



1 The APSIM Sorghum Model

1.1 The APSIM NextGen Sorghum Model – Structure and Function

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The APSIM-sorghum model is based on a framework of the physiological determinants of crop growth and development [Charles-Edwards, 1982](#), is focused at organ scale, and has been detailed in [Hammer et al., 2010](#) and [Hammer et al., 2019](#). It generates the phenotype of a crop as a consequence of underlying physiological processes (Fig. 1) by using the concept of supply and demand balances for light, carbon, water, and nitrogen [Hammer et al., 2001](#). The approach is focused around quantifying capture and use of radiation, water, and nitrogen within a framework that predicts the dynamics of crop development and the realized growth of major organs based on their potential growth and whether the supply of carbohydrate and nitrogen can satisfy this potential. Demand for resources is defined by potential organ growth and potential supply by resource capture ([Monteith et al., 1977](#); [Passioura, 1983](#); [Monteith et al., 1986](#)) (Figure. 1). Arbitration rules and organ level responses are invoked when resource capture cannot satisfy demand. The APSIM-sorghum model retains some features and concepts of earlier models: [Sinclair, 1986](#); [Rosenthal, 1989](#); [Birch et al., 1990](#); [Sinclair et al., 1992](#); [Chapman et al., 1993](#); [Hammer et al., 1994](#), but has been adapted and redesigned to generate a more explanatory approach to the modelling of the underlying physiology [Hammer et al., 2006](#).

APSIM-sorghum operates via the dynamic interaction of crop development, crop growth, and crop nitrogen with soil and weather attributes (Fig. 1). Predictive schemas can be separated into crop growth and development dynamics (Fig. 1a) and crop nitrogen dynamics (Fig. 1b) for purposes of description, but the interactions between these major components are critical.

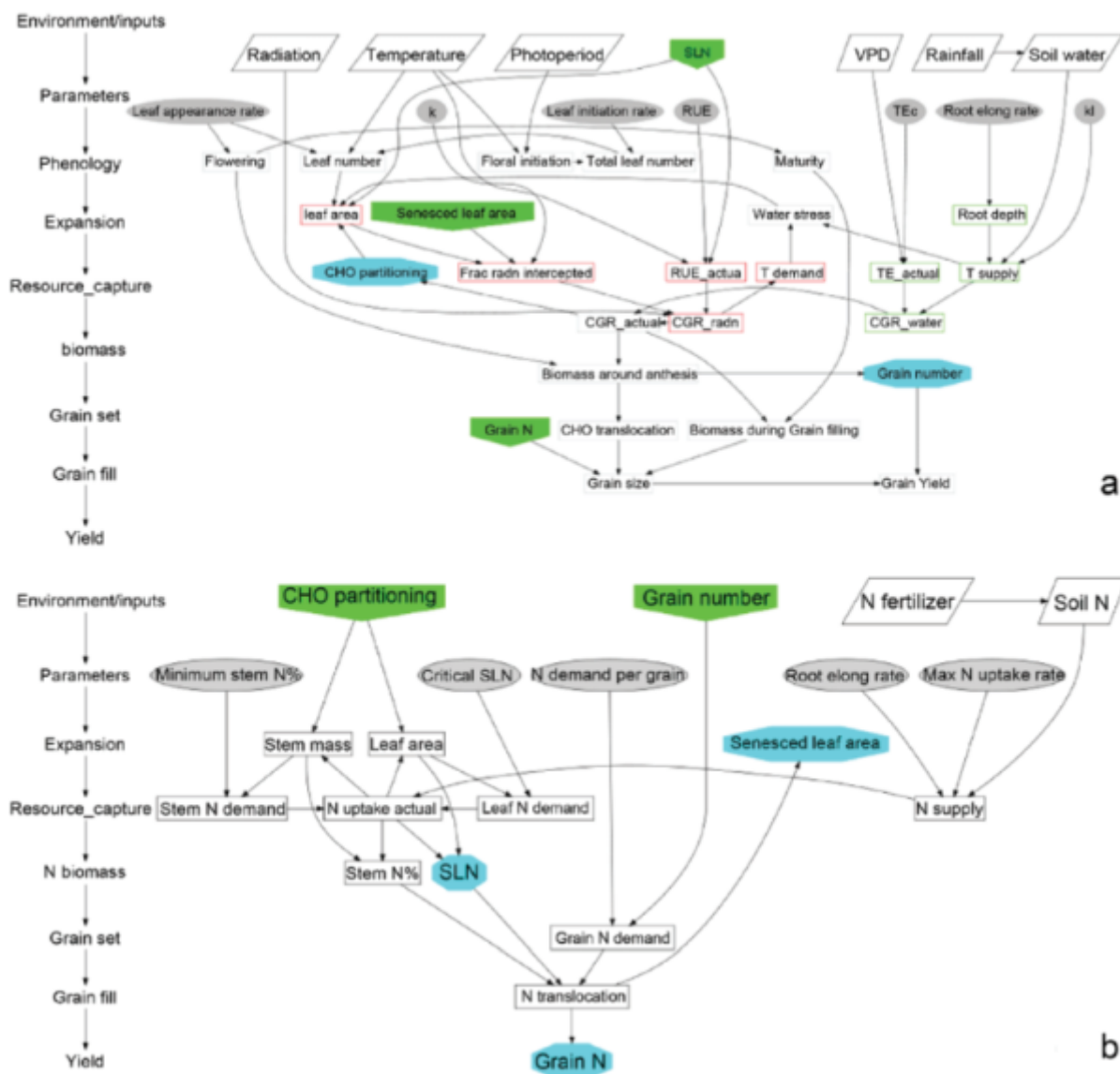


Figure 1: Schematic representation of crop growth and development dynamics (a) and crop nitrogen dynamics (b) in Agricultural Production System simulator (APSIM)-sorghum model. Connection points between the two schematics are shown by the shaded boxes.

Image Reference: [Hammer et al., 2010](#)

1.2 Crop Growth and Development Dynamics

Phenology is simulated through a number of development stages by using a thermal time approach [Muchow et al., 1990](#); [Hammer et al., 1994](#), with the temperature response characterized by a base (T_b), optimum (T_{opt}), and maximum (T_m) temperature. [Hammer et al., 1993](#) and [Carberry et al., 1993](#) reported values of T_b , T_{opt} , and T_m for sorghum of 11, 32, and 42°C, respectively. The thermal time target for the phase between emergence and panicle initiation is also a function of day length ([Hammer et al., 1989](#); [Ravi Kumar et al., 2009](#)), and its duration, when divided by the plastochron (°C per leaf), determines total leaf number once an allowance for leaf initials in the embryo has been included. Total leaf number multiplied by the phyllochron (°C per leaf) determines the thermal time to reach flag leaf stage, which is thus an emergent property of the model. Timing of the stages anthesis, and start and end of grain filling are also simulated through thermal time targets ([Muchow et al., 1990](#); [Hammer et al., 1994](#); [Ravi Kumar et al., 2009](#)). Drought stress and N stress can both reduce the leaf appearance rate and hence delay phenology during the vegetative stages ([Craufurd et al., 1993](#); [van Oosterom et al., 2010](#)).

Canopy development is simulated on a whole plant basis given the fertile tiller number and leaf size-leaf number distribution ([Carberry et al., 1993](#); [van Oosterom et al., 2001](#)). Expected fertile tiller number can be input or predicted using a dynamic tillering prediction routine. The total plant leaf area at any time is calculated as the sum of main culm and tiller leaf area. Main culm leaf area is determined from the number of fully expanded leaves on the main culm and their size, plus an adjustment for the area of expanding leaves in the whorl ([Hammer et al., 1993](#)). The area of leaves on tillers is determined from the number of fertile tillers and the size of their leaves, which is determined via the allometric association of leaf size distribution on each tiller with that on the main culm. The dynamic tillering routine predicts the total number of tillers produced from a relationship combining the genetic propensity to tiller (input) with availability of surplus assimilate at the time of tiller outgrowth early in crop development ([Alam et al., 2014](#)). Plant assimilate status is estimated

from the balance between radiation-driven supply and main culm leaf expansion-driven demand. Hence, tillering is favoured in high radiation-low temperature conditions as found by [Kim et al., 2010](#). The number of tillers surviving to produce grain is then dependent on internal plant competition for available assimilate, which will be influenced by the rate of leaf expansion for the entire plant and the plant density. The trajectory of specific leaf area (SLA $\text{cm}^2 \text{g}^{-1}$) is a good indicator of extent of internal plant competition and is used to drive tiller outgrowth cessation until a balance is reached ([LAFARGE et al., 2002](#)). It is also used to reduce potential leaf size on the main culm in situations of reduced assimilate availability per plant (eg under high density) where SLA will reach boundary conditions.

The number of fully expanded leaves at any time is the product of thermal time elapsed since emergence and the leaf appearance rate (phyllochron). This enables calculation of leaf area per plant at any time as outlined above. Actual crop leaf area is the product of plant density and leaf area per plant. Green leaf area index (LAI) is the difference between the total plant leaf area and the senesced leaf area. Under drought stress, the crop will initially cease expanding new leaves, thus reducing transpiration demand, and then commence senescing leaves until demand for transpiration no longer exceeds supply from uptake ([Hammer et al., 2001](#)).

Aboveground biomass accumulation is simulated as the minimum of light-limited or water-limited growth. In the absence of water limitation, biomass accumulation is the product of the amount of intercepted radiation (IR) and its conversion efficiency, the radiation use efficiency (RUE). The fraction of incident radiation intercepted is a function of the LAI and the canopy extinction coefficient (k), which is a measure of canopy structure ([LAFARGE et al., 2002](#)). The effects of N supply on crop growth are implicitly incorporated in this approach. Nitrogen limitation will reduce leaf area growth and hence LAI and IR. It can also reduce RUE, which is a function of the N status of the leaves ([Muchow et al., 1994](#); [Sinclair et al., 1992](#)). [Sinclair and Muchow Sinclair et al., 1999](#) reviewed studies that had measured RUE in many crops and noted a consistent value of 1.25 g MJ^{-1} for triple-dwarf sorghum under optimum growing conditions. The flexibility of the object-oriented template also allows simulation of crop biomass accumulation via diurnal canopy photosynthesis models where this is required, as in the studies of [Sinclair et al., 2005](#), [Hammer et al., 2009](#), and [Wu et al., 2019](#).

Under water limitation, aboveground biomass accumulation is the product of realized transpiration and its conversion efficiency, biomass produced per unit of water transpired, or transpiration efficiency (TE). It is necessary to adjust TE to allow for the prevailing vapor pressure deficit (vpd) ([Tanner et al., 1983](#); [Kemanian et al., 2005](#)). Numerous studies in sorghum ([Tanner et al., 1983](#); [Hammer et al., 1997](#)) have found a standard value of 9 Pa for the TE coefficient in sorghum, so that at a vpd of 2 kPa a TE of $4.5 \text{ gm}^{-2} \text{ mm}^{-1}$ results. The water supply accessible to the plant depends on the effective rooting depth and the rate at which soil water can be extracted from the soil by the roots. The potential extraction rate is related to the soil water content via an exponential function, parameterized via an extraction decay constant (k_l) that incorporates effects of both soil hydraulic conductivity and root length density on water uptake ([Passioura, 1983](#); [Monteith et al., 1986](#); [Robertson et al., 1993](#); [Hammer et al., 2001](#)). Water extraction occurs from multiple layers, and the total extraction is the sum of that calculated for individual layers. As RUE and TE are based on aboveground biomass only, root mass is not explicitly modelled, but is added to the aboveground biomass accumulation according to a root/shoot ratio that declines with successive growth stages of the crop.

Daily aboveground biomass accumulation is partitioned to plant parts in allometric ratios that depend on the growth stage of the crop via functions that have been found to describe these ratios well ([Jones et al., 1986](#)). Before the flag leaf stage, new biomass is allocated to stem and leaves. Leaves are partitioned a fraction that decreases with increasing node number up to a maximum absolute allocation to leaf that is set by the ratio of the new leaf area to be grown (described above) and a minimum specific leaf area ($\text{cm}^2 \text{g}^{-1}$). The remaining biomass is partitioned to stem and rachis. The stem fraction incorporates leaf sheaths, but a distinct allocation to rachis commences after panicle initiation. Between flag leaf and anthesis, accumulated biomass is allocated to the stem and rachis in a fixed ratio.

Grain yield is simulated as the product of grain number and grain size. Maximum grain number is a function of the change in plant biomass between panicle initiation and start grain filling ([Rosenthal, 1989](#)), while grain size is determined by grain growth rate, effective grain filling period, and redistribution of assimilates postanthesis ([Heiniger et al., 1997](#)). If grain mass demand for a day exceeds the daily increase in biomass, the shortfall will first be met through translocation from stem and, if that is insufficient to meet demand of the grain, through translocation from leaves, accelerating their senescence. Conversely, if the daily increase in biomass exceeds the grain mass demand, the excess biomass production is allocated to the stem.

1.3 Crop Nitrogen Dynamics

Crop N dynamics are modelled based on a physiological approach that accounts for the fact that the bulk of reduced N present in leaves is associated with photosynthesis structures and enzymes ([GRINDLAY, 1997](#)) (Fig. 1b). The rate of light-saturated net photosynthesis has been shown to be a linear function of the amount of leaf N per unit leaf area (specific leaf nitrogen [SLN]), until a species-specific maximum rate of photosynthesis has been reached ([Sinclair et al., 1989](#); [Anten et al., 1995](#); [GRINDLAY, 1997](#)). Expressing crop N demand relative to canopy expansion thus provides a physiological link between crop N status, light interception, and dry matter accumulation. In addition, the cardinal SLN values for new leaf growth and for leaf death in response to N deficiency are independent of growth stage ([van Oosterom et al., 2010](#)).

During the preanthesis period, only stems (including rachis) and leaves are expanding, and their N demand is met in a hierarchical fashion ([van Oosterom et al., 2010](#)). First, structural N demand of the stem (and rachis) is met, as structural stem mass is required to support leaf growth. Structural stem N demand is represented by the minimum stem N

concentration. If insufficient N has been taken up to meet structural stem N requirement, N can be translocated from leaves by dilution or, in extreme cases of early season N deficiency, by leaf senescence. Second, the N demand of expanding new leaves will be met, and this is determined from their critical SLN. Any additional N uptake will first be allocated to leaves to meet their target SLN and then to stem. For leaves, this N uptake represents "luxury" uptake that can occur after full expansion of a leaf, and which does not affect growth and development (van Oosterom et al., 2010). This hierarchical allocation of N is consistent with observations that under N stress a relatively larger proportion of N is allocated to the leaves (van Oosterom et al., 2010). Hence, preanthesis N allocation ratios are a consequence of model dynamics, rather than a model input.

