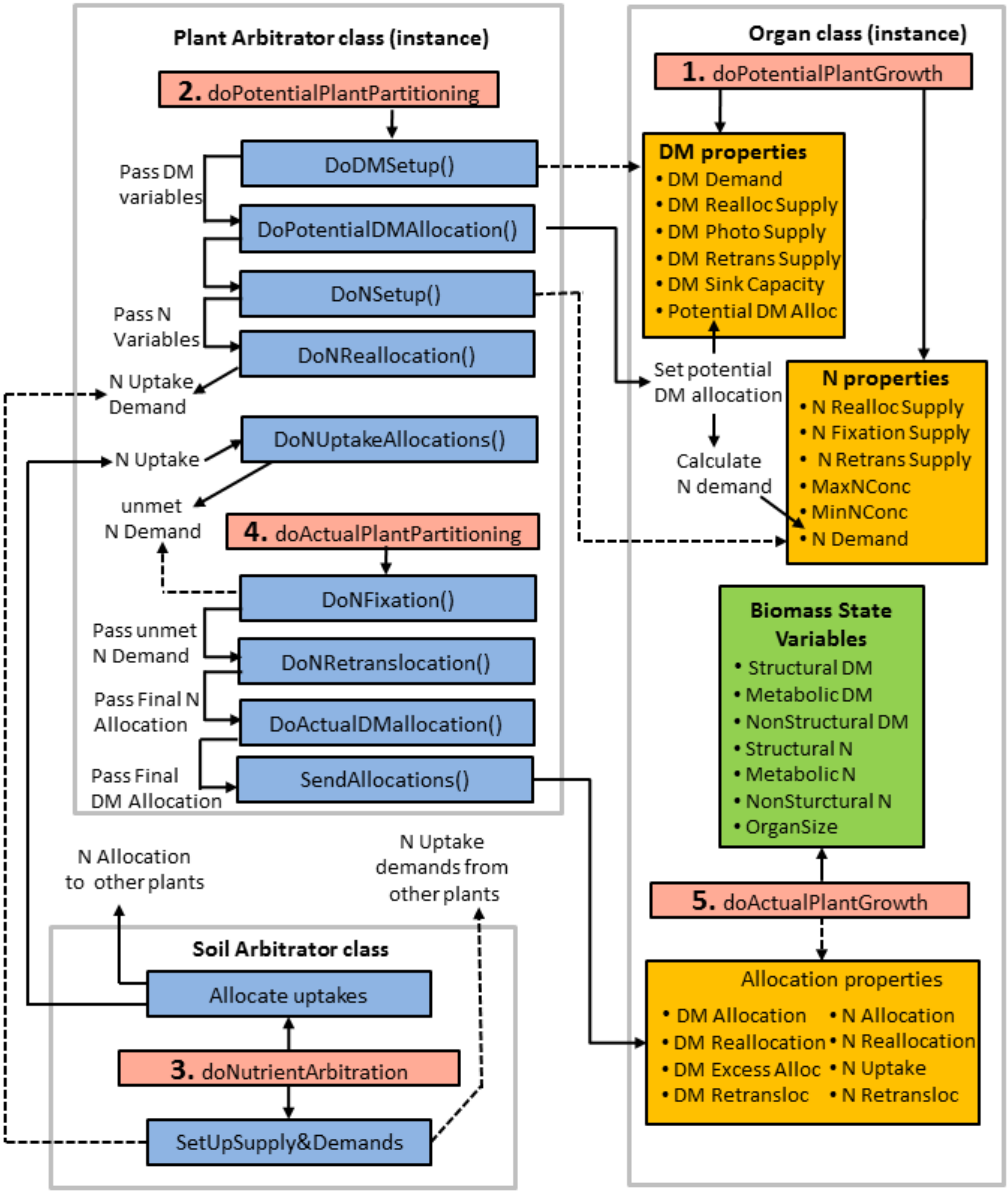
Plant Arbitrator class (instance)
2. doPotentialPlantPartitioning
DoDMSetup()
Pass DM variables
DoPotentialDMAllocation()
DoNSetup()
Pass N Variables
DoNReallocation()
N Uptake Demand
DoNUptakeAllocations()
N Uptake
unmet N Demand
4. doActualPlantPartitioning
DoNFixation()
Pass unmet N Demand
DoNRetranslocation()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

