



1 The APSIM Wheat Model

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The APSIM wheat 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 wheat model consists of:

- * a phenology model to simulate development through sequential developmental phases
- * a structure model to simulate plant morphology
- * a collection of organs to simulate the various plant parts
- * an arbitrator to allocate resources (N, biomass) to the various plant organs

This work builds upon earlier APSIM Wheat models such as NWheat ([S Asseng et al., 2002](#), [BA Keating, 2001](#)), NWheatS ([S Asseng et al., 1998](#)), Cropmod-Wheat ([Wang et al., 2002](#)), and the earlier versions developed in Plant (<http://www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Wheat.aspx>) and then within the Plant Modelling Framework ([Brown et al., 2014](#)).

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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
Structure	Models.PMF.Struct.Structure
Grain	Models.PMF.Organs.ReproductiveOrgan
Root	Models.PMF.Organs.Root
Leaf	Models.PMF.Organs.Leaf
Spike	Models.PMF.Organs.GenericOrgan
Stem	Models.PMF.Organs.GenericOrgan
MortalityRate	Models.Functions.Constant
SeedMortalityRate	Models.Functions.Constant

1.1 Arbitrator

1.1.1 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.

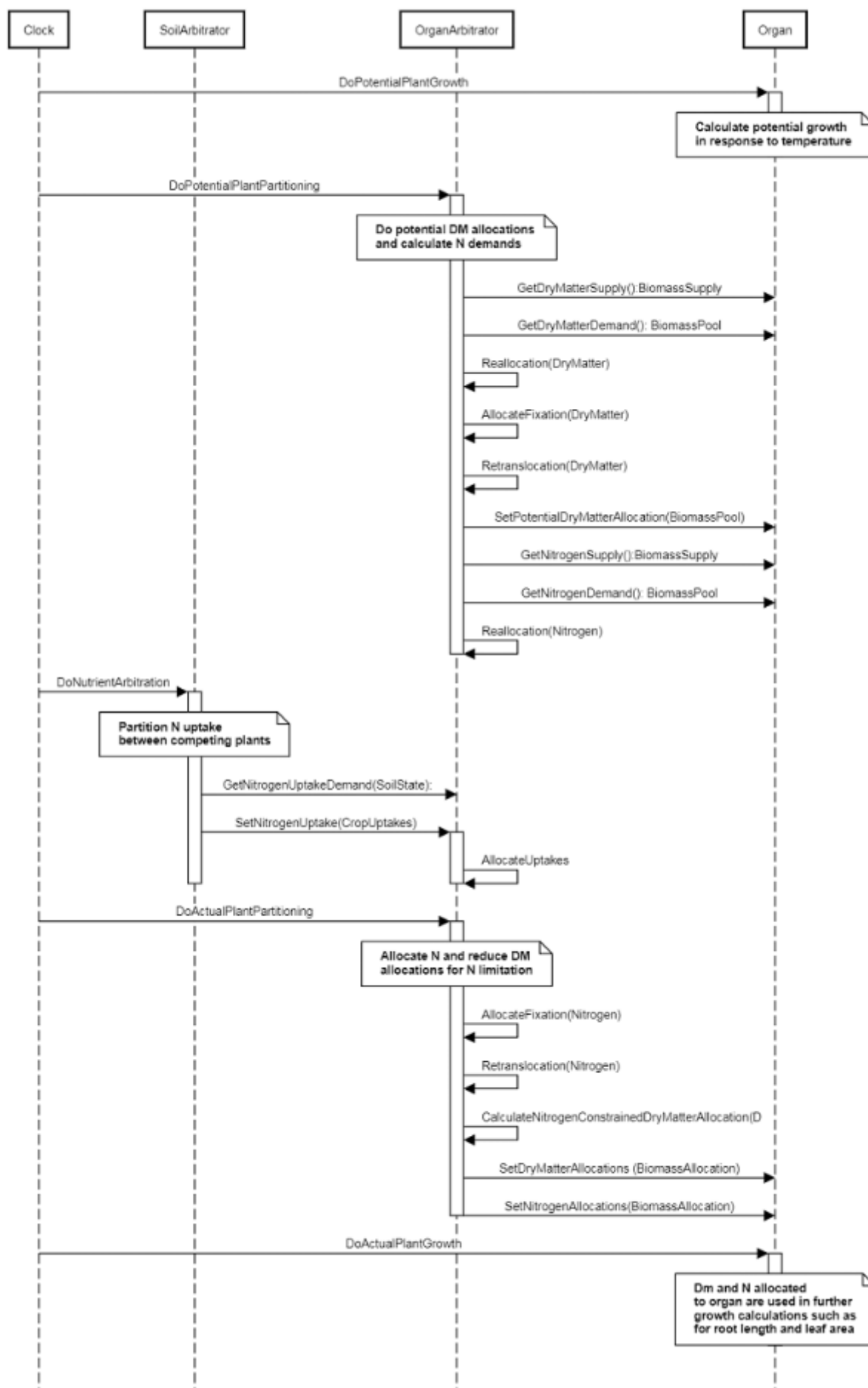


Figure 1: Schematic showing the procedure for arbitration of biomass partitioning. Pink boxes represent events that occur every day and their numbering shows the order of calculations. Blue boxes represent the methods that are called when these events occur. Orange boxes contain properties that make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

1.2 Phenology

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

Wheat exhibits a range of developmental responses to environment and these are strongly influenced by genotype characteristics. Temperature is the primary driver of development, increasing development rates and decreasing phase durations as it increases. These affects are captured by thermal time. However, wheat also exhibits cold and photoperiod sensitivities in its Vernalisaing phase and further photoperiod sensitivity in the SpikeletDifferentation and HeadEmergence phases. Photoperiod responses are seen as a reduction in the length of a phase for a photoperiod sensitive genotype in response to a longer photoperiod. Vernalisation responses are more complicated as they are driven by cool temperature but interact with photoperiod. For vernalisation sensitive varieties (Winter types), exposure to cool temperatures and/or short photoperiods during the Vernalising phase may reduce its thermal time duration.

APSIM wheat implements the Cereal Anthesis Molecular Phenology (CAMP) model to simulate development. It is based on the Kirby Framework which assumes the timing of anthesis is a result of the timing of flag leaf and an additional thermal time passage from there to heading then anthesis. It also assumes the timing of flag leaf is a result of the Final Leaf Number (which sets a target) and leaf appearance rate (which sets the rate of progress toward the target). Leaf appearance rate is a function of Thermal time and a genotype specific Phyllochron which changes with Haun stage as described by [Jamieson et al., 1995](#).

Final Leaf Number (FLN) is set on the day that terminal spikelet occurs as:

FLN = 2.85 + 1.1 * TSHS

Where TSHS is the Haun stage on the day terminal spikelet stage occurs. Terminal spikelet is at the end of the SpikeletDifferentiaition phase which is preceeded by the Emerging and Vernalising phases. The mechanisums for progress through each of these phase are described below

1.2.1 ThermalTime

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

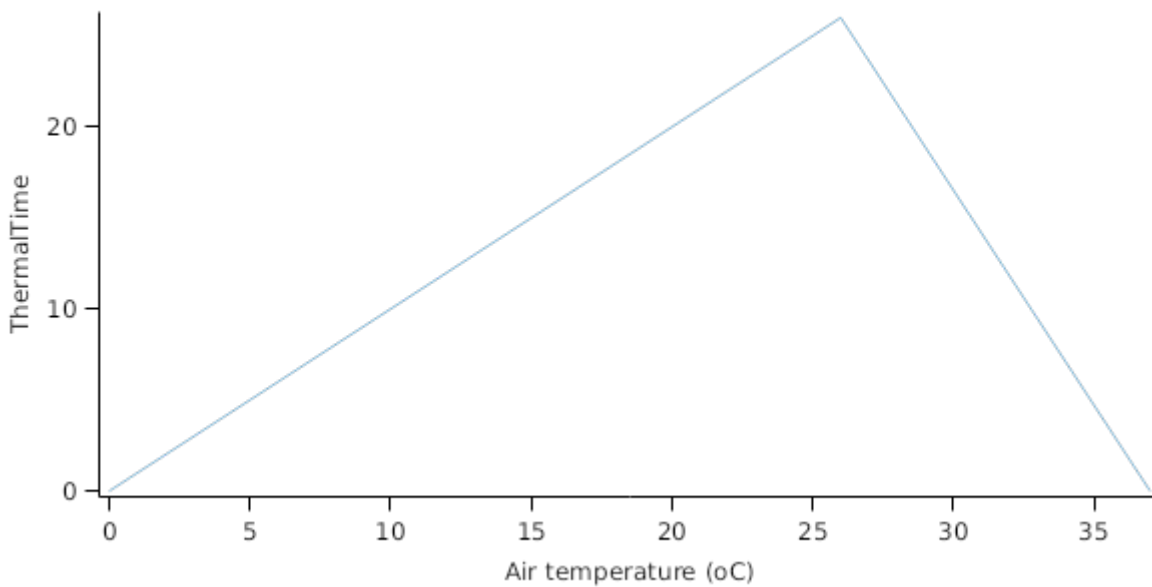
Thermal time determines the rate of developmental progress through many of the crops phases and is used by organs to determing potential growth rates.