After anthesis, grain becomes the major sink for N, and grain N demand is determined as the product of grain number and N demand per grain. During the first part of grain filling, N demand per grain is constant and independent of grain growth rate and N status of the crop (van Oosterom et al., 2010). At this time embryonic and endosperm cells are dividing, so that the accumulation of structural (metabolic) proteins in the grain is the key driver. During the second half of grain filling, grain N demand is linked with grain growth rate as cell division and simultaneous storage of carbohydrate and proteins assumes a greater role (Martre et al., 2006). Grain protein content can thus vary depending on the N supply–demand balance and the carbohydrate supply to the grain. Grain N demand is initially met through stem (plus rachis) N translocation, and if this becomes insufficient, then N translocation from leaf can occur. Maximum N translocation rates from stem and per unit leaf area are a function of the N status of these organs, so that sink demand determines the amount of leaf area that is senescing at any one time (van Oosterom et al., 2010). The source regulation of N translocation follows a first-order kinetic relationship that is representative of enzyme activity. Leaf SLN thus declines to its structural (minimum) level, and the amount of leaf area senesced, in the absence of other factors that can affect senescence, such as water limitation and shading, depends on the N supply–demand balance.

The daily rate of crop N uptake is the minimum of demand for N by the crop and potential supply of N from the soil and senescing leaves, capped at a maximum N uptake rate (van Oosterom et al., 2010). Potential N supply from the soil depends on the available soil N through the profile and on the extent to which roots have explored the soil. N supply from the soil is calculated from the combination of passive uptake, through mass flow of N taken up with the transpiration, and active uptake if there is a deficiency (Van Keulen et al., 1987). Soil N transformations and their modelling in APSIM have been detailed by Probert et al., 1998.

1.4 Crop Model Applications

The APSIM sorghum model has been tested (Hammer et al., 2010) and used extensively to support research and decision-making in agronomy (Meinke et al., 2000; Nelson et al., 2002; Whish et al., 2005) and plant breeding (Chapman et al., 2000, Chapman et al., 2000, Chapman et al., 2003; Hammer et al., 2005, Hammer et al., 2016). Comprehensive in silico adaptation (GxExM) studies have been reported for current Hammer et al., 2014 and future Hammer et al., 2020 climates. Sorghum crop modelling has evolved in capability and reached a credible level of acceptance in agronomy. This has been associated with strong connections between crop physiological experimentation, model development, and agronomists.

While advances in knowledge, model improvements, and enhanced interactions with decision-makers will undoubtedly further advance the utility of modelling in agronomy, it is the potential to add significant value to the revolution in plant breeding associated with genomic technologies that is the new modelling frontier (Hammer et al., 2019). This will require models where capturing biological understanding in a crop growth and development context is as important as the predictive capability of the model—the right answer for the right reason. Models developed for agronomic application will likely not be sufficient. Models with more robust biological underpinning and the ability to link parameters with the genetic architecture of adaptive traits in a stable manner will come to the fore (Cooper et al., 2014; Messina et al., 2018).

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
Arbitrator	Models.PMF.OrganArbitrator
Phenology	Models.PMF.Phen.Phenology
Grain	Models.PMF.Organs.ReproductiveOrgan
Root	Models.PMF.Organs.Root

Component Name	Component Type
Leaf	Models.PMF.Organs.SorghumLeaf
Rachis	Models.PMF.Organs.GenericOrgan
Stem	Models.PMF.Organs.GenericOrgan
TotalPlantDemand	Models.Functions.AddFunction
MortalityRate	Models.Functions.Constant
SeedMortalityRate	Models.Functions.Constant

1.5 Arbitrator

1.5.1 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 DoPotentialDMAAllocation() 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, DoActualDMAAllocation 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.

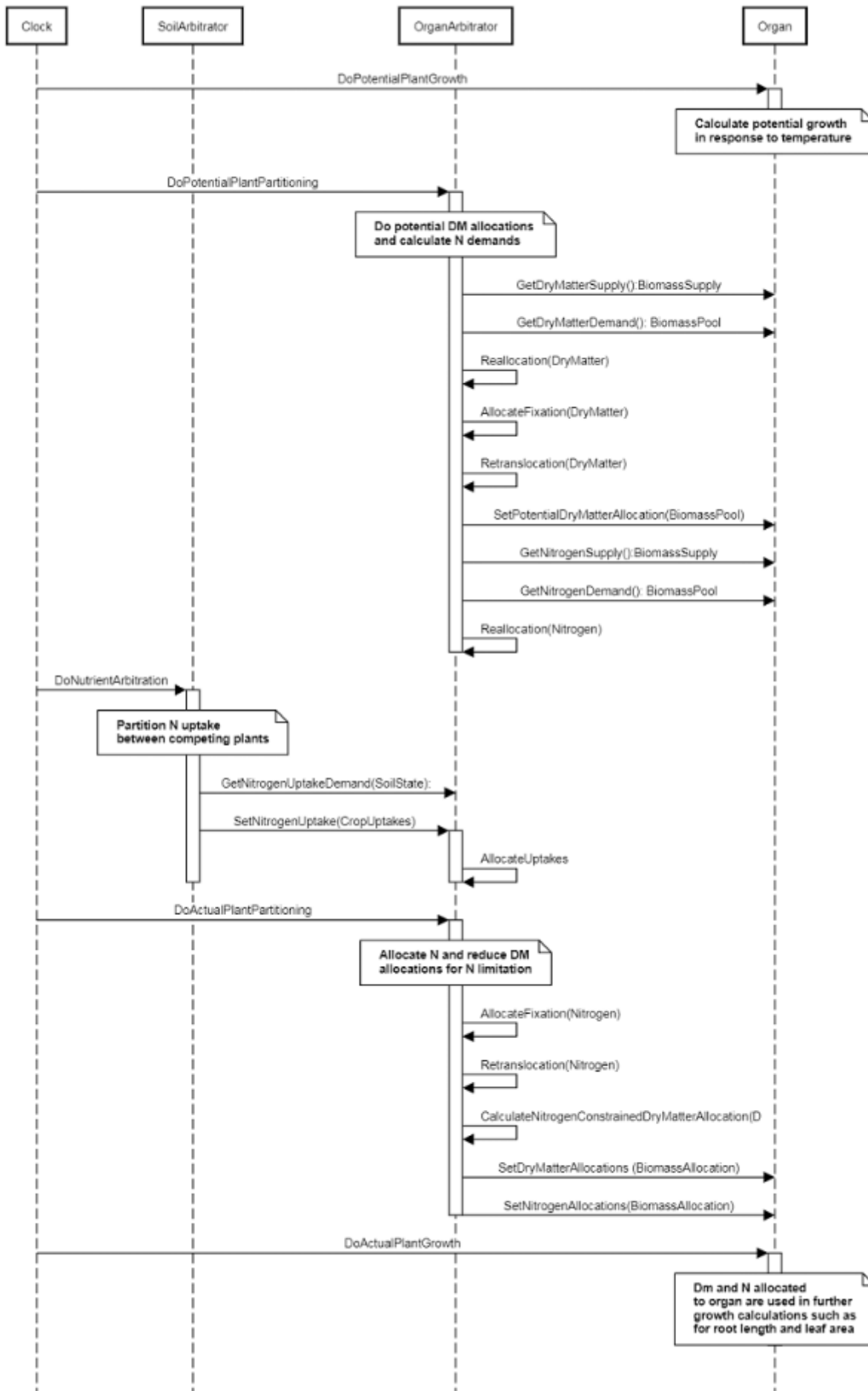


Figure 2: Schematic showing the procedure for arbitration of biomass partitioning. Pink boxes represent events that occur every day and their numbering shows the order of calculations. Blue boxes represent the methods that are called when these events occur. Orange boxes contain properties that make up the organ/arbitrator interface. Green boxes are organ specific properties.

1.6 Phenology

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

1.6.1 ThermalTime

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

BeforeFlowering has a value between Germination and Flowering calculated as:

$$DItTT = [Phenology].DItTT$$

PostFlowering has a value between Flowering and Maturity calculated as:

$$DItTTFM = [Phenology].DItTTFM$$

MaturityToRipe has a value between Maturity and HarvestRipe calculated as:

$$DItTT = [Phenology].DItTT$$

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	Juvenile	Emergence	EndJuvenile
4	JuvenileToFloralInit	EndJuvenile	FloralInitiation
5	FloralInitToFlagLeaf	FloralInitiation	FlagLeaf
6	FlagLeafToFlowering	FlagLeaf	Flowering
7	FloweringToGrainFilling	Flowering	StartGrainFill
8	GrainFilling	StartGrainFill	EndGrainFill
9	Maturing	EndGrainFill	Maturity
10	MaturityToHarvestRipe	Maturity	HarvestRipe
11	ReadyForHarvesting	HarvestRipe	Unused

1.6.2 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.

1.6.3 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:

$$Target = SowingDepth \times ShootRate + ShootLag$$

Where:

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

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

$$ThermalTime = [Phenology].ThermalTime$$

1.6.4 Juvenile

This phase goes from emergence to endjuvenile.

The *Target* for completion is calculated as:

Target = 100 (oD)

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

Progression = [Phenology].ThermalTime

1.6.5 JuvenileToFloralInit

This phase goes from endjuvenile to floralinitiation.

The *Target* for completion is calculated as:

Target = [Phenology].TTTargetPhotoSensitive

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

Progression = [Phenology].ThermalTime

1.6.6 FloralInitToFlagLeaf

This phase goes from floralinitiation to flagleaf.

The *Target* for completion is calculated as:

Target = [Phenology].TTEmergToFlagLeaf - [Phenology].Juvenile.Target - [Phenology].JuvenileToFloralInit.Target

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

Progression = [Phenology].ThermalTime

1.6.7 FlagLeafToFlowering

This phase goes from flagleaf to flowering.

The *Target* for completion is calculated as:

Target = 170 (oD)

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

Progression = [Phenology].ThermalTime

1.6.8 FloweringToGrainFilling

This phase goes from flowering to startgrainfill.

The *Target* for completion is calculated as:

Target = 80 (oD)

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

Progression = [Phenology].DItTTFM

1.6.9 GrainFilling

This phase goes from startgrainfill to endgrainfill.

The *Target* for completion is calculated as:

Target = [Phenology].TTFlowerToMaturity - [Phenology].FloweringToGrainFilling.Target - [Phenology].TTGrainFillToMaturity

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

Progression = [Phenology].DItTTFM

1.6.10 Maturing

This phase goes from endgrainfill to maturity.

The *Target* for completion is calculated as:

$$\text{Target} = [\text{Phenology}].\text{TTGrainFillToMaturity}$$

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

$$\text{Progression} = [\text{Phenology}].\text{DltTTFM}$$

1.6.11 MaturityToHarvestRipe

This phase goes from maturity to harvestripe.

The *Target* for completion is calculated as:

$$\text{Target} = 1 \text{ (oD)}$$

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

$$\text{Progression} = [\text{Phenology}].\text{ThermalTime}$$

1.6.12 ReadyForHarvesting

It is the end phase in phenology and the crop will sit, unchanging, in this phase until it is harvested or removed by other method

1.6.13 Constants

$$\text{TTEndJuvToInit} = 160$$

$$\text{TTFlowerToMaturity} = 761$$

1.6.14 DltTT

$$\text{DltTT} = \text{ThermalTime} \times \text{Stress}$$

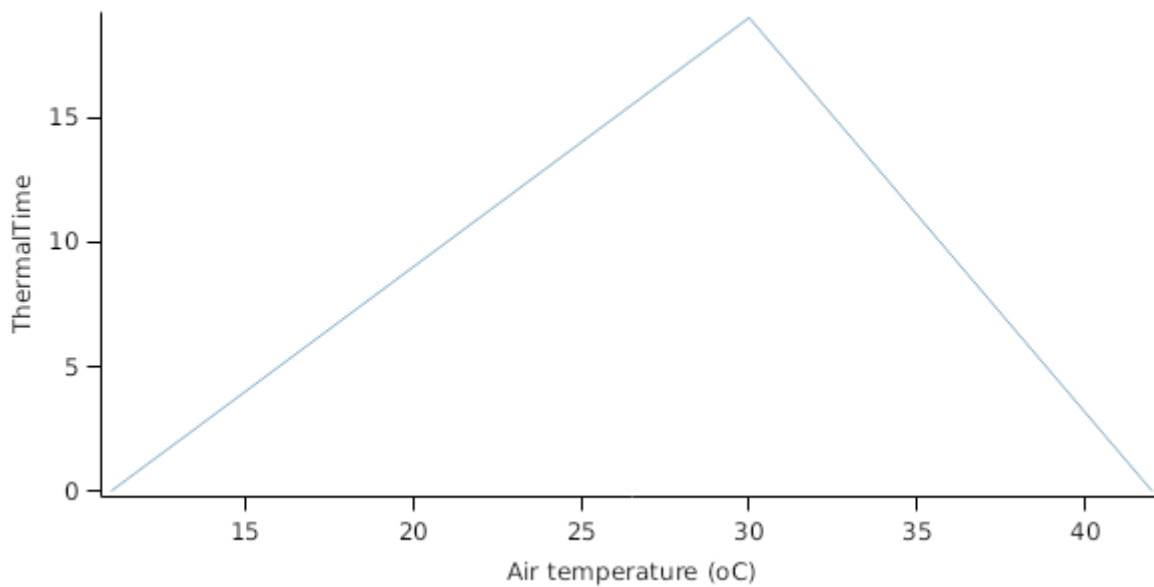
ThermalTime is the average of sub-daily values from a XYPairs.

Firstly 3-hourly estimates of air temperature (T_a) are interpolated using the method of [Jones et al., 1986](#) which assumes a sinusoidal temperature pattern between T_{max} and T_{min} .