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

2.1.3.7.1 NArbitrator

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

Relative allocation rules used to determine partitioning

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

2.1.3.7.2 DMArbitrator

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

Relative allocation rules used to determine partitioning

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

2.1.3.8 Root

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

Root Growth

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

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

Dry Matter Demands

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

Nitrogen Demands

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

Nitrogen Uptake

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

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

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

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

Water Uptake

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

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

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

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

2.1.3.8.1 InitialDM

InitialDM = InitialRootWt x [Plant].Population

Where:

InitialRootWt = 0.001 (g/plant)

2.1.3.8.2 StructuralFraction

StructuralFraction = 1 (g/g)

2.1.3.8.3 MinimumNConc

MinimumNConc = 0.005 (gN/gDM)

2.1.3.8.4 MaximumNConc

MaximumNConc = 0.015 (gN/gDM)

2.1.3.8.5 NitrogenDemandSwitch

A value of 1 is returned if phenology is between Germination and Ripening phases, otherwise a value of 0 is returned.

2.1.3.8.6 MaximumRootDepth

MaximumRootDepth = 1000 (mm)

2.1.3.8.7 RootFrontVelocity

2.1.3.8.7.1 PreEmergence

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

ReferenceVelocity = 5 (mm/day)

2.1.3.8.7.2 Vegetative

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

ReferenceVelocity = 10 (mm/day)

2.1.3.8.7.3 Reproductive

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

ReferenceVelocity = 7.5 (mm/day)

RootFrontVelocity has a value of zero for phases not specified above

2.1.3.8.8 TemperatureEffect

TemperatureEffect = 1

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

2.1.3.8.9 SoilWaterEffect

SoilWaterEffect = 1

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

2.1.3.8.10 SpecificRootLength

SpecificRootLength = 100 (m/g)

2.1.3.8.11 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

Where:

ReferenceRate = 0.005 (/day)

2.1.3.8.11.1 SoilMoistureFactor

SoilAerationFactor = 1

2.1.3.8.12 DMRetranslocationFactor

DMRetranslocationFactor = 0 (/day)

2.1.3.8.13 NRetranslocationFactor

NRetranslocationFactor = 0 (/day)

2.1.3.8.14 NReallocationFactor

NReallocationFactor = 0 (/day)

2.1.3.8.15 KLModifier

No adjustment of KL are considered for plantain at this stage. More analyses, preferebly with support from data specific to this issue, are needed to improve the description of this relationship.

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

2.1.3.8.16 MaxDailyNUptake

MaxDailyNUptake = 10 (kgN/ha)

2.1.3.8.17 BiomassRemovalDefaults

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

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

2.1.3.9 DMDemandFunction

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

2.1.3.9.1 PartitionFraction

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.

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

RootFraction = Numerator / Denominator

Where:

Numerator = [ShootRootRatio] x [TaprootRootRatio]

Denominator = SRs x TRs

Where:

SRs = TargetSRs + [ShootRootRatio]

Where:

TargetSRs = [TargetShootRootRatio] x [TargetShootRootRatio]

TRs = TargetTRs + [TaprootRootRatio]

Where:

TargetTRs = [TargetTaprootRootRatio] x [TargetTaprootRootRatio]

PartitionFraction has a value of zero for phases not specified above

2.1.3.9.1 DMConversionEfficiency

DMConversionEfficiency = 1

2.1.3.9.2 MaintenanceRespirationFunction

MaintenanceRespirationFunction = 1

2.1.3.9.3 RemobilisationCost

RemobilisationCost = 0

2.1.3.9.4 CarbonConcentration

CarbonConcentration = 0.4

2.1.3.10 AboveGround Biomass

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

AboveGround is a composite of the following biomass objects:

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

2.1.3.11 AboveGroundLive Biomass

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

AboveGroundLive is a composite of the following biomass objects:

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

- [Inflorescence].Live

2.1.3.12 BelowGround Biomass

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

BelowGround is a composite of the following biomass objects:

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

2.1.3.13 BelowGroundLive Biomass

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

BelowGroundLive is a composite of the following biomass objects:

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

2.1.3.14 Total Biomass

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

Total is a composite of the following biomass objects:

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

2.1.3.15 PerPlantBelowGroundWt

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

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

2.1.3.16 ShootRootRatio

2.1.3.16.1 AllPhases

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

2.1.3.16.1.1 CurrentSR

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

ShootRootRatio has a value of zero for phases not specified above

2.1.3.17 TargetShootRootRatio

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.