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

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

Air temperature (oC)	ThermalTime
0.0	0.0
26.0	26.0
37.0	0.0

ThermalTime



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	Vernalising	Emergence	VernalSaturation
4	SpikeletDifferentiation	VernalSaturation	TerminalSpikelet
5	StemElongation	TerminalSpikelet	FlagLeaf
6	HeadEmergence	FlagLeaf	Heading
7	EarlyFlowering	Heading	Flowering
8	GrainDevelopment	Flowering	StartGrainFill
9	GrainFilling	StartGrainFill	EndGrainFill
10	Maturing	EndGrainFill	Maturity
11	Ripening	Maturity	HarvestRipe
12	ReadyForHarvesting	HarvestRipe	Unused

1.2.2 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.

1.2.3 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:

$$\text{Target} = \text{SowingDepth} \times \text{ShootRate} + \text{ShootLag}$$

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:

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

1.2.4 Vernalising

The Vernalising phase goes from the Emergence stage to the VernalSaturation stage and reaches VernalSaturation when vernalisation saturation occurs.

1.2.5 SpikeletDifferentiation

This phase goes from vernalsaturation to terminalspikelet.

Progress through the Spike differentiation phase is determined by the apparent expression of Vrn3 as predicted by CAMP.

Vrn3 is a photoperiod sensitive gene that promotes expression of Vrn1. Vrn1 is not able to express to adequate levels to achieve reproductive transition without Vrn3 upregulation. Here we assume an apparent Vrn3 expression of 1.0 is sufficient to upregulate Vrn1 enough to trigger terminal spikelet.

Each genotype has a base rate of Vrn3 expression (baseDVrn3) at low photoperiods and a maximum rate of Vrn3 expression (maxDVrn3) under long photoperiods. These two rates are derived internally by the CAMP model from the genotypes FLNparams.

The *Target* for completion is calculated as:

Target = 1 (oD)

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

Progression = [Phenology].CAMP.dVrn

1.2.6 StemElongation

This phase goes from terminalspikelet to flagleaf and it continues until the final main-stem leaf has finished expansion. The duration of this phase is determined by leaf appearance rate (Structure.Phyllochron) and the number of leaves produced on the mainstem (Structure.FinalLeafNumber)

The Final leaf number is fixed at Terminal Spikelet and leaves contune to appear at a rate set by thermal time and phyllochron until flag leaf liguale appears and this phase is completed.

ThermalTime = [Phenology].ThermalTime

FinalLeafNumber = [Structure].FinalLeafNumber

LeafNumber = [Leaf].ExpandedCohortNo + [Leaf].NextExpandingLeafProportion

FullyExpandedLeafNo = [Leaf].ExpandedCohortNo

InitialisedLeafNumber = [Leaf].InitialisedCohortNo

1.2.7 HeadEmergence

This phase goes from flagleaf to heading.

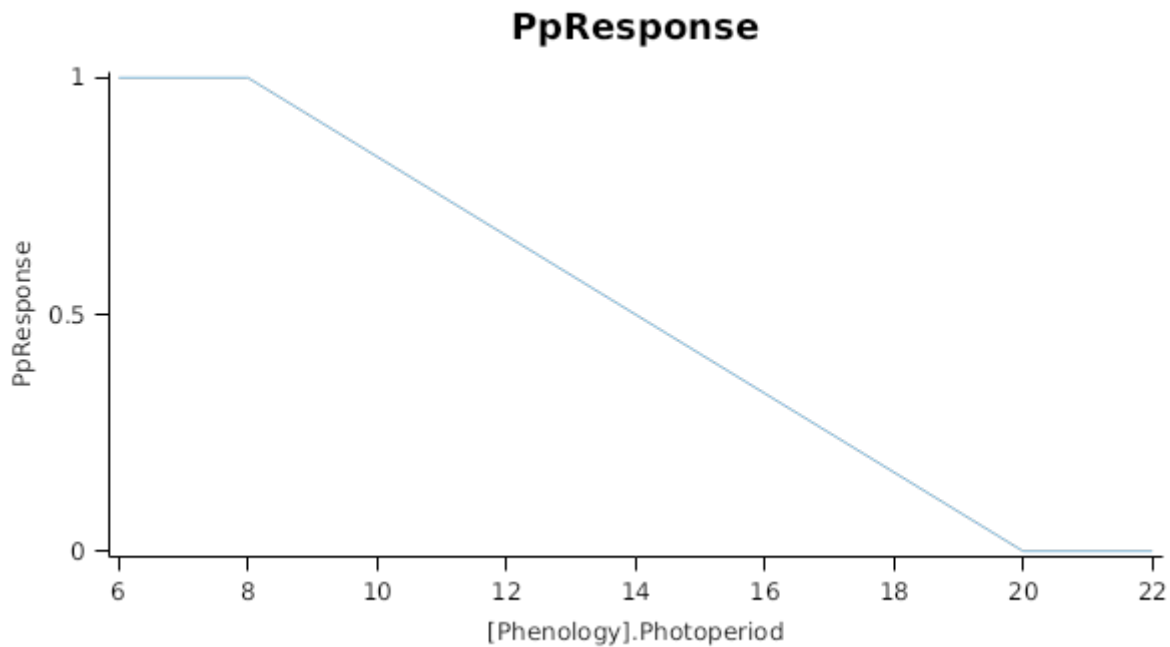
The *Target* for completion is calculated as:

Target = [Phenology].HeadEmergenceLongDayBase.FixedValue + *ShortPpExtension*

ShortPpExtension = [Phenology].HeadEmergenceLongDayBase.FixedValue x [Phenology].HeadEmergencePpSensitivity.FixedValue x *PpResponse*

PpResponse is calculated using linear interpolation

[Phenology].Photoperiod	PpResponse
6.0	1.0
8.0	1.0
20.0	0.0
22.0	0.0



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

Progression = *[Phenology].ThermalTime*

1.2.8 EarlyFlowering

This phase goes from heading to flowering.

The *Target* for completion is calculated as:

Target = 80 (oCd)

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

Progression = *[Phenology].ThermalTime*

1.2.9 GrainDevelopment

This phase goes from flowering to startgrainfill.

The *Target* for completion is calculated as:

Target = 120 (oD)

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

Progression = *[Phenology].ThermalTime*

1.2.10 GrainFilling

This phase goes from startgrainfill to endgrainfill.

The *Target* for completion is calculated as:

Target = 545 (oD)

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

Progression = *[Phenology].ThermalTime*

1.2.11 Maturing

This phase goes from endgrainfill to maturity.

The *Target* for completion is calculated as:

Target = 35 (oD)

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

Progression = *[Phenology].ThermalTime*

1.2.12 Ripening

This phase goes from maturity to harvestripe.

The *Target* for completion is calculated as:

Target = 300 (oD)

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

Progression = *[Phenology].ThermalTime*

1.2.13 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

1.2.14 Constants

The phyllochrons duration for the plant to go from flag leaf ligual appearance at 16 h Pp compared to the phyllochron duration for the same phase at 8 h Pp.

HeadEmergencePpSensitivity = 2

The phyllochrons duration for the plant to go from flag leaf ligual appearance at 16 h Pp.