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

Air temperature (oC)	ThermalTime
11.0	0.0
30.0	19.0
42.0	0.0

ThermalTime



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

SowingToEndJuvenile has a value between Sowing and EndJuvenile calculated as:

$$\text{PhenoWaterStress} = [\text{Phenology}].\text{PhenoWaterStress}$$

EndJuveToFlag has a value between EndJuvenile and FlagLeaf calculated as:

$$\text{MinimumFunction} = \text{Min}(\text{PhenoWaterStress}, \text{NitrogenPhenoStress})$$

Where:

$$\text{PhenoWaterStress} = [\text{Phenology}].\text{PhenoWaterStress}$$

$$\text{NitrogenPhenoStress} = [\text{Leaf}].\text{NitrogenPhenoStress}$$

FlagToFlowering has a value between FlagLeaf and Flowering calculated as:

$$\text{PhenoWaterStress} = [\text{Phenology}].\text{PhenoWaterStress}$$

PostFlowering has a value between Flowering and HarvestRipe calculated as:

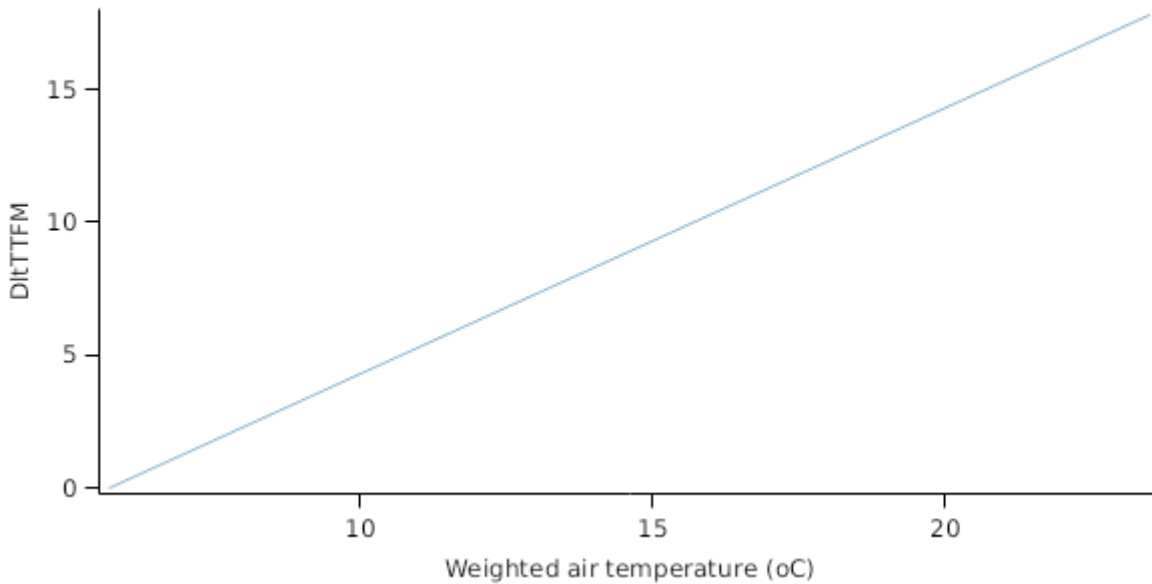
$$\text{Constant} = 1$$

1.6.15 DItTTFM

DItTTFM 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.

$$\text{MaximumTemperatureWeighting} = 0.5$$

DItTTFM



1.6.16 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 = -2.2 (degrees)

1.6.17 FloweringDAS

Before Flowering

PreEventValue = 0

On Flowering the value is set to:

PostEventValue = [Plant].DaysAfterSowing

1.6.18 MaturityDAS

Before Maturity

PreEventValue = 0

On Maturity the value is set to:

PostEventValue = [Plant].DaysAfterSowing

1.6.19 TTGrainFillToMaturity

TTGrainFillToMaturity = [Phenology].TTFlowerToMaturity x Proportion

Proportion = 0.05

1.6.20 TTTargetPhotoSensitive

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

PhaseLookupValue has a value between Sowing and Emergence calculated as:

PreEventValue = [Phenology].TTEndJuvToInit

EmergenceToEndJuve has a value between Emergence and EndJuvenile calculated as:

$Add = [Phenology].PhotoModifier + [Phenology].TTEndJuvToInit$

EndJuveToMaturity has a value between EndJuvenile and HarvestRipe calculated as:

Before EndJuvenile

$PreEventValue = [Phenology].TTEndJuvToInit$

On EndJuvenile the value is set to:

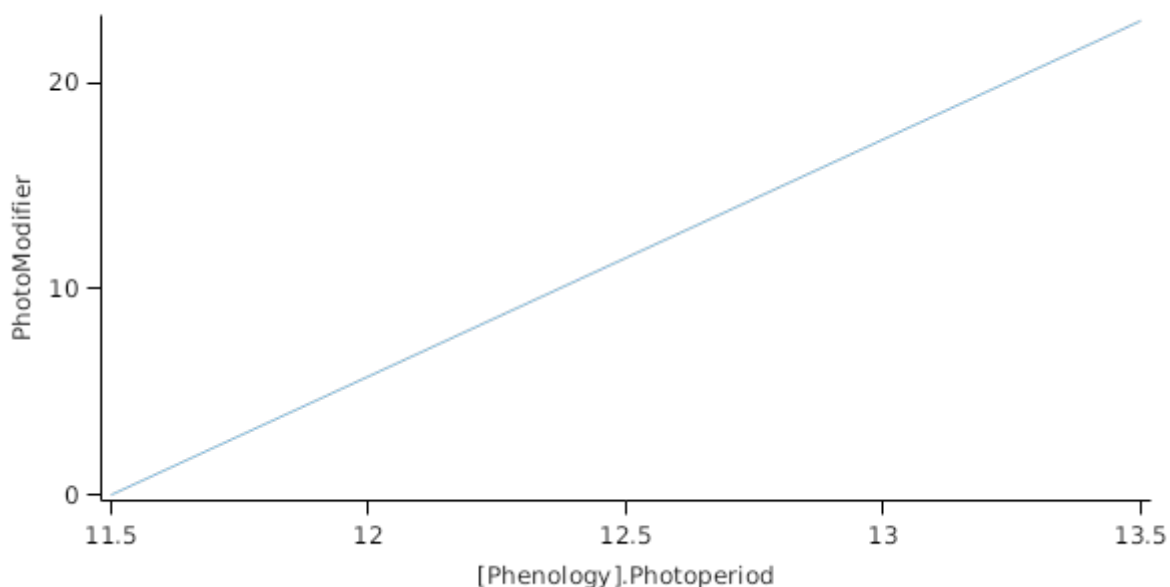
$PostEventValue = [Phenology].PhotoModifier + [Phenology].TTEndJuvToInit$

1.6.21 PhotoModifier

PhotoModifier is calculated using linear interpolation

[Phenology].Photoperiod	PhotoModifier
11.5	0.0
13.5	23.0

PhotoModifier



1.6.22 TTEmergToFlagLeaf

$TTEmergToFlagLeaf = LeafAppearingPhase1 + LeafAppearingPhase2$

$LeafAppearingPhase1 = NoLeavesRate1 \times [Leaf].Parameters.appearanceRate1$

$NoLeavesRate1 = [Leaf].FinalLeafNo - [Leaf].Parameters.LeafNoAtEmergence - [Leaf].Parameters.noRateChange1$

$LeafAppearingPhase2 = [Leaf].Parameters.appearanceRate2 \times [Leaf].Parameters.noRateChange1$

1.6.23 TTEmergToFloralInit

$TTEmergToFloralInit = [Phenology].Juvenile.Target + [Phenology].JuvenileToFloralInit.Target$

1.6.24 TTTtoFlowering

$TTTtoFlowering = [Emerging].Target + [TTEmergToFlagLeaf] + [FlagLeafToFlowering].Target$

1.6.25 TTFromEmergence

TTFromEmergence = Accumulated ThermalTime between emergence and maturity

$ThermalTime = [Phenology].CurrentPhase.ProgressionForTimeStep$

1.6.26 TTFMFromFlowering

TTFMFromFlowering = Accumulated *ThermalTime* between flowering and maturity

ThermalTime = *[Phenology].CurrentPhase.ProgressionForTimeStep*

1.6.27 TTFMSgfToMaturity

TTFMSgfToMaturity = Accumulated *ThermalTime* between startgrainfill and maturity

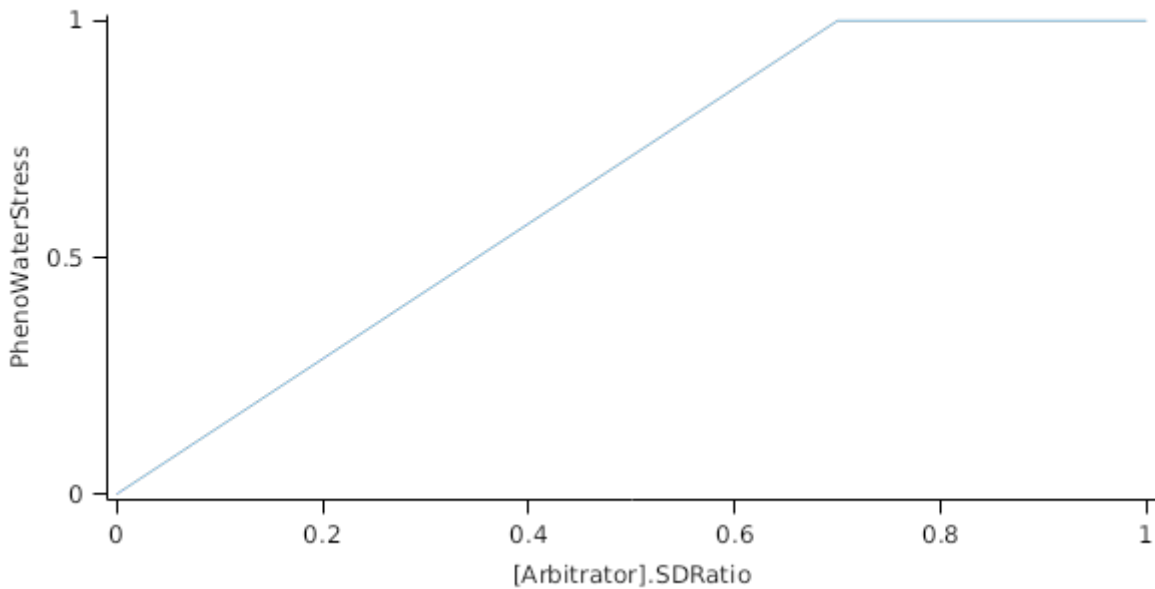
ThermalTime = *[Phenology].CurrentPhase.ProgressionForTimeStep*

1.6.28 PhenoWaterStress

PhenoWaterStress is calculated using linear interpolation

[Arbitrator].SDRatio	PhenoWaterStress
0.0	0.0
0.7	1.0
1.0	1.0

PhenoWaterStress

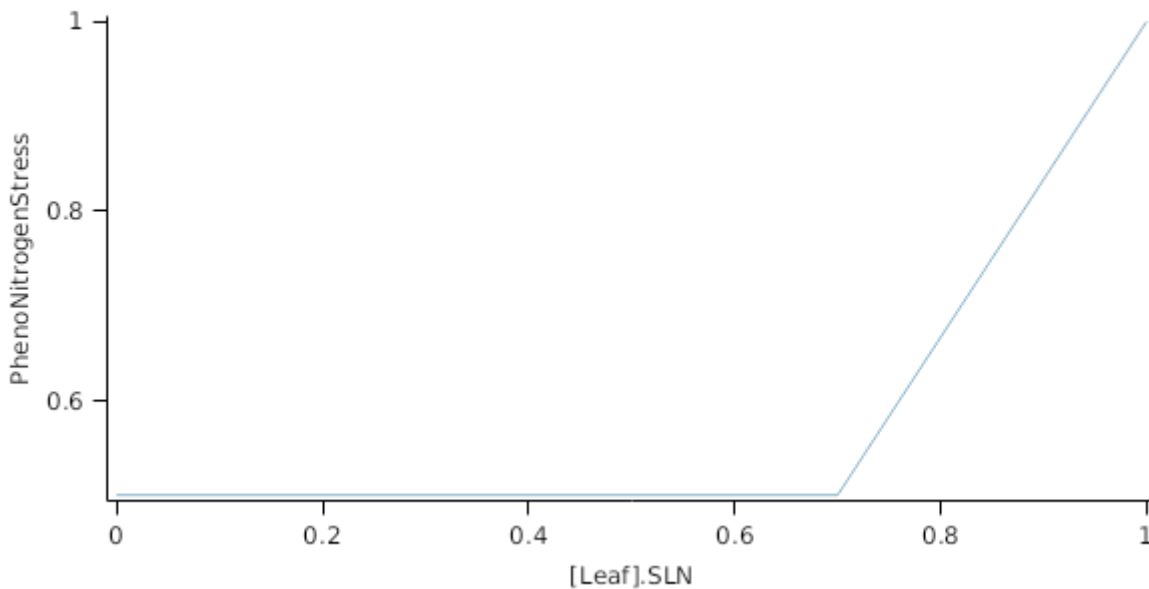


1.6.29 PhenoNitrogenStress

PhenoNitrogenStress is calculated using linear interpolation

[Leaf].SLN	PhenoNitrogenStress
0.0	0.5
0.7	0.5
1.0	1.0

PhenoNitrogenStress



1.7 Grain

This organ uses a generic model for plant reproductive components. Yield is calculated from its components in terms of organ number and size (for example, grain number and grain size).

1.7.1 Constants

InitialGrainProportion = 0.05

MaximumPotentialGrainSize = 0.3

MinimumNConc = 0.008

WaterContent = 0.13

DMPerSeed = 0.00083

DMConversionEfficiency = 1

RemobilisationCost = 0

CarbonConcentration = 0.4

1.7.2 MaximumNConc

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

InitialPhase has a value between Flowering and StartGrainFill calculated as:

InitialNconc = 0.05

LinearPhase has a value between StartGrainFill and Maturity calculated as:

FinalNconc = 0.0175

1.7.3 NFillingRate

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

First half of the Grainfilling Period is calculated using Grain Filling Rate. 2nd half is calculated using the maximum N Concentration of today's Biomass

Amount of N filled per day is limited by the Target N Concentration at all times.

GrainFilling has a value between StartGrainFill and Maturity calculated as:

IF gfFract < GrainFillFraction THEN

InitialGrainFilling = Min(*FillingRate*, *FinalGrainFilling*)

Where:

FillingRate = [Grain].NumberFunction x [Phenology].DItTTFM x *DivideFunction*

DivideFunction = *GrainFillRate* / *Thousand*

GrainFillRate = 0.001 (mg/grain/dd)

Thousand = 1000 (mg/g)

FinalGrainFilling = [Grain].potentialDMAAllocation.Structural x [Grain].MaximumNConc

ELSE

FinalGrainFilling = [Grain].potentialDMAAllocation.Structural x [Grain].MaximumNConc

1.7.4 FinalGrainNum

Before StartGrainFill

PreEventValue = 0

On StartGrainFill the value is set to:

PostEventValue = *GrowthRate* / [Grain].DMPerSeed

GrowthRate = *PlantGrowth* / *DaysFIToStartGrainFill*

Maximum function here prevents grain from returning negative dm demand in the event that plant growth is negative.