2.1.3.17.1 Vegetative

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

TargetSR = 1.75 (g/g)

2.1.3.17.2 Reproductive

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

2.1.3.17.2.1 TargetSR

TargetSR = [TargetShootRootRatio].Vegetative.TargetSR + PlusTarget

Where:

PlusTarget = DeltaTarget x PhotoperiodEffect

Where:

DeltaTarget = MaxTargetSR - [TargetShootRootRatio].Vegetative.TargetSR

Where:

MaxTargetSR = 2 (g/g)

TargetShootRootRatio has a value of zero for phases not specified above

2.1.3.18 StemsLeafRatio

2.1.3.18.1 Reproductive

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

2.1.3.18.1.1 CurrentSL

CurrentSL = StemFlowerDM / [Leaf].Live.Wt

Where:

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

StemsLeafRatio has a value of zero for phases not specified above

2.1.3.19 TargetStemsLeafRatio

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).

2.1.3.19.1 Reproductive

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

2.1.3.19.1.1 TargetSL

TargetSL = MaximumSL x PhotoperiodEffect

Where:

MaximumSL = 0.25 (g/g)

TargetStemsLeafRatio has a value of zero for phases not specified above

2.1.3.20 FlowerStemRatio

2.1.3.20.1 Reproductive

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

2.1.3.20.1.1 CurrentFS

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

FlowerStemRatio has a value of zero for phases not specified above

2.1.3.21 TargetFlowerStemRatio

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).

2.1.3.21.1 Reproductive

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

2.1.3.21.1.1 TargetFS

TargetFS = MaximumFS x PhotoperiodEffect

Where:

MaximumFS = 0.25 (g/g)

TargetFlowerStemRatio has a value of zero for phases not specified above

2.1.3.22 TaprootRootRatio

2.1.3.22.1 AllPhases

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

2.1.3.22.1.1 CurrentTR

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

TaprootRootRatio has a value of zero for phases not specified above

2.1.3.23 TargetTaprootRootRatio

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.

2.1.3.23.1 AllPhases

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

2.1.3.23.1.1 TargetTR

TargetTR = MaximumTR x BiomassFactor

Where:

MaximumTR = 1 (g/g)

TargetTaprootRootRatio has a value of zero for phases not specified above

2.1.3.24 Cultivars

Lancelot, Tonic

2.1.3.25 Tonic

Cultivar class for holding cultivar overrides.

Tonic is the basic forage plantain cultivar. It was develop later than *Lancelot* and was developed from a northern Portugal germplasm. It has very erect and large leaves, produce less tillers than *Lancelot* and perhaps less seed heads. *Tonic* cultivar is heat tolerante and also witnter active, typically with higher yields when compared to *Lancelot*.

2.1.3.26 Lancelot

Cultivar class for holding cultivar overrides.

Lancelot is the first forage plantain cultivar released, it was selected from New Zealand pastures. It has a semi-erect growth habit, medium to large leaves, and produce many tillers. This cultivar has good heat tolerance but growth is low over winter. *Lancelot* has been used for many years as grazing forage, in monoculture or in mixed swards, in several countries worldwide. However, currently the most common cultivar is *Tonic*.

A report class for writing output to the data store.

Biomass

PlantParts

Harvests

Water

3 References

Adiku, S. G. K., Carberry, P. S., Rose, C. W., McCown, R. L., Braddock, R., 1995. A maize (zea-mays) - cowpea (vigna-unguiculata) intercrop model. Ecophysiology of Tropical Intercropping, Inst Natl Recherche Agronomique, Paris, 397-406.

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.

Carberry, P.S., McCown, R. L., Muchow, R. C., Dimes, J. P., Probert, M. E., 1996. Simulation of a legume ley farming system in northern Australia using the Agricultural Production Systems Simulator. Australian Journal of Experimental Agriculture 36 (8), 1037-1048.

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.

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.

Huth, N.I., Bristow, K.L., Verburg, K., 2012. SWIM3: Model use, calibration, and validation. Transactions of the ASABE 55 (4), 1303-1313.

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.

Keating, B. A., Carberry, P. S., 1993. Resource capture and use in inter cropping - solar radiation. Field Crops Research 34 (3-4), 273-301.

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.

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.

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.

Richards, Lorenzo Adolph, 1931. Capillary conduction of liquids through porous mediums. Journal of Applied Physics 1 (5), 318-333.

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.

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.

Snow, V. O., Huth, N. I., 2004. The APSIM MICROMET Module. HortResearch Internal Report, HortResearch, Auckland.

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.

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.