HeadEmergenceLongDayBase = 200

PhyllochronPpSensitivity = 0.6

1.2.15 Photoperiod

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

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

Twilight = -6 (degrees)

1.2.16 HaunStage

HaunStage = Accumulated *Delta* between emergence and flagleaf

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

Growing has a value between Germination and HarvestRipe calculated as:

Value = *[Phenology].ThermalTime* / *[Phenology].Phyllochron*

1.2.17 Phyllochron

This is the thermal time between the emergence of leaf tips. The model used here is based on [Jamieson et al., 1998](#) where leaf appearace could be described by a base phyllochron determined between leaves 2 and 7 and a phyllochron that was 70% of base phyllochron for leaves < 2 and 130% of base phyllochron for leaves > 7

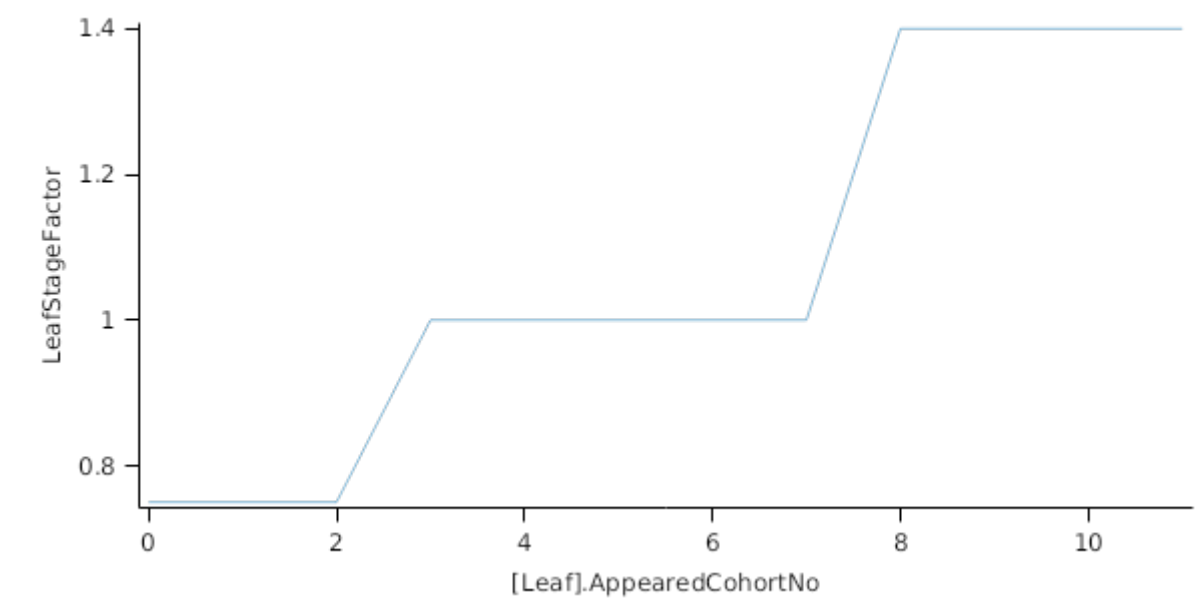
Phyllochron = *LeafStageFactor* x *BasePhyllochron* x *PhotoperiodEffect*

LeafStageFactor is calculated using linear interpolation

<i>[Leaf].AppearedCohortNo</i>	<i>LeafStageFactor</i>
0.0	0.75
2.0	0.75

[Leaf].AppearedCohortNo	LeafStageFactor
3.0	1.0
7.0	1.0
8.0	1.4
11.0	1.4

LeafStageFactor



BasePhyllochron = 120 (oC.d)

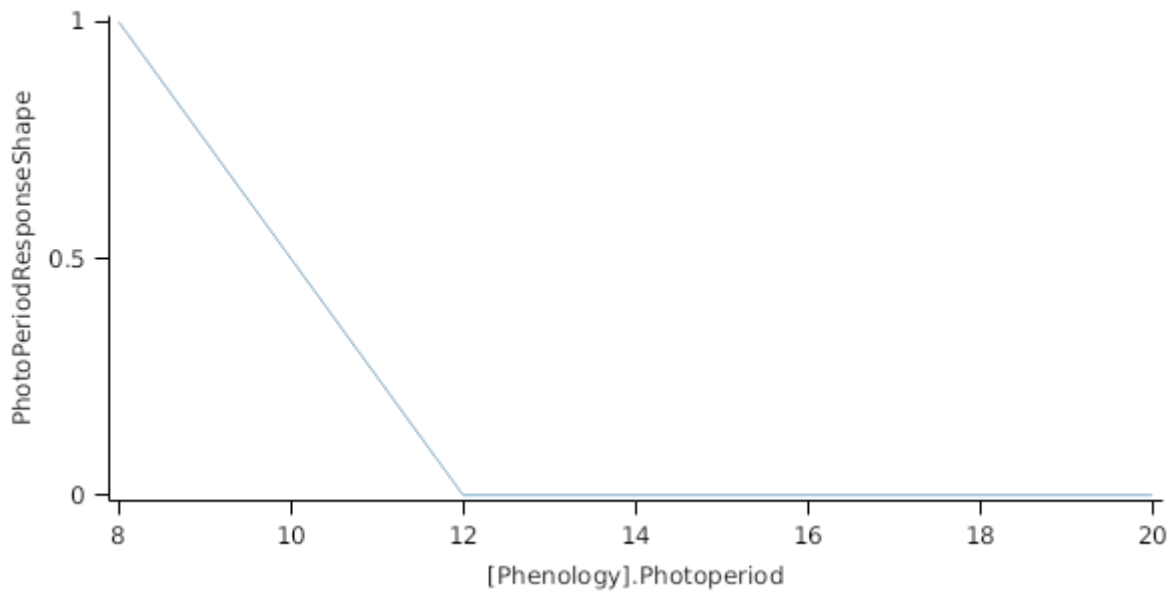
$PhotoperiodEffect = 1 + PhotoperiodResponse$

$PhotoperiodResponse = [Phenology].PhyllochronPpSensitivity \times PhotoPeriodResponseShape$

PhotoPeriodResponseShape is calculated using linear interpolation

[Phenology].Photoperiod	PhotoPeriodResponseShape
8.0	1.0
12.0	0.0
20.0	0.0

PhotoPeriodResponseShape



1.2.18 FinalLeafNumber

$FinalLeafNumber = [Phenology].CAMP.FLN$

1.2.19 Zadok

This model calculates a Zadok growth stage value based upon the current phenological growth stage within the model. The model uses information regarding germination, emergence, leaf appearance and tiller appearance for early growth stages (Zadok stages 0 to 30). The model then uses simulated phenological growth stages for Zadok stages 30 to 100.

List of growth phases

Growth Phase	Description
Germinating	$ZadokStage = 5 \times FractionThroughPhase$
Emerging	$ZadokStage = 5 + 5 \times FractionThroughPhase$
Vegetative	$ZadokStage = 10 + Structure.LeafTipsAppeared$
Reproductive	ZadokStage is interpolated from values of stage number using the following table

List of growth stages

Growth Stage	Stage Name	ZadokStage
4.3	Pseudostem	30
4.9	Third node detectable	33
5	Flag leaf ligule just visible	39
6	Heading (Ear half emerged)	55
7	Flowering (Anthesis half-way)	65
8	Kernel water ripe	71
9	Hard dough	87
10	Ripening	90

1.2.20 TerminalSpikeletDAS

Before TerminalSpikelet

PreEventValue = 0

On TerminalSpikelet the value is set to:

PostEventValue = [Plant].DaysAfterSowing

1.2.21 FlagLeafDAS

Before FlagLeaf

PreEventValue = 0

On FlagLeaf the value is set to:

PostEventValue = [Plant].DaysAfterSowing

1.2.22 HeadingDAS

Before Heading

PreEventValue = 0

On Heading the value is set to:

PostEventValue = [Plant].DaysAfterSowing

1.2.23 FloweringDAS

Before Flowering

PreEventValue = 0

On Flowering the value is set to:

PostEventValue = [Plant].DaysAfterSowing

1.2.24 MaturityDAS

Before Maturity

PreEventValue = 0

On Maturity the value is set to:

PostEventValue = [Plant].DaysAfterSowing

1.2.25 EmergenceDAS

Before Emergence

PreEventValue = 0

On Emergence the value is set to:

PostEventValue = [Plant].DaysAfterSowing

1.2.26 PTQ

PTQ = Radn_mol_per_m2 / [Phenology].ThermalTime

Multiply Radn (MJ/m2/d) by 4.57 to convert to mol/m2/day and divide by 2 to convert to mol PAR/m2/d

Radn_mol_per_m2 = [Weather].Radn x 2.285 x [Leaf].Photosynthesis.FT

1.2.27 CAMP

1.2.27.1 CAMP

Development Gene Expression

1.3 Structure

The structure model simulates morphological development of the plant to inform the Leaf class when and how many leaves and branches appear and provides an estimate of height.