PlantGrowth = Max(*PlantGrowthSinceFloralInit*, Zero)

Where:

PlantGrowthSinceFloralInit = [Sorghum].Total.Wt - *GreenWtAtFI*

Before FloralInitiation

PreEventValue = 0

On FloralInitiation the value is set to:

PostEventValue = [Sorghum].Total.Wt

Zero = 0

DaysFIToStartGrainFill = Accumulated *One* between floralinitiation and startgrainfill

One = 1

1.7.5 NumberFunction

1.7.5.1 NumberFunction

Calculates the current grain number.

1.7.6 DMCaryopsis

DMCaryopsis = [Arbitrator].DM.TotalFixationSupply / [Grain].NumberFunction / [Phenology].DItTTFM

1.7.7 PotGrainFillRate

PotGrainFillRate = Min(*MultiplyFunction*, *MaxGrainFillRate*)

Where:

MultiplyFunction = *AddFunction* x 1000

$AddFunction = MultiplyFunction + 3.19E-05$

$MultiplyFunction = [Grain].DMCaryopsis \times 0.4026$

$MaxGrainFillRate = 0.09$

1.7.8 DMDemandFunction

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

SowingToMaturity has a value between Sowing and Maturity calculated as:

$DMDemandFunction = [Grain].PotGrainFillRate \times [Phenology].DlTTFM \times [Grain].NumberFunction \times 0.001$

1.7.9 BiomassRemovalDefaults

1.7.9.1 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.

1.7.10 DMDemandPriorityFactors

1.7.10.1 DMDemandPriorityFactors

This class holds the functions for calculating values for each Nutrient component.

1.7.11 NDemandPriorityFactors

1.7.11.1 NDemandPriorityFactors

This class holds the functions for calculating values for each Nutrient component.

1.8 Root

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

1.8.1 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.

$Root\ Depth\ Increase = RootFrontVelocity \times XF_i \times RootDepthStressFactor$

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

$DMAllocated_i = TotalDMAllocated \times RAw_i / TotalRAw$

1.8.2 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.

1.8.3 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 than zero.

1.8.4 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. $NO_3 \text{ uptake} = NO_{3_i} \times kNO_3 \times NO_{3_{ppm, i}} \times NUptakeSWFactor$ $NH_4 \text{ uptake} = NH_{4_i} \times kNH_4 \times NH_{4_{ppm, i}} \times NUptakeSWFactor$ 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 demand each plant instance will be allowed to take up.

1.8.5 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. $SW \text{ uptake} = (SW_i - LL_i) \times KL_i \times KLModifier$

1.8.6 Constants

SoilWaterEffect = 1

TemperatureEffect = 1

MaxDailyNUptake = 20

SenescenceRate = 0.002

MaximumNConc = 0.02

MinimumNConc = 0.002

MaximumRootDepth = 1000000

SpecificRootLength = 100000 (m/g)

DMConversionEfficiency = 1

MaintenanceRespirationFunction = 1

RemobilisationCost = 0

CarbonConcentration = 0.4

1.8.7 RootShape

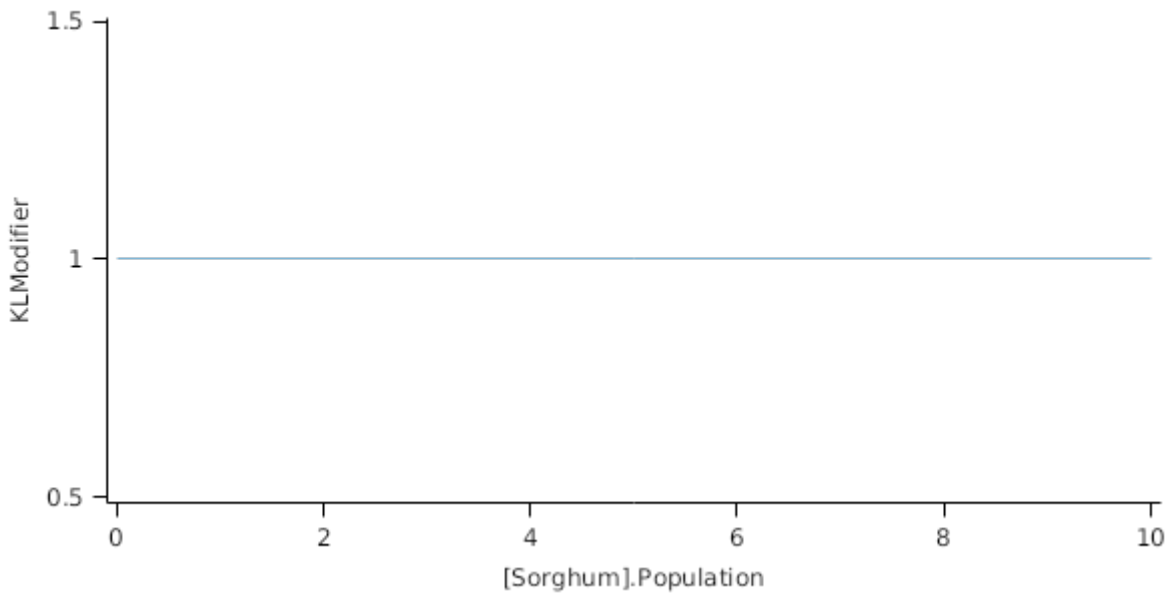
This model calculates the proportion of each soil layer occupied by roots. The formula used for the circle is wrong as it does not account for the coordinate of the centre!

1.8.8 KLModifier

KLModifier is calculated using linear interpolation

[Sorghum].Population	KLModifier
0.0	1.0
10.0	1.0

KLModifier



1.8.9 CriticalNConc

$CriticalNConc = [Root].MinimumNConc$

1.8.10 RootFrontVelocity

$RootFrontVelocity = PotentialRootFrontVelocity \times RootDepthStressFactor$

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

Hammer et al (2009) used a constant extraction front velocity of 2.5cm per day in their analysis of historical sorghum yield trends in the US corn belt.

PreGrainFill has a value between Germination and StartGrainFill calculated as:

Function = 27

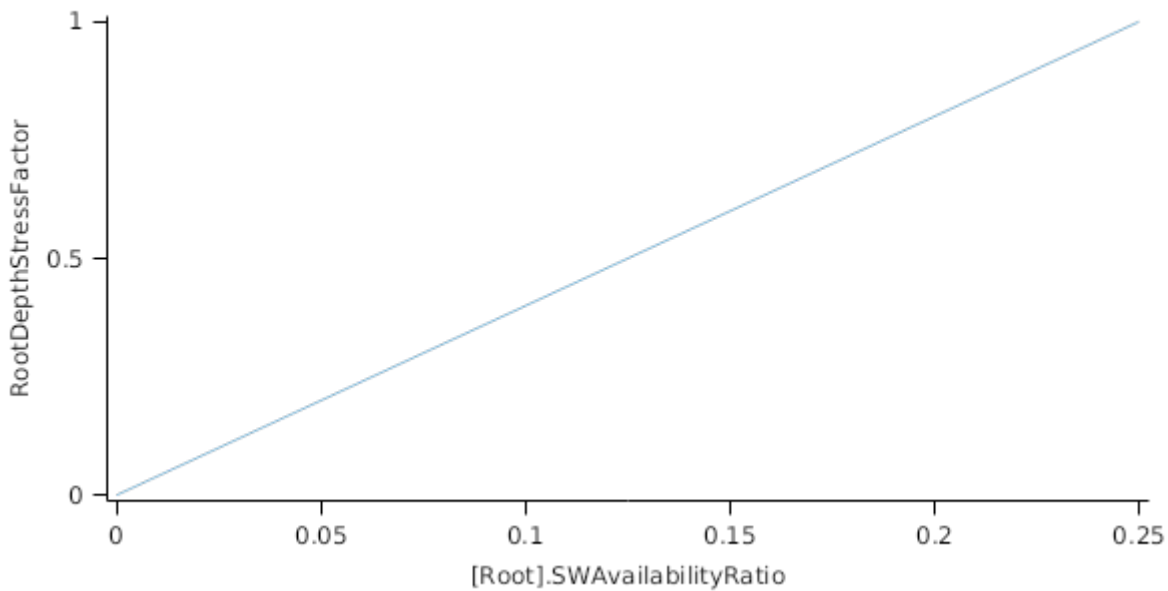
GrainfillToMaturity has a value between StartGrainFill and Maturity calculated as:

Function = 0

$RootDepthStressFactor$ is calculated using linear interpolation

[Root].SWAvailabilityRatio	RootDepthStressFactor
0.0	0.0
0.25	1.0

RootDepthStressFactor



1.8.11 NitrogenDemandSwitch

NitrogenDemandSwitch has a value between Germination and Maturity calculated as:

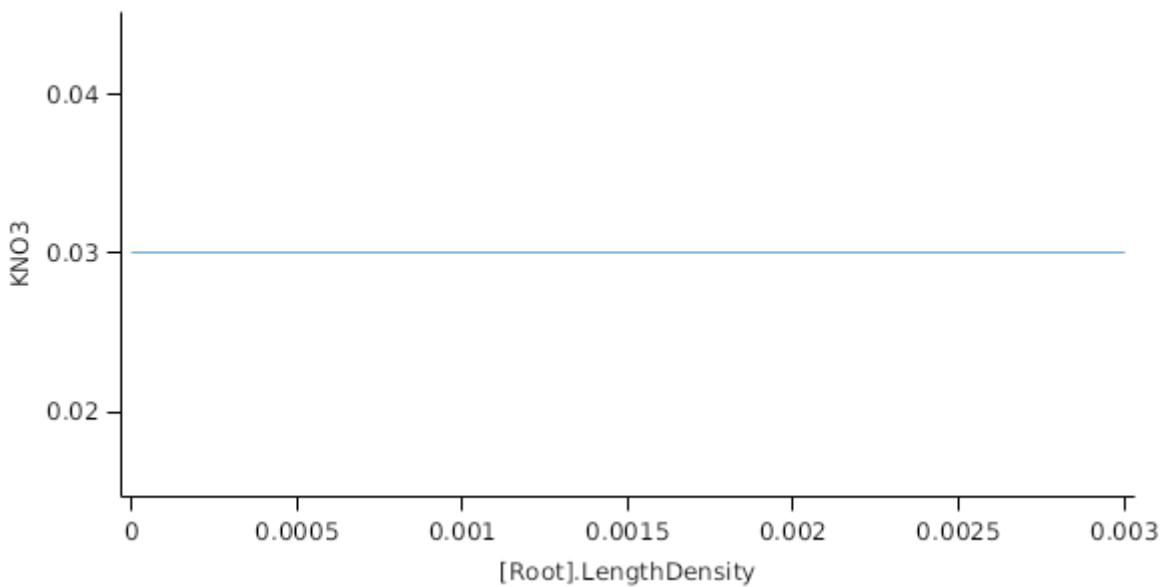
Constant = 1

1.8.12 KNO3

KNO3 is calculated using linear interpolation

[Root].LengthDensity	KNO3
0.0	0.03
0.003	0.03

KNO3

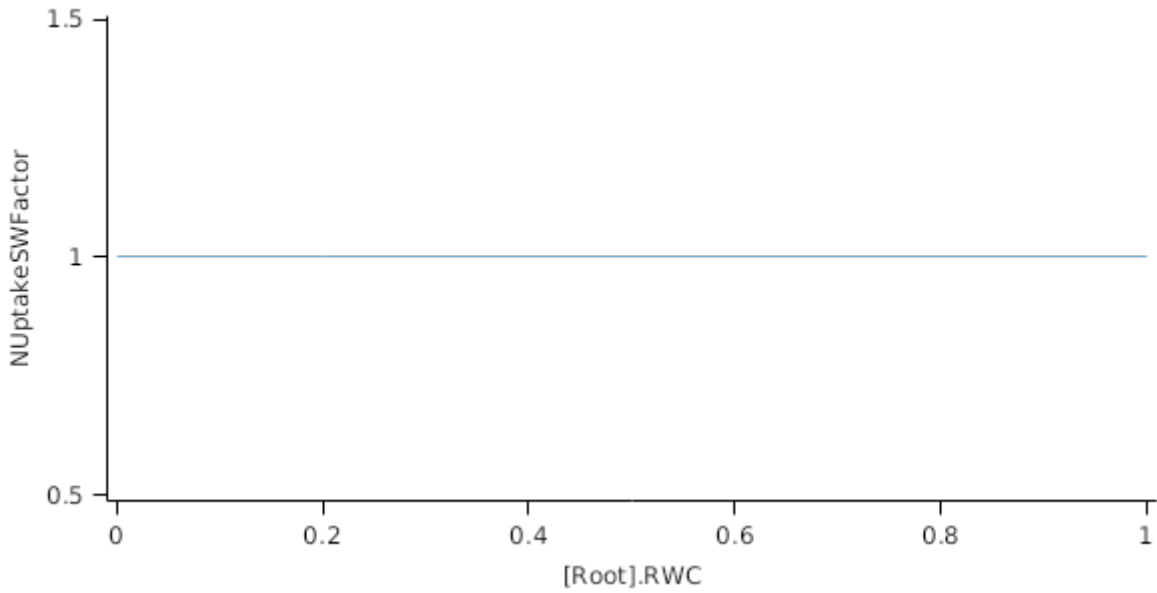


1.8.13 NUptakeSWFactor

NUptakeSWFactor is calculated using linear interpolation

[Root].RWC	NUptakeSWFactor
0.0	1.0
0.2	1.0
1.0	1.0

NUptakeSWFactor

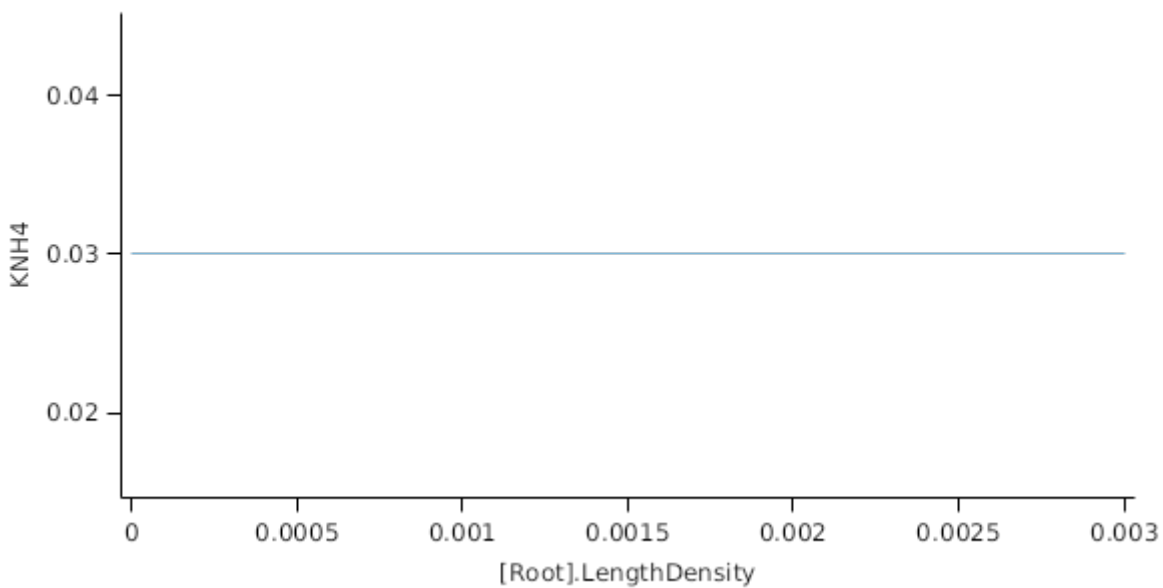


1.8.14 KNH4

KNH4 is calculated using linear interpolation

[Root].LengthDensity	KNH4
0.0	0.03
0.003	0.03

KNH4



1.8.15 BiomassRemovalDefaults

1.8.15.1 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.

1.8.16 DMDemands

1.8.16.1 DMDemands

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

1.8.17 NDemands

1.8.17.1 NDemands

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

1.8.18 SWAvailabilityRatio

1.8.18.1 SWAvailabilityRatio

[DocumentMathFunction /] Returns special values if the numerator is 0 or if the denominator is 0.

Currently used in sorghum/maize code to mimic divide functions in old apsim which return 10 if the denominator is 0 or 0 if the numerator is 0.

1.8.19 InitialWt

1.8.19.1 InitialWt

This class holds the functions for calculating values for each Nutrient component.

1.9 Leaf

SorghumLeaf reproduces the functionality provided by the sorghum and maize models in Apsim Classic. It provides the core functions of intercepting radiation, producing biomass through photosynthesis, and determining the plant's transpiration demand.

1.9.1 LeafCulms

The LeafCulms model manages the canopy resources produced by tillering. Two main tillering strategies are provided by default, and are managed via the TilleringMethod switch defined in SorghumLeaf, which can be manipulated via script methods. FixedTillering will use the FTN property provided as part of the sowing method to determine the total number of fertile tillers. Setting FTN to a negative value will calculate the number of fixed tillers using latitude and sowing density to provide a rule of thumb value. These values have been derived using data from the Australian sorghum growing area, and may not be suitable for other locations. DynamicTillering will calculate the potential number of tillers - usually determined by the time the 6th leaf has appeared. The number of fertile tillers is then maintained by the addition or removal of active tillers. Further information provided below for each method.

1.9.2 Dry Matter Fixation

Aboveground biomass accumulation is simulated as the minimum of light-limited or water-limited growth. In the absence of water limitation, biomass accumulation is the product of the amount of intercepted radiation (IR) and its conversion efficiency, the radiation use efficiency (RUE).

Under water limitation, aboveground biomass accumulation is the product of realized transpiration and its conversion efficiency, biomass produced per unit of water transpired, or transpiration efficiency(TE)

1.9.3 Radiation Use Efficiency

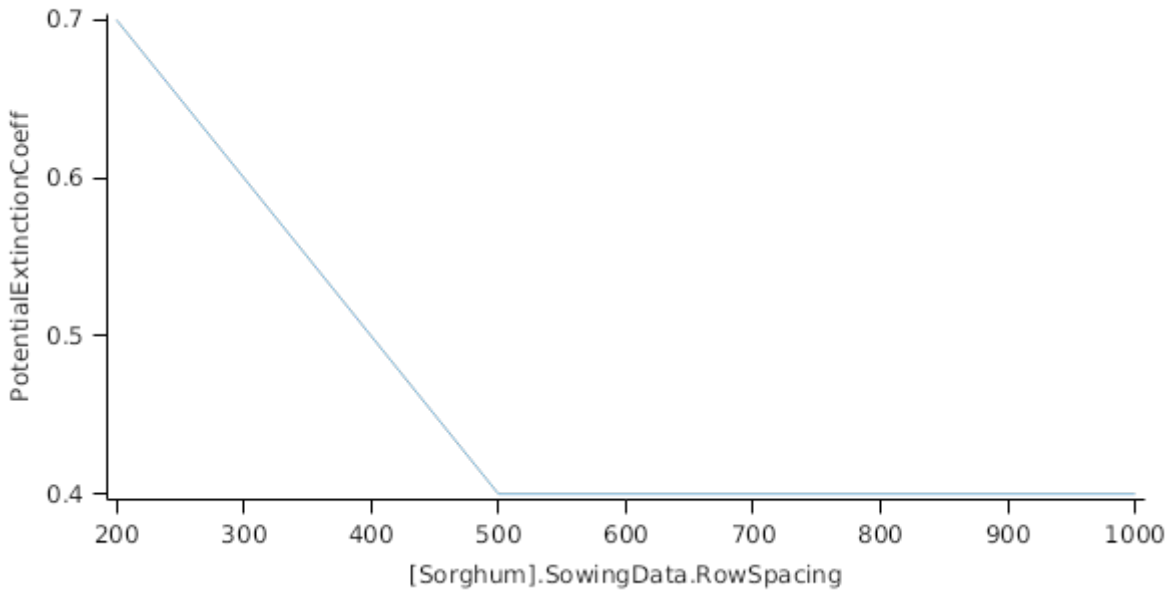
ExtinctionCoefficientFunction = *PotentialExtinctionCoeff*

PotentialExtinctionCoeff is calculated using linear interpolation

[Sorghum].SowingData.RowSpacing	PotentialExtinctionCoeff
200.0	0.7

[Sorghum].SowingData.RowSpacing	PotentialExtinctionCoeff
500.0	0.4
1000.0	0.4

PotentialExtinctionCoeff



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 CO₂ concentration (FCO₂).

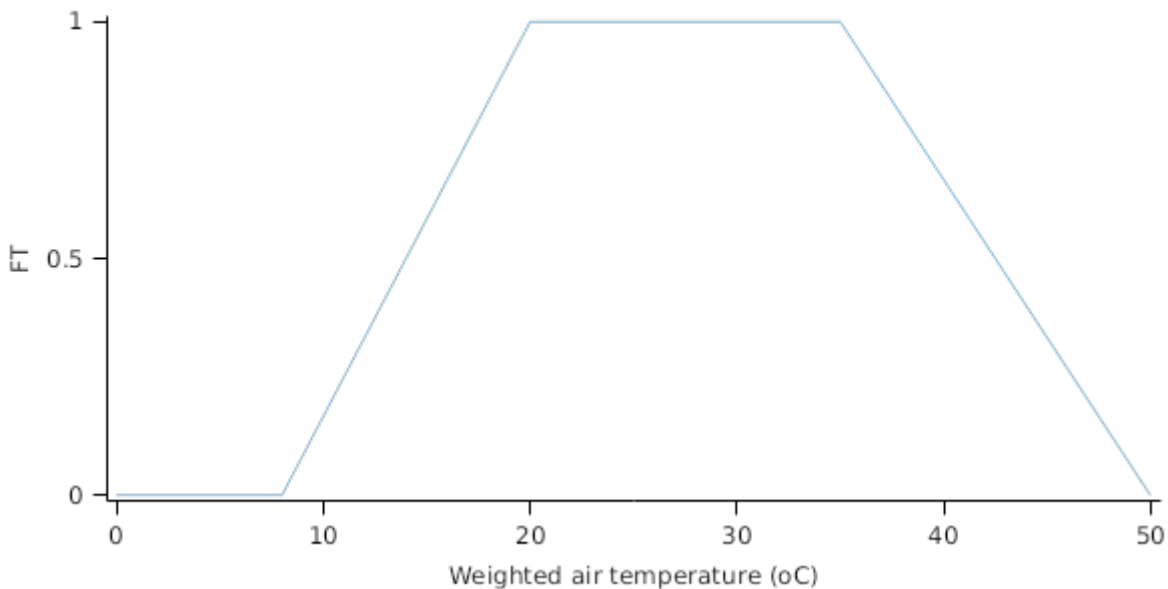
NOTE: RUE in this model is expressed as g/MJ for a whole plant basis, including both above and below ground growth.

RUE = 1.25

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 = 0.5

FT



$FN = [Leaf].NitrogenPhotoStress$

$RadnInt = [Leaf].RadiationIntercepted$

$FVPD = 1$

$FW = 1$

This model calculates the CO₂ impact on RUE using the approach of [Reyenga et al., 1999](#).

For C3 plants,

$$F_{CO_2} = (CO_2 - CP) \times (350 + 2 \times CP) / (CO_2 + 2 \times CP) \times (350 - CP)$$

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

$$CP = (163.0 - T) / (5.0 - 0.1 \times T)$$

For C4 plants,

$$F_{CO_2} = 0.000143 \times CO_2 + 0.95$$

When pathway is set to "C4", this model modifier will be have the same as the `double Plant::rue_cow_modifier()` function in the APSIM Classic sorghum model.

1.9.4 Transpiration Efficiency

$PotentialBiomassTEFunction = TE \times [Arbitrator].WatSupply \times CO_2Modifier$

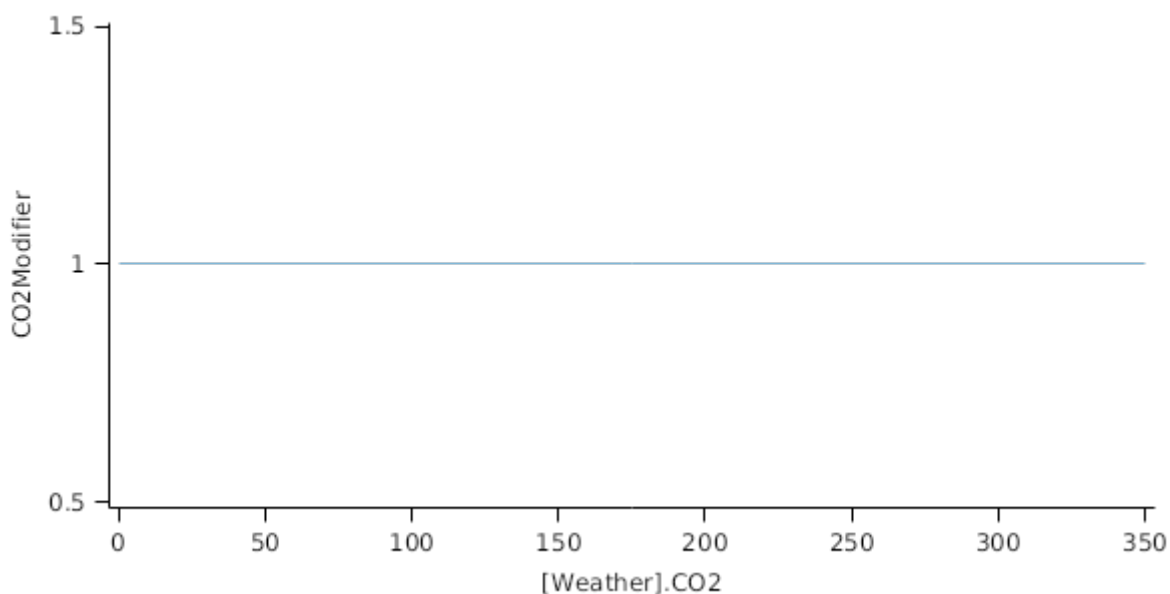
$TE = [Leaf].WaterDemandFunction.TranspirationEfficiencyCoefficient / [Leaf].WaterDemandFunction.VPD / g2mm$

$g2mm = 0.001$

$CO_2Modifier$ is calculated using linear interpolation

[Weather].CO2	CO2Modifier
0.0	1.0
350.0	1.0

CO2Modifier



Initial DM mass = 0.1 gm⁻²

1.9.5 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.

1.9.5.1 DM Demands

This class holds the functions for calculating values for each Nutrient component.

1.9.6 Nitrogen Demand

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

1.9.6.1 NDemands

This class holds the functions for calculating values for each Nutrient component.

1.9.7 DM Retranslocation Factor

Leaf does not retranslocate non-structural DM.

1.9.8 Nitrogen Supply

Leaf does not reallocate N when senescence of the organ occurs.

1.9.9 Nitrogen Retranslocation Factor

Leaf does not retranslocate non-structural N.

1.9.10 Canopy Properties

Before FlorallInitiation

PreEventValue is the value of AddFunction bound between a lower and upper bound where:

$$AddFunction = LeavesInitiated + [NumberOfLeaves].leafNumSeed$$

$$LeavesInitiated = [Phenology].TTEmergToFloralInit / [NumberOfLeaves].leafInitRate$$

Lower = 10

Upper = 40

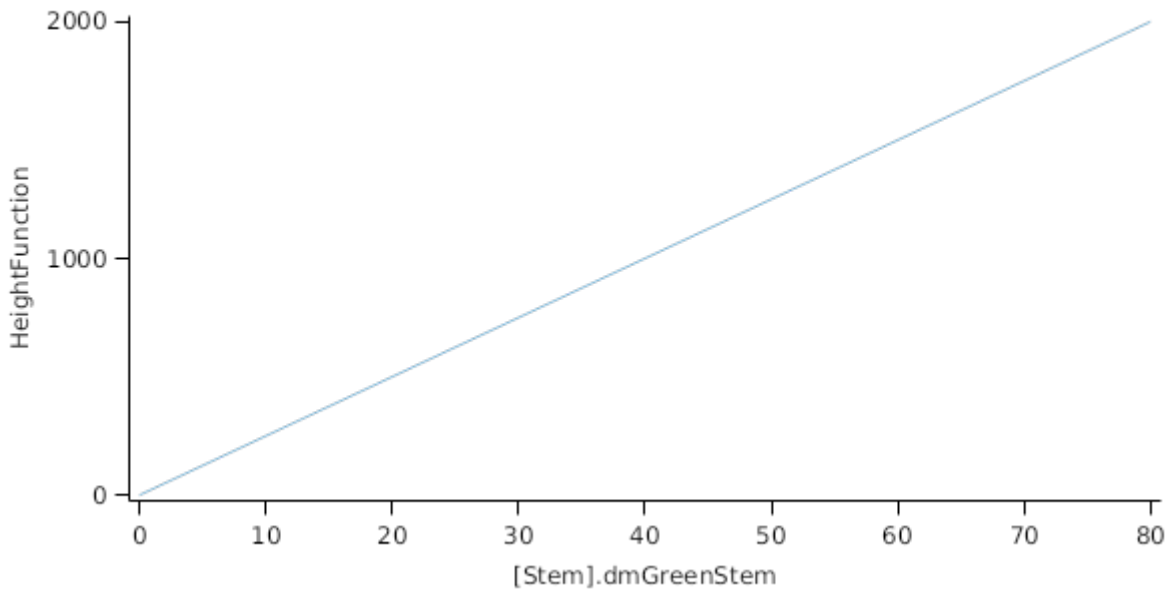
On FlorallInitiation the value is set to:

$$PostEventValue = [LeafCulms].FinalLeafNo$$

HeightFunction is calculated using linear interpolation

[Stem].dmGreenStem	HeightFunction
0.0	0.0
80.0	2000.0

HeightFunction



1.9.11 Senescence and Detachment

1.9.11.1 Light Senescence

radiation level for onset of light senescence

senRadnCrit = 2 (Mj/m²)

delay factor for light senescence

SenLightTimeConst = 10

1.9.11.2 Water Senescence

SenWaterTimeConst = 10

SenThreshold = 0.25

SDRatio is the Water Supply divided by the Water Demand (found in Arbitrator). It will return 1.0 unless there is less Supply than Demand

1.9.11.3 FrostSenescence

FrostKill: 1 ° C

FrostKillSevere: -3.5 ° C

If minimum temperature falls below FrostKillSevere then all LAI is removed causing plant death

If the minimum temperature is above FrostKillSevere, but below FrostKill, then the effect on the plant will depend on which phenological stage the plant is in:

Before Floral Initiation: Nearly all of the LAI will be removed, but if not under any other stress, the plant can survive.