1.3.1 Plant and Main-Stem Population

The *Plant.Population* is set at sowing with information sent from a manager script in the Sow method. The *PrimaryBudNumber* is also sent with the Sow method. The main-stem population (*MainStemPopn*) for Wheat is calculated as:

$$\text{MainStemPopn} = \text{Plant.Population} \times \text{PrimaryBudNumber}$$

Primary bud number is > 1 for crops like potato and grape vine where there are more than one main-stem per plant

1.3.2 Main-Stem leaf appearance

Each day the number of main-stem leaf tips appeared (*LeafTipsAppeared*) is calculated as:

$$\text{LeafTipsAppeared} += \text{DeltaTips}$$

Where *DeltaTips* is calculated as:

$$\text{DeltaTips} = \text{ThermalTime} / \text{Phyllochron}$$

Where *Phyllochron* is the thermal time duration between the appearance of leaf tips given by:

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

ThermalTime is given by

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

LeafTipsAppeared continues to increase until *FinalLeafNumber* is reached where *FinalLeafNumber* is calculated as:

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

1.3.3 Branching and Branch Mortality

The total population of stems (*TotalStemPopn*) is calculated as:

$$\text{TotalStemPopn} = \text{MainStemPopn} + \text{NewBranches} - \text{NewlyDeadBranches}$$

Where:

$$\text{NewBranches} = \text{MainStemPopn} \times \text{BranchingRate}$$

BranchingRate is given by:

Potential branching rate is determined by the commonly observed pattern of tillering in wheat, in which each tiller emerges with the third leaf on its parent axis (e.g. first tiller emerges at the same time as the third leaf on the main stem, the first secondary tiller appears with the third leaf on tiller 1). This is described as a simple function of main stem leaf number.

$$\text{BranchingRate} = \text{PotentialBranchingRate} \times \text{StressFactors}$$

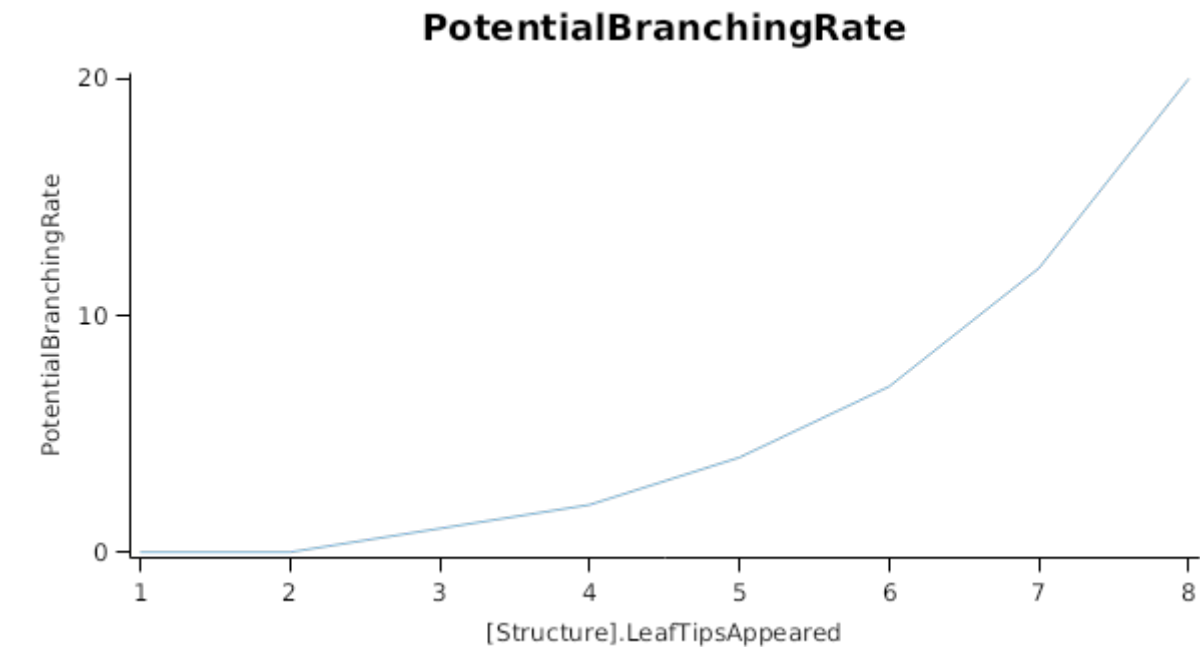
PotentialBranchingRate is calculated using specific values or functions for various growth phases. The function will use a value of zero for phases not specified below.

Vegetative has a value between Emergence and TerminalSpikelet calculated as:

PotentialBranchingRate is calculated using linear interpolation

[Structure].LeafTipsAppeared	PotentialBranchingRate
1.0	0.0
2.0	0.0
3.0	1.0
4.0	2.0

[Structure].LeafTipsAppeared	PotentialBranchingRate
5.0	4.0
6.0	7.0
7.0	12.0
8.0	20.0



Reproductive has a value between TerminalSpikelet and HarvestRipe calculated as:

Zero = 0

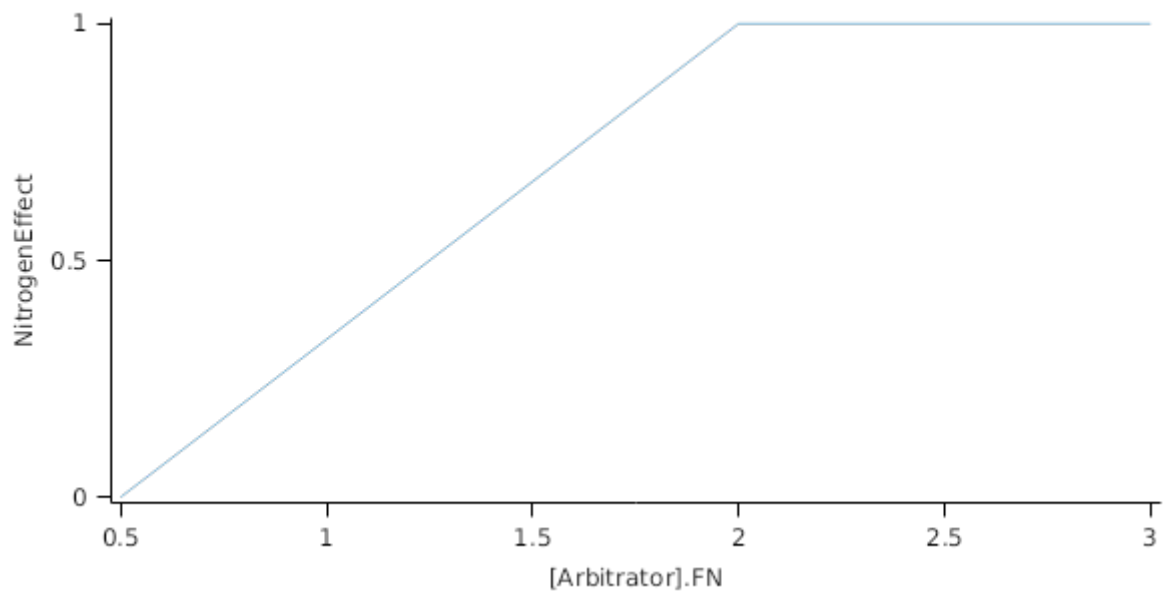
StressFactors = Min(*NitrogenEffect*, *CoverEffect*, *WaterStressEffect*)

Where:

NitrogenEffect is calculated using linear interpolation

[Arbitrator].FN	NitrogenEffect
0.5	0.0
2.0	1.0
3.0	1.0

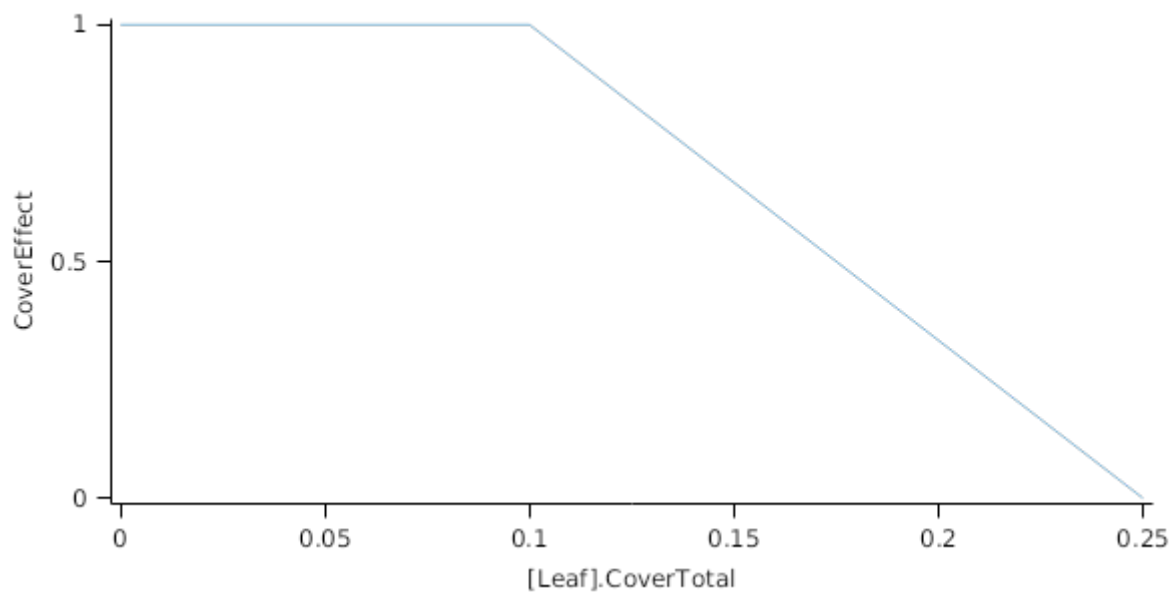
NitrogenEffect



CoverEffect is calculated using linear interpolation

[Leaf].CoverTotal	CoverEffect
0.0	1.0
0.1	1.0
0.25	0.0

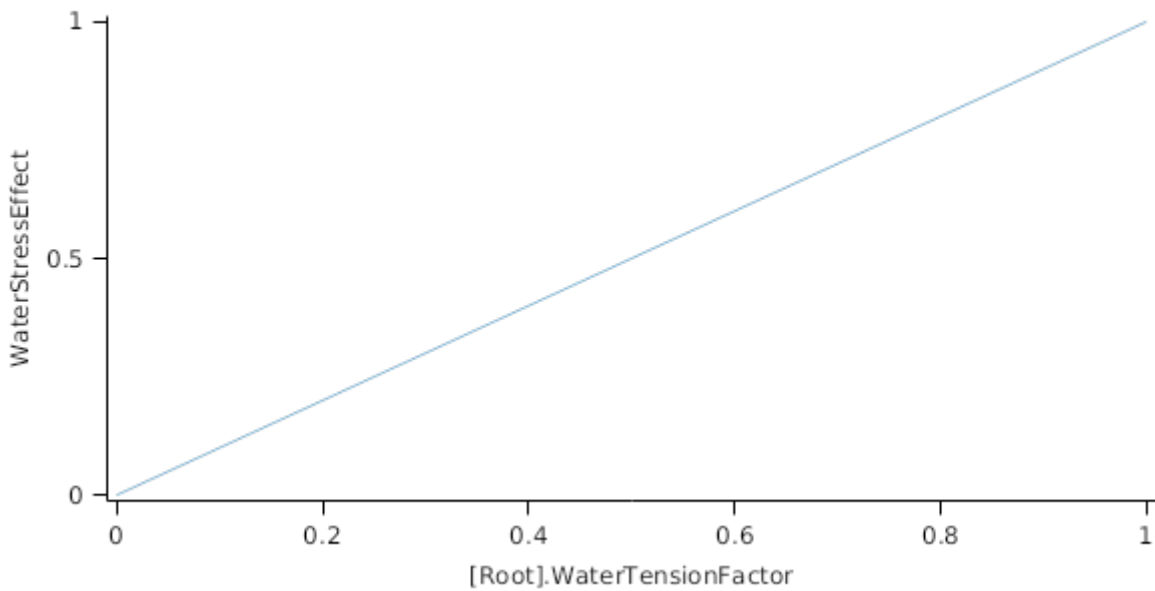
CoverEffect



WaterStressEffect is calculated using linear interpolation

[Root].WaterTensionFactor	WaterStressEffect
0.0	0.0
1.0	1.0

WaterStressEffect



NewlyDeadBranches is calculated as:

$$\text{NewlyDeadBranches} = (\text{TotalStemPopn} - \text{MainStemPopn}) \times \text{BranchMortality}$$

where *BranchMortality* is given by:

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

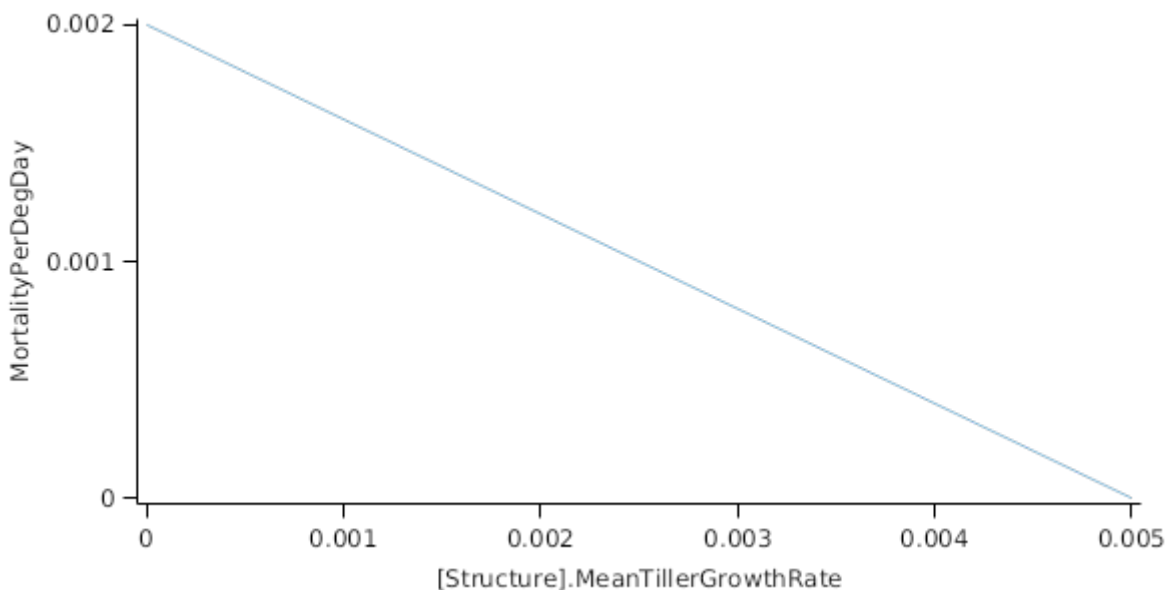
MortalityPhase has a value between FlagLeaf and Flowering calculated as:

$$\text{Mortality} = \text{MortalityPerDegDay} \times [\text{Phenology}].\text{ThermalTime}$$

MortalityPerDegDay is calculated using linear interpolation

[Structure].MeanTillerGrowthRate	MortalityPerDegDay
0.0	0.002
0.005	0.0

MortalityPerDegDay



1.3.4 Height

The height of the crop is calculated by the *HeightModel*

Height is used by the MicroClimate model to calculate the aerodynamic resistance used for calculation of potential transpiration. Calculates the potential height increment and then multiplies it by the smallest of any children functions (Child functions represent stress).

1.4 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).

1.4.1 Constants

DMConversionEfficiency = 1

RemobilisationCost = 0

InitialGrainProportion = 0.05

MaximumPotentialGrainSize = 0.05 (g)

MinimumNConc = 0.0123

MaxNConcDailyGrowth = 0.03

MaximumNConc = 0.03

WaterContent = 0.12

CarbonConcentration = 0.4

1.4.2 NumberFunction

NumberFunction = *GrainNumber* until Flowering after which the value is fixed.

GrainNumber = *GrainsPerGramOfStem* x [*StemPlusSpike*].Wt

GrainsPerGramOfStem = 26 (grains)

1.4.3 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.

InitialPhase has a value between Flowering and StartGrainFill calculated as:

Filling rate is calculated from grain number, a maximum mass to be filled and the duration of the filling process.

NumberFunction = [*Grain*].*NumberFunction*

FillingDuration = [*Phenology*].*GrainDevelopment.Target*

ThermalTime = [*Phenology*].*ThermalTime*

PotentialSizeIncrement = [*Grain*].InitialGrainProportion x [*Grain*].MaximumPotentialGrainSize

LinearPhase has a value between StartGrainFill and EndGrainFill calculated as:

Filling rate is calculated from grain number, a maximum mass to be filled and the duration of the filling process.