Before Flowering: All of the LAI will be removed, causing plant death.

After Flowering: The leaf is not damaged.

1.9.11.4 Biomass Removal

1.9.11.4.1 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.

1.10 Rachis

1.10.1 Rachis

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.

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.

1.10.4 N Concentration Thresholds

MinimumNConc = 0.003

CriticalNConc = 0.01

MaximumNConc = 0.008

The demand for N is reduced by a factor specified by the NitrogenDemandSwitch.

NitrogenDemandSwitch has a value between Emergence and StartGrainFill calculated as:

Constant = 1

1.10.5 Dry Matter Supply

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

Rachis does not retranslocate non-structural DM.

1.10.6 Nitrogen Supply

Rachis does not reallocate N when senescence of the organ occurs.

The proportion of non-structural N that is allocated each day is quantified by the NReallocationFactor.

$NRetranslocationFactor = NRetranslocationAmount$

$NRetranslocationAmount = \text{Max}(\text{MinimumFunction}, \text{Zero})$

Where:

$\text{MinimumFunction} = \text{Min}(\text{availableDilnN}, \text{SubtractFunction})$

Where:

$\text{availableDilnN} = \text{DivideFunction} \times \text{DMToday}$

$\text{DivideFunction} = \text{dltStemNConc} / 100$

$\text{dltStemNConc} = \text{AddFunction} \times [\text{Phenology}].\text{ThermalTime}$

$\text{AddFunction} = \text{MultiplyFunction} + \text{dilnNInt}$

$MultiplyFunction = dilnNSlope \times stemNConc$

$dilnNSlope = 0.0062$

$stemNConc = divide \times Percentage$

$divide = [Rachis].Live.N / DMToday$

$DMToday = [Rachis].potentialDMAAllocation.Structural + [Rachis].Live.Wt$

Percentage = 100

$dilnNInt = -0.001$

$DMToday = [Rachis].potentialDMAAllocation.Structural + [Rachis].Live.Wt$

$SubtractFunction = [Rachis].Live.N - [Rachis].NDemands.Structural$

Zero = 0

1.10.7 Senescence and Detachment

Rachis has senescence parameterised to zero so all biomass in this organ will remain alive.

Rachis has detachment parameterised to zero so all biomass in this organ will remain with the plant until a defoliation or harvest event occurs.

1.10.8 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.

1.11 Stem

1.11.1 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.

1.11.2 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.

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.

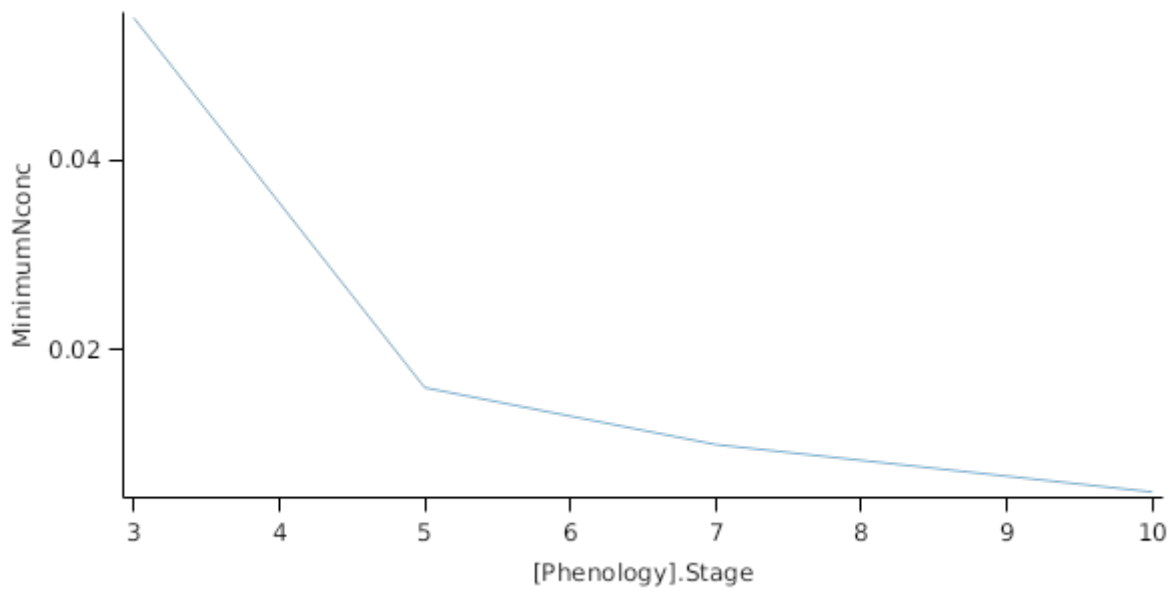
1.11.4 N Concentration Thresholds

MinimumNconc is calculated using linear interpolation

[Phenology].Stage	MinimumNconc
3.0	0.055
5.0	0.016

[Phenology].Stage	MinimumNconc
7.0	0.01
10.0	0.005

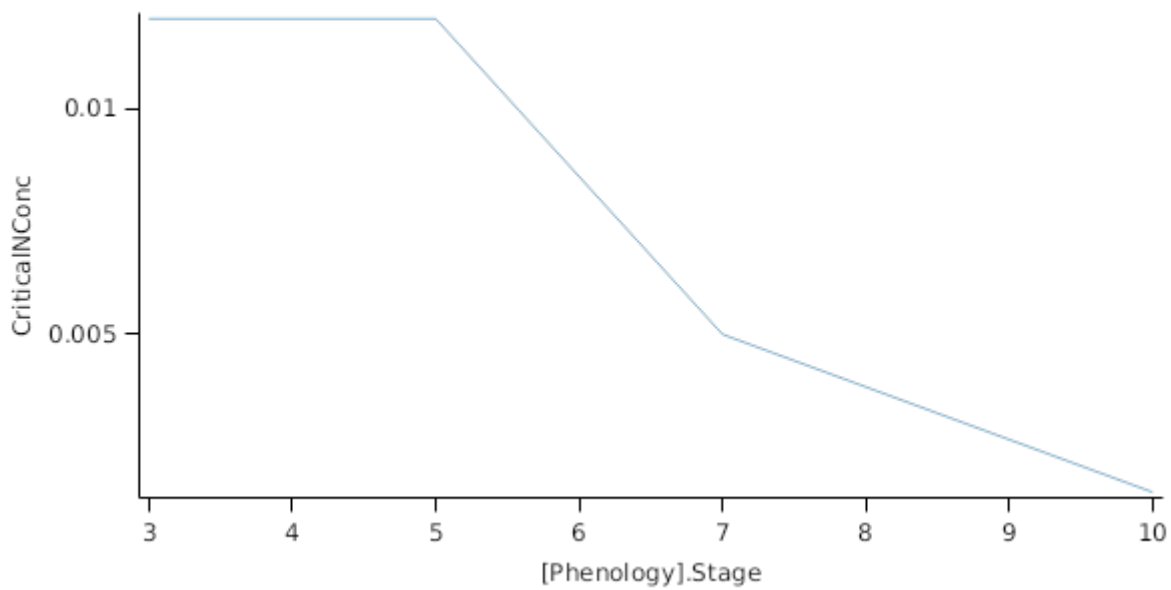
MinimumNconc



CriticalNConc is calculated using linear interpolation

[Phenology].Stage	CriticalNConc
3.0	0.012
5.0	0.012
7.0	0.005
10.0	0.0015

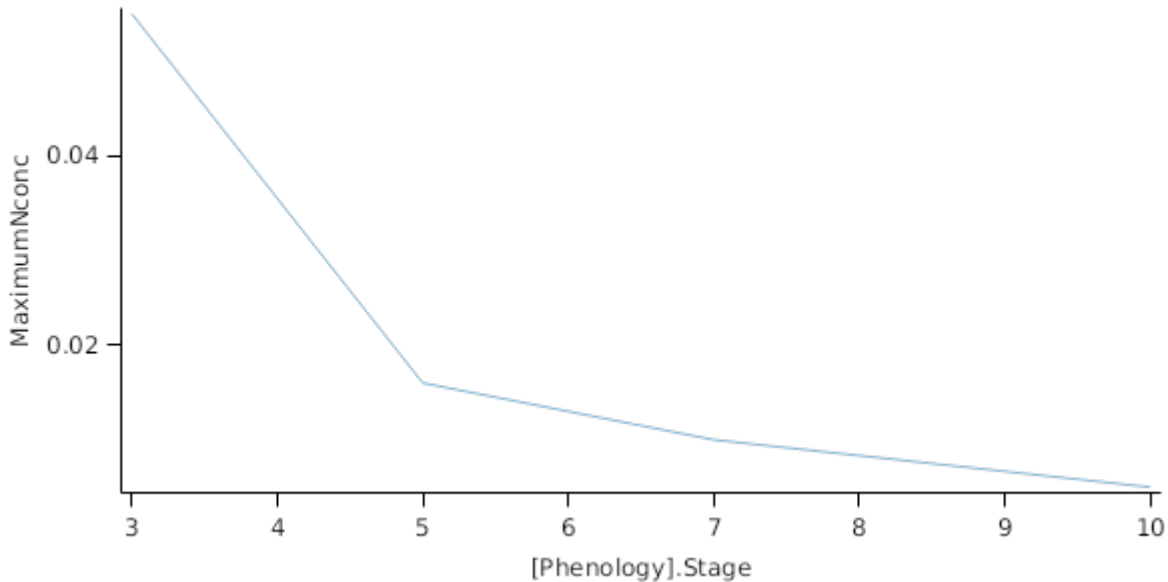
CriticalNConc



MaximumNconc is calculated using linear interpolation

[Phenology].Stage	MaximumNconc
3.0	0.055
5.0	0.016
7.0	0.01
10.0	0.005

MaximumNconc



1.11.5 Dry Matter Supply

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

The proportion of non-structural DM that is allocated each day is quantified by the DMReallocationFactor.

$$DMRetranslocationFactor = DMRetranslocationAmount / [Stem].Live.Wt$$

$$DMRetranslocationAmount = \text{Max}(StemWtAvail, Zero)$$

Where:

$$StemWtAvail = SubtractFunction \times retransRate$$

$$SubtractFunction = DMToday - MultiplyFunction$$

$$DMToday = [Stem].potentialDMAAllocation.Structural + [Stem].Live.Wt$$

$$MultiplyFunction = PlantMinDM \times [Plant].SowingData.Population$$

Before Flowering

$$PreEventValue = 0$$

On Flowering the value is set to:

$$PostEventValue = dmPlantStem \times SubtractFunction$$

$$dmPlantStem = [Stem].Live.Wt / [Plant].SowingData.Population$$

$$SubtractFunction = 1 - translocFrac$$

$$translocFrac = 0.2$$

$$retransRate = 0.15$$

$$Zero = 0$$

1.11.6 Nitrogen Supply

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

The proportion of non-structural N that is allocated each day is quantified by the *NReallocationFactor*.

$$NRetranslocationFactor = NRetranslocationAmount / [Stem].Live.Wt$$

$$NRetranslocationAmount = \text{Max}(\text{MinimumFunction}, \text{Zero})$$

Where:

$$\text{MinimumFunction} = \text{Min}(\text{availableDilnN}, \text{SubtractFunction})$$

Where:

$$\text{availableDilnN} = \text{DivideFunction} \times \text{DMToday}$$

$$\text{DivideFunction} = \text{dltStemNConc} / 100$$

$$\text{dltStemNConc} = \text{AddFunction} \times [\text{Phenology}].\text{ThermalTime}$$

$$\text{AddFunction} = \text{MultiplyFunction} + \text{dilnNInt}$$

$$\text{MultiplyFunction} = \text{dilnNSlope} \times \text{stemNConcPct}$$

$$\text{dilnNSlope} = 0.0062$$

$$\text{stemNConcPct} = \text{divide} \times \text{Percentage}$$

$$\text{divide} = [\text{Stem}].\text{Live.N} / \text{DMToday}$$

$$\text{DMToday} = [\text{Stem}].\text{potentialDMAAllocation.Structural} + [\text{Stem}].\text{Live.Wt}$$

$$\text{Percentage} = 100$$

$$\text{dilnNInt} = -0.001$$

$$\text{DMToday} = [\text{Stem}].\text{potentialDMAAllocation.Structural} + [\text{Stem}].\text{Live.Wt}$$

$$\text{SubtractFunction} = [\text{Stem}].\text{Live.N} - \text{MultiplyFunction}$$

$$\text{MultiplyFunction} = \text{DMToday} \times [\text{Stem}].\text{MinimumNconc}$$

$$\text{DMToday} = [\text{Stem}].\text{potentialDMAAllocation.Structural} + [\text{Stem}].\text{Live.Wt}$$

$$\text{Zero} = 0$$

1.11.7 Senescence and Detachment

Stem has senescence parameterised to zero so all biomass in this organ will remain alive.

Stem has detachment parameterised to zero so all biomass in this organ will remain with the plant until a defoliation or harvest event occurs.

1.11.8 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.