NumberFunction = [*Grain*].*NumberFunction*

FillingDuration = [*Phenology*].*GrainFilling.Target*

ThermalTime = [*Phenology*].*ThermalTime*

PotentialSizeIncrement = *ProportionLinearPhase* x [*Grain*].MaximumPotentialGrainSize

ProportionLinearPhase = 1 - [*Grain*].InitialGrainProportion

1.4.4 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.

GrainFilling has a value between Flowering and EndGrainFill calculated as:

Filling rate is calculated from grain number, a maximum mass to be filled and the duration of the filling process.

NumberFunction = [Grain].NumberFunction

FillingDuration = [Phenology].GrainDevelopment.Target + [Phenology].GrainFilling.Target

ThermalTime = [Phenology].ThermalTime

PotentialSizeIncrement = [Grain].MaximumPotentialGrainSize x [Grain].MaximumNConc

1.4.5 AccumThermalTime

AccumThermalTime = Accumulated *DailyThermalTimeValue* between flowering and maturity

DailyThermalTimeValue = [Phenology].ThermalTime

1.4.6 Protein

Protein = divide((([Grain].Live.N + [Grain].Dead.N),([Grain].Live.Wt + [Grain].Dead.Wt)) x 100 x 5.71

1.4.7 BiomassRemovalDefaults

1.4.7.1 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.

1.4.8 DMDemandPriorityFactors

1.4.8.1 DMDemandPriorityFactors

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

1.4.9 NDemandPriorityFactors

1.4.9.1 NDemandPriorityFactors

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

1.5 Root

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

1.5.1 Growth

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

Root Depth Increase = *RootFrontVelocity* x XF_i x *RootDepthStressFactor*

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

Root depth is also constrained by a maximum root depth.

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

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

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

$$DMA_{allocated_i} = TotalDMA_{allocated} \times RAw_i / TotalRAw$$

1.5.2 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.

1.5.3 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.

1.5.4 Nitrogen Uptake

Potential N uptake by the root system is calculated for each soil layer (i) that the roots have extended into. In each layer potential uptake is calculated as the product of the mineral nitrogen in the layer, a factor controlling the rate of extraction (kNO3 or kNH4), the concentration of N form (ppm), and a soil moisture factor (NUptakeSWFactor) which typically decreases as the soil dries. $NO3_{uptake} = NO3_i \times kNO3 \times NO3_{ppm, i} \times NUptakeSWFactor$ $NH4_{uptake} = NH4_i \times kNH4 \times NH4_{ppm, i} \times NUptakeSWFactor$ As can be seen from the above equations, the values of kNO3 and kNH4 equate to the potential fraction of each mineral N pool which can be taken up per day for wet soil when that pool has a concentration of 1 ppm. Nitrogen uptake demand is limited to the maximum daily potential uptake (MaxDailyNUptake) and the plant's N demand. The former provides a means to constrain N uptake to a maximum value observed in the field for the crop as a whole. The demand for soil N is then passed to the soil arbitrator which determines how much of the N uptake demand each plant instance will be allowed to take up.

1.5.5 Water Uptake

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

1.5.6 Constants

DMConversionEfficiency = 1

RemobilisationCost = 0

KLModifier = 1

SoilWaterEffect = 1

MaxDailyNUptake = 20

SenescenceRate = 0.005

MaximumRootDepth = 1000000

MaximumNConc = 0.01

MinimumNConc = 0.01

KNO3 = 0.02

KNH4 = 0.01

SpecificRootLength = 105 (m/g)

CarbonConcentration = 0.4

MaintenanceRespirationFunction = 0

1.5.7 RootShape

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

1.5.8 NitrogenDemandSwitch

NitrogenDemandSwitch has a value between Germination and Maturity calculated as:

Constant = 1

1.5.9 BiomassRemovalDefaults

1.5.9.1 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.

1.5.10 RootFrontVelocity

$RootFrontVelocity = PotentialRootFrontVelocity \times TemperatureFactor \times WaterFactor$

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.

PreEmergence has a value between Germination and Emergence calculated as:

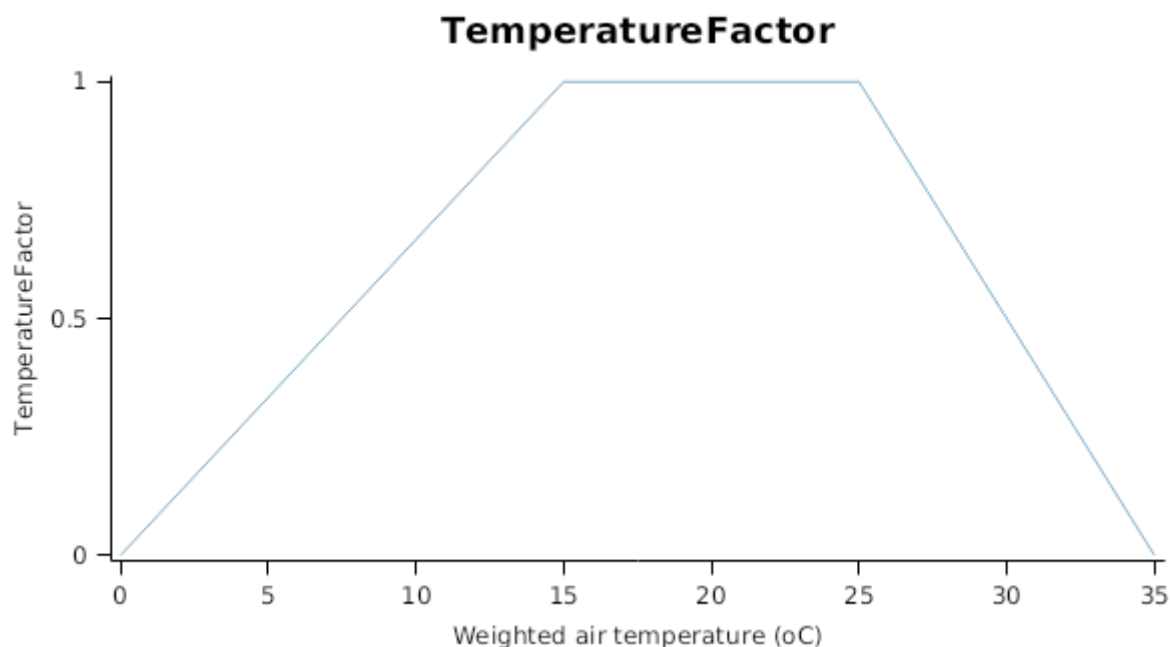
Value = 5 (mm/d)

PostEmergence has a value between Emergence and StartGrainFill calculated as:

Value = 20 (mm/d)

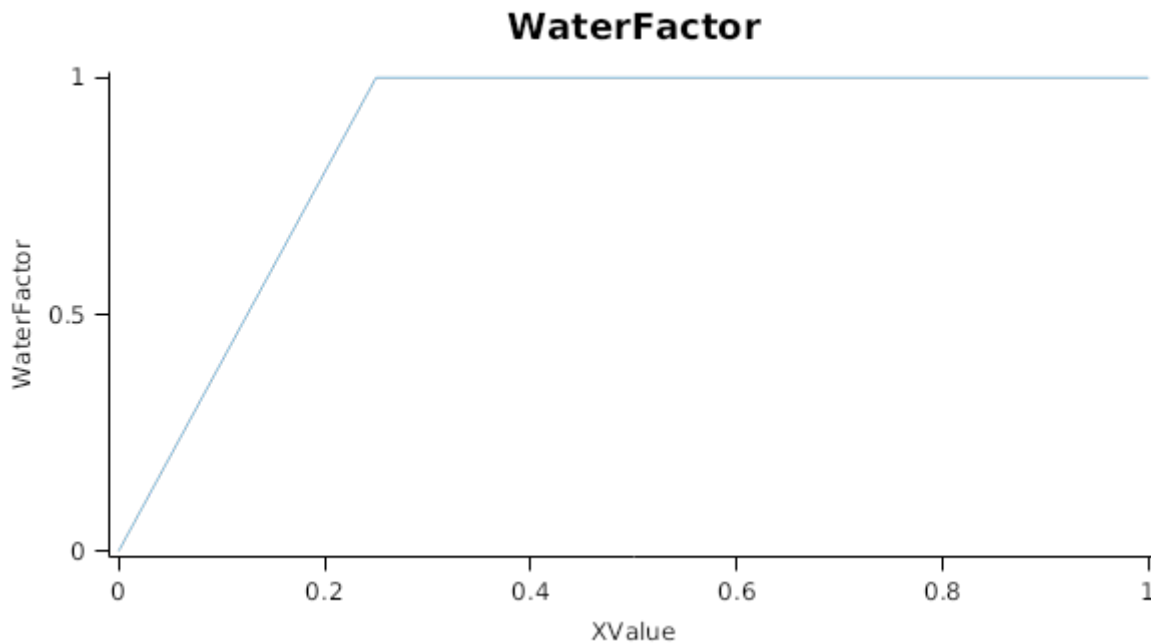
TemperatureFactor is calculated as a function of daily min and max temperatures, these are weighted toward max temperature according to the specified MaximumTemperatureWeighting factor. A value equal to 1.0 means it will use max temperature, a value of 0.5 means average temperature.

MaximumTemperatureWeighting = 0.5



WaterFactor is calculated using linear interpolation

XValue	WaterFactor
0.0	0.0
0.25	1.0
1.0	1.0



1.5.11 NUptakeSWFactor

$NUptakeSWFactor = \text{Min}(\text{SoilWaterScale}, \text{One})$

Where:

1.5.11.1 SoilWaterScale

A simple scale to convert soil water content into a value between 0 and 2 where 0 = LL15, 1 = DUL and 2 = SAT

One = 1

1.5.12 DMDemands

1.5.12.1 DMDemands

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

1.5.13 NDemands

1.5.13.1 NDemands

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

1.5.14 CriticalNConc

$CriticalNConc = [Root].MinimumNConc$

1.5.15 InitialWt

1.5.15.1 InitialWt

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

1.6 Leaf

The leaves are modelled as a set of leaf cohorts and the properties of each of these cohorts are summed to give overall values for the leaf organ.

A cohort represents all the leaves of a given main-stem node position including all of the branch leaves appearing at the same time as the given main-stem leaf ([Lawless et al., 2005](#)).

The number of leaves in each cohort is the product of the number of plants per m² and the number of branches per plant. The *Structure* class models the appearance of main-stem leaves and branches. Once cohorts are initiated the *Leaf* class models the area and biomass dynamics of each.

It is assumed all the leaves in each cohort have the same size and biomass properties. The modelling of the status and function of individual cohorts is delegated to *LeafCohort* classes.

1.6.1 Dry Matter Fixation

The most important DM supply from leaf is the photosynthetic fixation supply. Radiation interception is calculated from LAI using an extinction coefficient of:

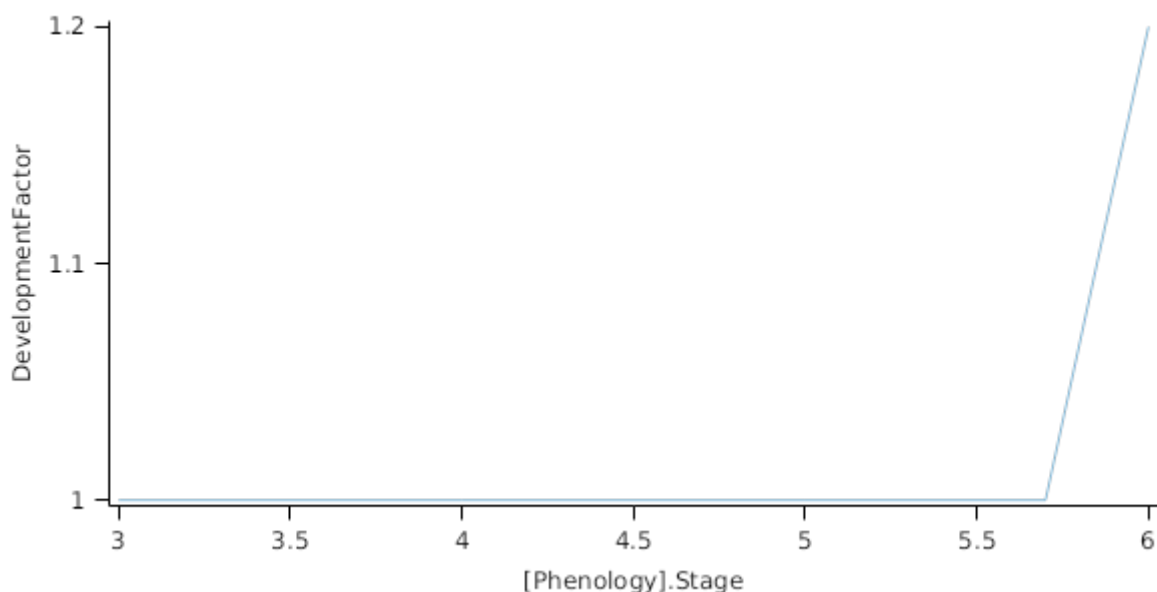
$$\text{ExtinctionCoeff} = \text{VegetativePhase} \times \text{DevelopmentFactor}$$

$$\text{VegetativePhase} = 0.5$$

DevelopmentFactor is calculated using linear interpolation

[Phenology].Stage	DevelopmentFactor
3.0	1.0
4.0	1.0
5.0	1.0
5.7	1.0
6.0	1.2

DevelopmentFactor



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.

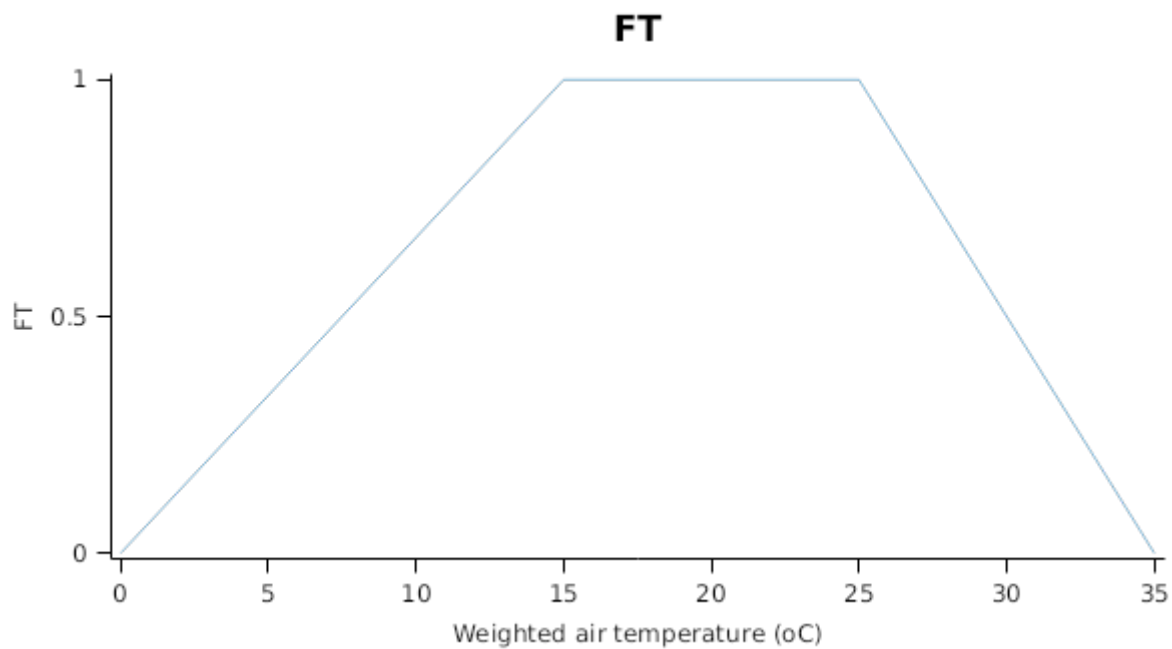
The potential photosynthesis calculated using RUE is then adjusted according to stress factors, these account for plant nutrition (FN), air temperature (FT), vapour pressure deficit (FVPD), water supply (FW) and atmospheric CO₂ concentration (FCO₂).