1.12 TotalPlantDemand

$$\text{TotalPlantDemand} = [\text{Leaf}].\text{DMDemands.Structural.DMDemandFunction} + [\text{Stem}].\text{DMDemands.Structural.DMDemandFunction} + [\text{Rachis}].\text{DMDemands.Structural.DMDemandFunction} + [\text{Grain}].\text{DMDemands.Structural.DMDemandFunction}$$

1.13 AboveGround

1.13.1 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
- * Rachis
- * Grain

1.14 AboveGroundLive

1.14.1 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
- * Grain
- * Rachis

1.15 AboveGroundDead

1.15.1 AboveGroundDead

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

AboveGroundDead summarises the following biomass objects:

- * Leaf
- * Stem
- * Grain
- * Rachis

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

1.17 Total

1.17.1 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
- * Root
- * Rachis
- * Grain

1.18 TotalLive

1.18.1 TotalLive

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

TotalLive summarises the following biomass objects:

- * Leaf
- * Stem
- * Root
- * Rachis
- * Grain

1.19 TotalDead

1.19.1 TotalDead

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

TotalDead summarises the following biomass objects:

- * Leaf
- * Stem
- * Root
- * Rachis
- * Grain

1.20 MortalityRate

MortalityRate = 0

1.21 SeedMortalityRate

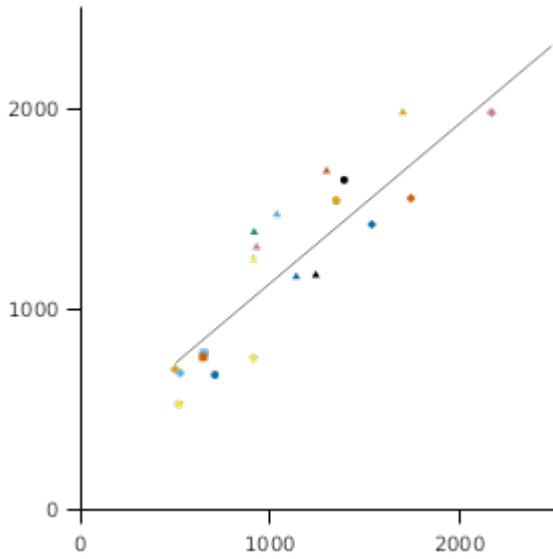
SeedMortalityRate = 0

2 Validation

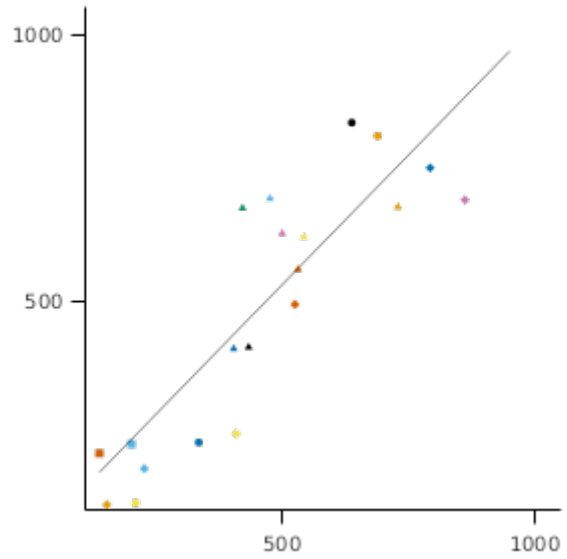
2.1 Combined Results

Simulation results for the combined datasets from the various countries are shown in the following graphs. The model is able to adequately capture the influence of growing conditions (soil, climate) and management (population, Nitrogen, irrigation, sowing date).

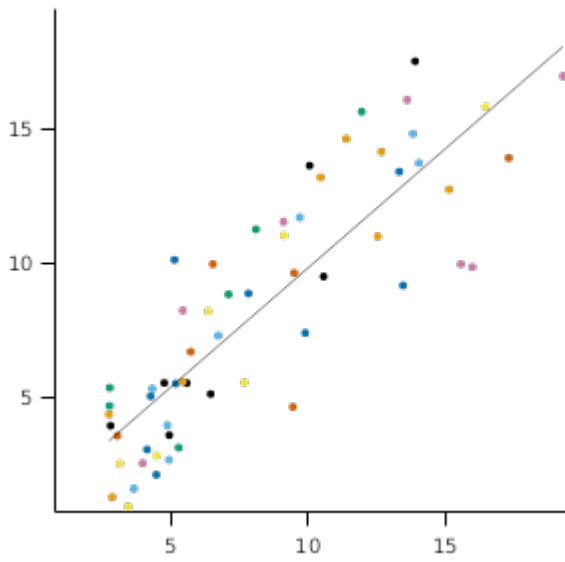
Harvest Biomass



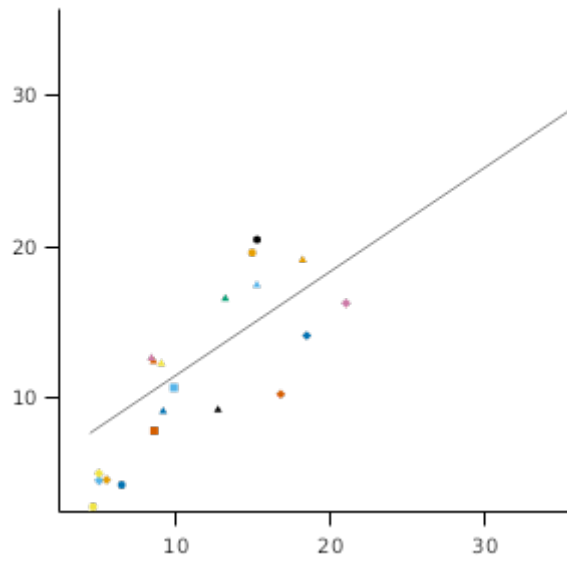
Yield



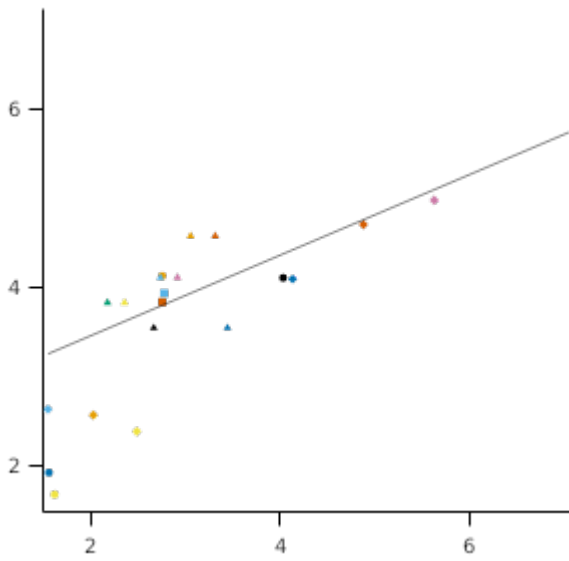
GrainN



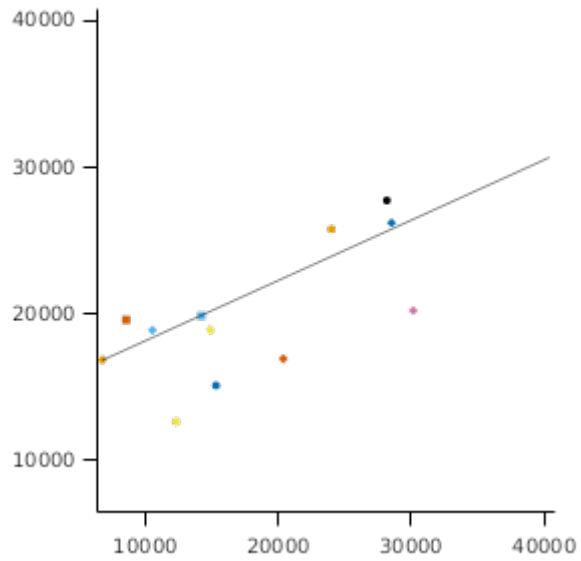
BiomassN



LaiAnth



GrainNumber



End Date: 30/06/1997

SimulationName	Cultivar
Sorghum_HE1_T1	QL41xQL36
Sorghum_HE1_T2	Buster
Sorghum_HE1_T3	M35-1

2.2.3 HE3

Experiment: HE3

Description: HE3 - High N/No Irrig. - 3 Indian/Aust. Cultivars

Start Date: 1/12/1996

End Date: 30/06/1997

SimulationName	Cultivar
Sorghum_HE3_T1	QL41xQL36
Sorghum_HE3_T2	Buster
Sorghum_HE3_T3	M35-1

2.2.4 HE4

Experiment: HE4

Description: HE4 - Low N/No Irrig. - 3 Indian/Aust. Cultivars

Start Date: 1/12/1996

End Date: 30/06/1997

SimulationName	Cultivar
Sorghum_HE4_T1	QL41xQL36
Sorghum_HE4_T2	Buster
Sorghum_HE4_T3	M35-1

2.2.5 HE5

Experiment: HE5

Description: HE5 - High N/Irrig. - 3 Indian/Aust. Cultivars

Start Date: 18/11/1997

End Date: 15/04/1998

SimulationName	Cultivar
Sorghum_HE5_T1	Buster
Sorghum_HE5_T2	M35-1
Sorghum_HE5_T3	CSH13R

2.2.6 HE6

Experiment: HE6

Description: HE6 - Low N/Irrig. - 3 Indian/Aust. Cultivars

Start Date: 18/11/1997

End Date: 15/04/1998

SimulationName	Cultivar
Sorghum_HE6_T1	Buster
Sorghum_HE6_T2	M35-1
Sorghum_HE6_T3	CSH13R

2.2.7 HE7

Experiment: HE7

Description: HE7 - High N/No Irrig. - 3 Indian/Aust. Cultivars

Start Date: 18/11/1997

End Date: 15/04/1998

SimulationName	Cultivar
Sorghum_HE7_T1	Buster
Sorghum_HE7_T2	M35-1
Sorghum_HE7_T3	CSH13R

2.2.8 HE8

Experiment: HE8

Description: HE8 - Low N/No Irrig - 3 Indian/Aust. Cultivars

Start Date: 17/11/1997

End Date: 15/04/1998

SimulationName	Cultivar
Sorghum_HE8_T1	Buster
Sorghum_HE8_T2	M35-1
Sorghum_HE8_T3	CSH13R

2.3 Icrisat

List of experiments.

Experiment Name	Design (Number of Treatments)
BW5	Cv x Fert x Irrig (12)
BW8	Cv x Fert x Irrig (12)

2.3.1 BW5

Experiment: BW5_GxE

Description: Genotype x Management Environment (Rabi Sorghum)

Start Date: 26/09/1996

End Date: 20/02/1997

Treatment	Cultivar	N Rates	Irrigation
Sorghum_BW5_GxE_T1	M35-1	240	Irrigated

Treatment	Cultivar	N Rates	Irrigation
Sorghum_BW5_GxE_T2	CSH13R	240	Irrigated
Sorghum_BW5_GxE_T3	ATx623/RTx430	240	Irrigated
Sorghum_BW5_GxE_T4	QL41/QL36	240	Irrigated
Sorghum_BW5_GxE_T5	M35-1	120	Dryland
Sorghum_BW5_GxE_T6	CSH13R	120	Dryland
Sorghum_BW5_GxE_T7	ATx623/RTx430	120	Dryland
Sorghum_BW5_GxE_T8	QL41/QL36	120	Dryland
Sorghum_BW5_GxE_T9	M35-1	10	Dryland
Sorghum_BW5_GxE_T10	CSH13R	10	Dryland
Sorghum_BW5_GxE_T11	ATx623/RTx430	10	Dryland
Sorghum_BW5_GxE_T12	QL41/QL36	10	Dryland

2.3.2 BW8

Experiment: BW8_GxE

Description: BW8 - GENO x ENVIRON (RABI SORGHUM)

Start Date: 26/09/1996

End Date: 20/02/1997

Treatment	Cultivar	N Rates	Irrigation
Sorghum_BW8_GxE_T1	M35-1	240	Irrigated
Sorghum_BW8_GxE_T2	CSH13R	240	Irrigated
Sorghum_BW8_GxE_T3	ATx623/RTx430	240	Irrigated
Sorghum_BW8_GxE_T4	QL41/QL36	240	Irrigated
Sorghum_BW8_GxE_T5	M35-1	120	Dryland
Sorghum_BW8_GxE_T6	CSH13R	120	Dryland
Sorghum_BW8_GxE_T7	ATx623/RTx430	120	Dryland
Sorghum_BW8_GxE_T8	QL41/QL36	120	Dryland
Sorghum_BW8_GxE_T9	M35-1	20	Dryland
Sorghum_BW8_GxE_T10	CSH13R	20	Dryland
Sorghum_BW8_GxE_T11	ATx623/RTx430	20	Dryland
Sorghum_BW8_GxE_T12	QL41/QL36	20	Dryland

2.4 Lawes

List of experiments.

Experiment Name	Design (Number of Treatments)
LE13	(6)
LE14	Cv (3)

Experiment Name	Design (Number of Treatments)
LE15	Cv (3)
LE17	Cv (3)
LE19	(8)
LE21	Cv x Fert (9)

2.4.1 LE13

Experiment: LE13

Description: 2 Cultivars x 2 Water regimes x 2 N Potential Yield

Start Date: 28/11/1995

End Date: 1/05/1996

SimulationName	Irrigation	N Rates	Cultivar
Lawes1995FertLowirrigOffCvBuster	Irrigation to establish & fert inco	10 N	Buster
Lawes1995FertHighIrrigOffCvBuster	Irrigation to establish & fert inco	240 N	Buster
Lawes1995FertHighIrrigOnCvBuster	Irrigated	240 N	Buster
Lawes1995FertLowIrrigOffCvM351	Irrigation to establish & fert inco	10 N	M35-1
Lawes1995FertHighIrrigOffCvM351	Irrigation to establish & fert inco	240 N	M35-1
Lawes1995FertHighIrrigOnCvM351	Irrigated	240 N	M35-1

2.4.2 LE14

Experiment: LE14

Description: Early Sow - 3 Indian/Aust Cultivars

Start Date: 5/09/1996

End Date: 19/02/1997

SimulationName	Cultivar
Lawes1996EarlyCvBuster	Buster
Lawes1996EarlyCvM351	M35-1
Lawes1996EarlyCvQL41xQL36	QL41xQL36

2.4.3 LE15

Experiment: LE15

Description: Late Sow - 3 Indian/Aust Cultivars

Start Date: 5/09/1996

End Date: 8/05/1997

SimulationName	Cultivar
Lawes1996LateCvBuster	Buster
Lawes1996LateCvM351	M35-1
Lawes1996LateCvQL41xQL36	QL41xQL36

2.4.4 LE17

Experiment: LE17

Description: LE17 Growth Analysis- Late Sow - 2 Indian/ 1 Aust. Cultivars

Start Date: 27/11/1997

End Date: 27/04/1998

SimulationName	Cultivar
Lawes1997LateCvBuster	Buster
Lawes1997LateCvM351	M35-1
Lawes1997LateCvCSH13R	CSH13R

2.4.5 LE19

Experiment: LE19

Description: LE19 - Genotypic variation in Radiation Use Efficiency

Start Date: 9/11/1998

End Date: 7/03/1999

SimulationName	N Rates	Cultivar
Lawes1998FertOffBuster	0 kg/ha	Buster
Lawes1998FertLowBuster	120 kg/ha	Buster
Lawes1998FertMedBuster	240 kg/ha	Buster
Lawes1998FertHighBuster	360 kg/ha	Buster
Lawes1998FertOffCSH13R	0 kg/ha	CSH13R
Lawes1998FertLowCSH13R	120 kg/ha	CSH13R
Lawes1998FertMedCSH13R	240 kg/ha	CSH13R
Lawes1998FertHighCSH13R	360 kg/ha	CSH13R

2.4.6 LE21

Experiment: Gatton_RUE

Description: N Rates x Genotype LE21

Start Date: 22/11/1999

End Date: 3/04/2000

SimulationName	Cultivar	N Rates
Lawes1999FertLowCvCSH13R	CSH13R	0kg/ha
Lawes1999FertLowCvA35xQL36	A35xQL36	0kg/ha
Lawes1999FertLowCvQL39xQL36	QL39xQL36	0kg/ha
Lawes1999FertMedCvCSH13R	CSH13R	45kg/ha
Lawes1999FertMedCvA35xQL36	A35xQL36	45kg/ha
Lawes1999FertMedCvQL39xQL36	QL39xQL36	45kg/ha
Lawes1999FertHighCvCSH13R	CSH13R	360kg/ha

SimulationName	Cultivar	N Rates
Lawes1999FertHighCvA35xQL36	A35xQL36	360kg/ha
Lawes1999FertHighCvQL39xQL36	QL39xQL36	360kg/ha

3 References

- Alam, Mohammad Mobashwer, Hammer, Graeme L., Oosterom, Erik J., Cruickshank, Alan W., Hunt, Colleen H., Jordan, David R., 2014. A physiological framework to explain genetic and environmental regulation of tillering in sorghum. *New Phytologist* 203 (1), 155-167.
- Anten, N. P. R., Schieving, F., Werger, M. J. A., 1995. Patterns of light and nitrogen distribution in relation to whole canopy carbon gain in C3 and C4 mono- and dicotyledonous species. *Oecologia* 101 (4), 504-513.
- Birch, C.J., Carberry, P.S., Muchow, R.C., McCown, R.L., Hargreaves, J.N.G., 1990. Development and evaluation of a sorghum model based on CERES-Maize in a semi-arid tropical environment. *Field Crops Research* 24 (1-2), 87-104.
- [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., Muchow, R.C., Hammer, G.L., 1993. Modelling genotypic and environmental control of leaf area dynamics in grain sorghum. II. Individual leaf level. *Field Crops Research* 33 (3), 311-328.
- Chapman, S. C., Cooper, M., Hammer, G. L., Butler, D. G., 2000. Genotype by environment interactions affecting grain sorghum. II. Frequencies of different seasonal patterns of drought stress are related to location effects on hybrid yields. *Australian Journal of Agricultural Research* 51 (2), 209.
- Chapman, S. C., Hammer, G. L., Butler, D. G., Cooper, M., 2000. Genotype by environment interactions affecting grain sorghum. III. Temporal sequences and spatial patterns in the target population of environments. *Australian Journal of Agricultural Research* 51 (2), 223-233.
- Chapman, S. C., Hammer, G. L., Meinke, H., 1993. A Sunflower simulation model.1. Model development. *Agronomy Journal* 85 (3), 725-735.
- Chapman, S., Cooper, M., Podlich, D.W., Hammer, G., 2003. Evaluating plant breeding strategies by simulating gene action and dryland environment effects.. *Agron. J.* 95, 99-113.
- Charles-Edwards, D.A., 1982. Physiological Determinants of Crop Growth. XF2006232780.
- Cooper, Mark, Messina, Carlos D., Podlich, Dean, Totir, L. Radu, Baumgarten, Andrew, Hausmann, Neil J., Wright, Deanne, Graham, Geoffrey, 2014. Predicting the future of plant breeding: complementing empirical evaluation with genetic prediction. *Crop and Pasture Science* 65 (4), 311.
- Craufurd, P. Q., Flower, D. J., Peacock, J. M., 1993. Effect of Heat and Drought Stress on Sorghum (texititSorghum Bicolor). I. Panicle Development and Leaf Appearance. *Experimental Agriculture* 29 (1), 61-76.
- GRINDLAY, D. J. C., 1997. REVIEW Towards an explanation of crop nitrogen demand. *The Journal of Agricultural Science* 128 (4), 377-396.
- Hammer, G. L., Chapman, S., van Oosterom, E., Podlich, D. W., 2005. Trait physiology and crop modelling as a framework to link phenotypic complexity to underlying genetic systems. *Australian Journal of Agricultural Research* 56 (9), 947-960.
- [Hammer, G. L., Muchow, R. C., 1994. Assessing climatic risk to sorghum production in water-limited subtropical environments I. Development and testing of a simulation model. *Field Crops Research* 36 \(3\), 221-234.](#)
- Hammer, G. L., Vanderlip, R. L., Gibson, G., Wade, L. J., Henzell, R. G., Younger, D. R., Warren, J., Dale, A. B., 1989. Genotype-by-Environment Interaction in Grain Sorghum. II. Effects of Temperature and Photoperiod on Ontogeny. *Crop Science* 29 (2), 376.
- Hammer, G.L., Carberry, P.S., Muchow, R.C., 1993. Modelling genotypic and environmental control of leaf area dynamics in grain sorghum. I. Whole plant level. *Field Crops Research* 33 (3), 293-310.
- [Hammer, Graeme L., Dong, Zhanshan, McLean, Greg, Doherty, Al, Messina, Carlos, Schussler, Jeff, Zinselmeier, Chris, Paszkiewicz, Steve, Cooper, Mark, 2009. Can Changes in Canopy and/or Root System Architecture Explain Historical Maize Yield Trends in the U.S. Corn Belt?. *Crop Sci* 49 \(1\), 299-312.](#)

- Hammer, Graeme L., Farquhar, Graham D., Broad, Ian J., 1997. On the extent of genetic variation for transpiration efficiency in sorghum. *Australian Journal of Agricultural Research* 48 (5), 649.
- Hammer, Graeme L., McLean, Greg, Chapman, Scott, Zheng, Bangyou, Doherty, Al, Harrison, Matthew T., van Oosterom, Erik, Jordan, David, 2014. Crop design for specific adaptation in variable dryland production environments. *Crop and Pasture Science* 65 (7), 614.
- Hammer, Graeme L., van Oosterom, Erik, McLean, Greg, Chapman, Scott C., Broad, Ian, Harland, Peter, Muchow, Russell C., 2010. Adapting APSIM to model the physiology and genetics of complex adaptive traits in field crops. *Journal of Experimental Botany* 61 (8), 2185-2202.
- Hammer, Graeme, Cooper, Mark, Tardieu, Francois, Welch, Stephen, Walsh, Bruce, van Eeuwijk, Fred, Chapman, Scott, Podlich, Dean, 2006. Models for navigating biological complexity in breeding improved crop plants. *Trends in Plant Science* 11 (12), 587-593.
- Hammer, Graeme, Erik J. van Oosterom, Scott C. Chapman, Greg McLean, 2001. The economic theory of water and nitrogen dynamics and management in field crops..
- Hammer, Graeme, McLean, Greg, Doherty, Al, van Oosterom, Erik, Chapman, Scott, 2019. *Agronomy Monographs*. *Agronomy Monographs*, 215-239.
- Hammer, Graeme, Messina, Charlie, van Oosterom, Erik, Chapman, Scott, Singh, Vijaya, Borrell, Andrew, Jordan, David, Cooper, Mark, 2016. *Crop Systems Biology*. *Crop Systems Biology*, 147-162.
- Hammer, Graeme, Messina, Charlie, Wu, Alex, Cooper, Mark, 2019. Biological reality and parsimony in crop models--why we need both in crop improvement!. in *in silico Plants* 1 (1).
- Hammer, Graeme. L., McLean, Greg, Oosterom, Erik, Chapman, Scott, Zheng, Bangyou, Wu, Alex, Doherty, Alastair, Jordan, David, 2020. Designing crops for adaptation to the drought and hightemperature risks anticipated in future climates. *Crop Science* 60 (2), 605-621.
- Heiniger, Ronnie W., Vanderlip, Richard L., Welch, Stephen M., Muchow, Russell C., 1997. Developing Guidelines for Replanting Grain Sorghum: II. Improved Methods of Simulating Caryopsis Weight and Tiller Number. *Agronomy Journal* 89 (1), 84-92.
- [Jones, C.A., Kiniry, J.R., Dyke, P.T., 1986. CERES-Maize: a simulation model of maize growth and development..](#)
- Kemarian, Armen R., Stöckle, Claudio O., Huggins, David R., 2005. Transpiration-use efficiency of barley. *Agricultural and Forest Meteorology* 130 (1-2), 1-11.
- Kim, Hae Koo, van Oosterom, Erik, Dingkuhn, Michael, Luquet, Delphine, Hammer, Graeme, 2010. Regulation of tillering in sorghum: environmental effects. *Annals of Botany* 106 (1), 57-67.
- LAFARGE, T. A., HAMMER, G. L., 2002. Tillering in Grain Sorghum over a Wide Range of Population Densities: Modelling Dynamics of Tiller Fertility. *Annals of Botany* 90 (1), 99-110.
- Martre, Pierre, Jamieson, Peter D., Semenov, Mikhail A., Zyskowski, Robert F., Porter, John R., Triboulet, Eugène, 2006. Modelling protein content and composition in relation to crop nitrogen dynamics for wheat. *European Journal of Agronomy* 25 (2), 138-154.
- Meinke, Holger, Hochman, Zvi, 2000. Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems. *Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems*, 149-165.
- Messina, C.D., Technow, F., Tang, T., Totir, R., Gho, C., Cooper, M., 2018. Leveraging biological insight and environmental variation to improve phenotypic prediction: Integrating crop growth models (CGM) with whole genome prediction (WGP). *European Journal of Agronomy* 100, 151-162.
- [Monteith, J. L., Greenwood, D. J., 1986. How Do Crops Manipulate Water Supply and Demand? \[and Discussion\]. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 316 \(1537\), 245-259.](#)
- 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.
- Muchow, R. C., Sinclair, T. R., 1994. Nitrogen Response of Leaf Photosynthesis and Canopy Radiation Use Efficiency in FieldGrown Maize and Sorghum. *Crop Science* 34 (3), 721-727.
- Muchow, R.C., Carberry, P.S., 1990. Phenology and leaf-area development in a tropical grain sorghum. *Field Crops Research* 23 (3-4), 221-237.

- Nelson, R. A., Holzworth, D. P., Hammer, G. L., Hayman, P. T., 2002. Infusing the use of seasonal climate forecasting into crop management practice in North East Australia using discussion support software. *Agricultural Systems* 74 (3), 393-414.
- Passioura, J.B., 1983. Roots and drought resistance. *Agricultural Water Management* 7 (1-3), 265-280.
- Probert, M. E., Dimes, J. P., Keating, B. A., Dalal, R. C., Strong, W. M., 1998. APSIM's Water and Nitrogen Modules and Simulation of the Dynamics of Water and Nitrogen in Fallow Systems. *Agricultural Systems* 56 (1), 1-28.
- Ravi Kumar, S., Hammer, Graeme L., Broad, Ian, Harland, Peter, McLean, Greg, 2009. Modelling environmental effects on phenology and canopy development of diverse sorghum genotypes. *Field Crops Research* 111 (1-2), 157-165.
- 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.
- Robertson, M.J., Fukai, S., Ludlow, M.M., Hammer, G.L., 1993. Water extraction by grain sorghum in a sub-humid environment. I. Analysis of the water extraction pattern. *Field Crops Research* 33 (1-2), 81-97.
- Rosenthal, W.D., 1989. SORKAM: A Grain Sorghum Crop Growth Model.. Texas A and M University, College Station, Texas.
- Sinclair, T. R., 1986. Water and nitrogen limitations in soybean grain production. I. Model development.. *Field Crops Research* 15, 125-141.
- [Sinclair, T. R., Horie, T., 1989. Leaf Nitrogen, Photosynthesis, and Crop Radiation Use Efficiency: A Review. *Crop Science* 29 \(1\), crops1989.0011183X002900010023x.](#)
- Sinclair, T.R., Amir, J., 1992. A model to assess nitrogen limitations on the growth and yield of spring wheat. *Field Crops Research* 30 (1-2), 63-78.
- Sinclair, Thomas R., Hammer, Graeme L., van Oosterom, Erik J., 2005. Potential yield and water-use efficiency benefits in sorghum from limited maximum transpiration rate. *Functional Plant Biology* 32 (10), 945.
- Sinclair, Thomas R., Muchow, Russell C., 1999. Advances in Agronomy. *Advances in Agronomy*, 215-265.
- Tanner, C. B., Sinclair, T. R., 1983. Limitations to Efficient Water Use in Crop Production. *Limitations to Efficient Water Use in Crop Production*, 1-27.
- Van Keulen, H., Seligman, N. G., 1987. Simulation of water use, nitrogen nutrition and growth of a spring wheat crop. *Simulation of water use, nitrogen nutrition and growth of a spring wheat crop..*
- van Oosterom, E.J., Borrell, A.K., Chapman, S.C., Broad, I.J., Hammer, G.L., 2010. Functional dynamics of the nitrogen balance of sorghum: I. N demand of vegetative plant parts. *Field Crops Research* 115 (1), 19-28.
- [van Oosterom, E.J., Carberry, P.S., Hargreaves, J.N.G., O'Leary, G.J., 2001. Simulating growth, development, and yield of tillering pearl millet: II. Simulation of canopy development. *Field Crops Research* 72 \(1\), 67 - 91.](#)
- Whish, J., Butler, G., Castor, M., Cawthray, S., Broad, I., Carberry, P., Hammer, G., McLean, G., Routley, R., Yeates, S., 2005. Modelling the effects of row configuration on sorghum yield reliability in north-eastern Australia. *Australian Journal of Agricultural Research* 56 (1), 11-23.
- Wu, Alex, Hammer, Graeme L., Doherty, Al, von Caemmerer, Susanne, Farquhar, Graham D., 2019. Quantifying impacts of enhancing photosynthesis on crop yield. *Nature Plants* 5 (4), 380-388.