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

$$\text{RUE} = 1.5$$

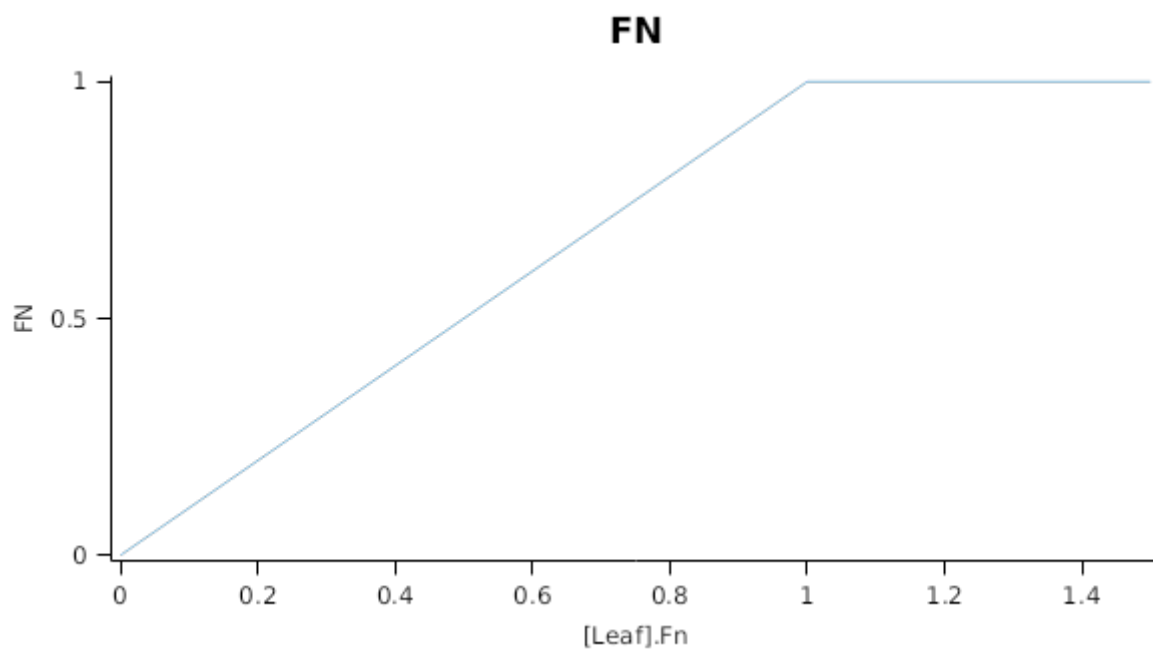
FT is calculated as a function of daily min and max temperatures, these are weighted toward max temperature according to the specified MaximumTemperatureWeighting factor. A value equal to 1.0 means it will use max temperature, a value of 0.5 means average temperature.

$$\text{MaximumTemperatureWeighting} = 0.75$$



FN is calculated using linear interpolation

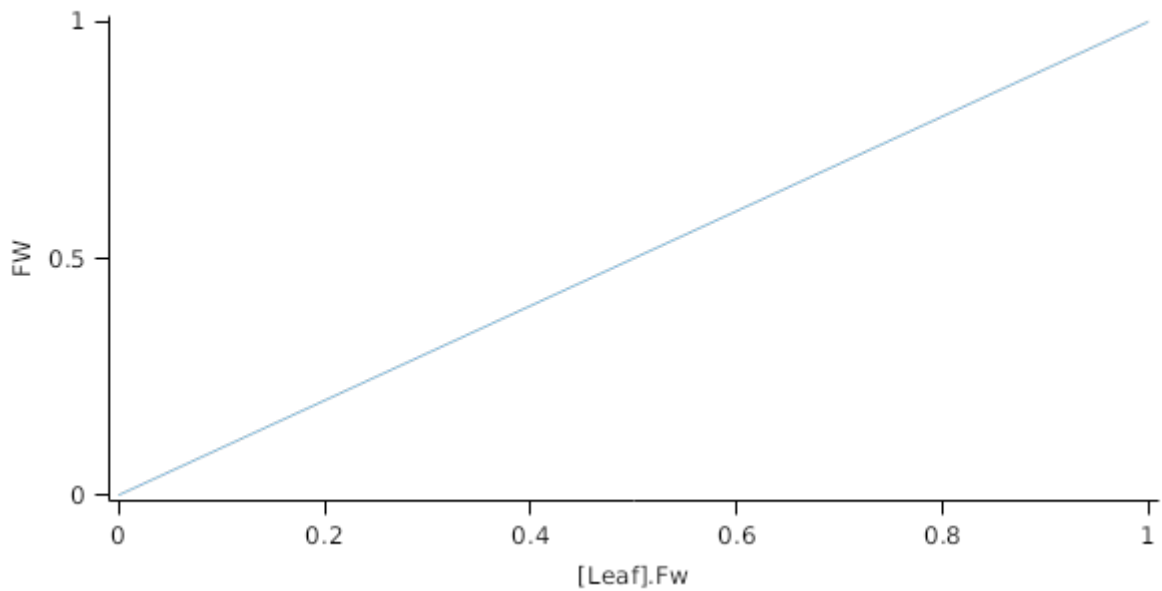
[Leaf].Fn	FN
0.0	0.0
1.0	1.0
1.5	1.0



FW is calculated using linear interpolation

[Leaf].Fw	FW
0.0	0.0
1.0	1.0
1.0	1.0

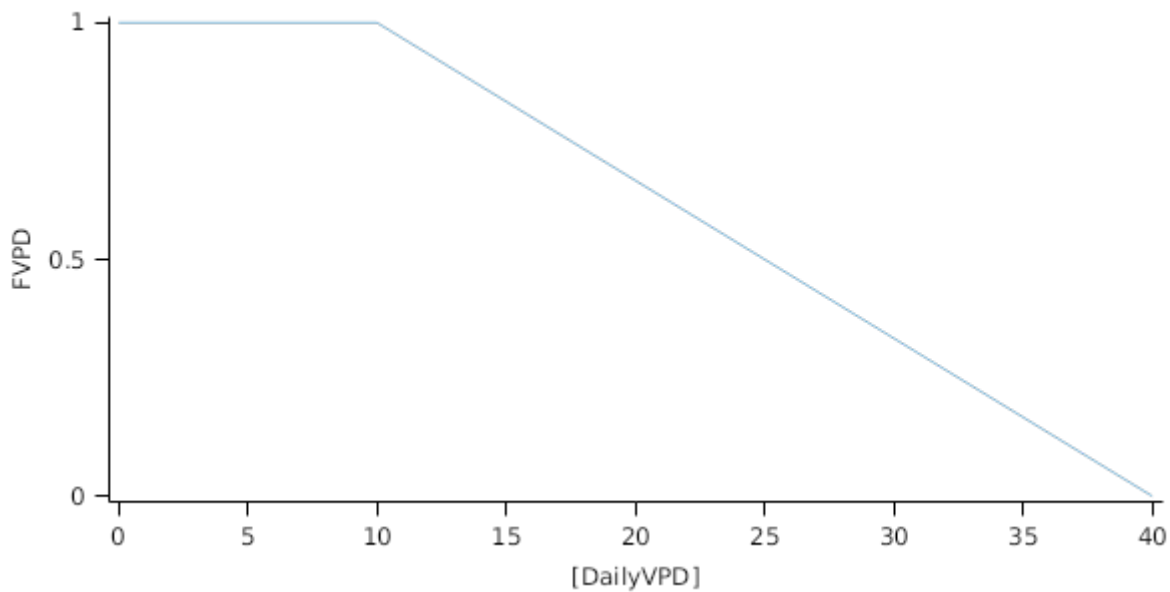
FW



FVPD is calculated using linear interpolation

[DailyVPD]	FVPD
0.0	1.0
10.0	1.0
40.0	0.0

FVPD



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,

$$F_{CO_2} = 0.000143 * CO_2 + 0.95$$

$$RadnInt = [Leaf].RadiationIntercepted$$

1.6.2 Constants

$$FrostFraction = 0$$

$$RemobilisationCost = 0$$

$$StructuralFraction = 0.5$$

$$DMConversionEfficiency = 1$$

$$CarbonConcentration = 0.4$$

$$WidthFunction = 0$$

1.6.3 StomatalConductanceCO2Modifier

This model calculates the CO₂ impact on stomatal conductance using the approach of [Elli et al., 2020](#).

$$StomatalConductanceCO2Modifier = PhotosynthesisCO2Modifier \times (350 - CP) / (CO_2 - CP)$$

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

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

$$PhotosynthesisCO2Modifier = [Leaf].Photosynthesis.FCO_2$$

1.6.4 InitialLeaves[1]

$$Area = 200$$

1.6.5 InitialLeaves[2]

$$Area = 0$$

1.6.6 CohortParameters

1.6.6.1 Potential Leaf Area index

Leaf area index is calculated as the sum of the area of each cohort of leaves. The appearance of a new cohort of leaves occurs each time Structure.LeafTipsAppeared increases by one. From tip appearance the area of each cohort will increase for a certain number of degree days defined by the *GrowthDuration*

$$GrowthDuration = 1.3 \times [Phenology].Phyllochron$$

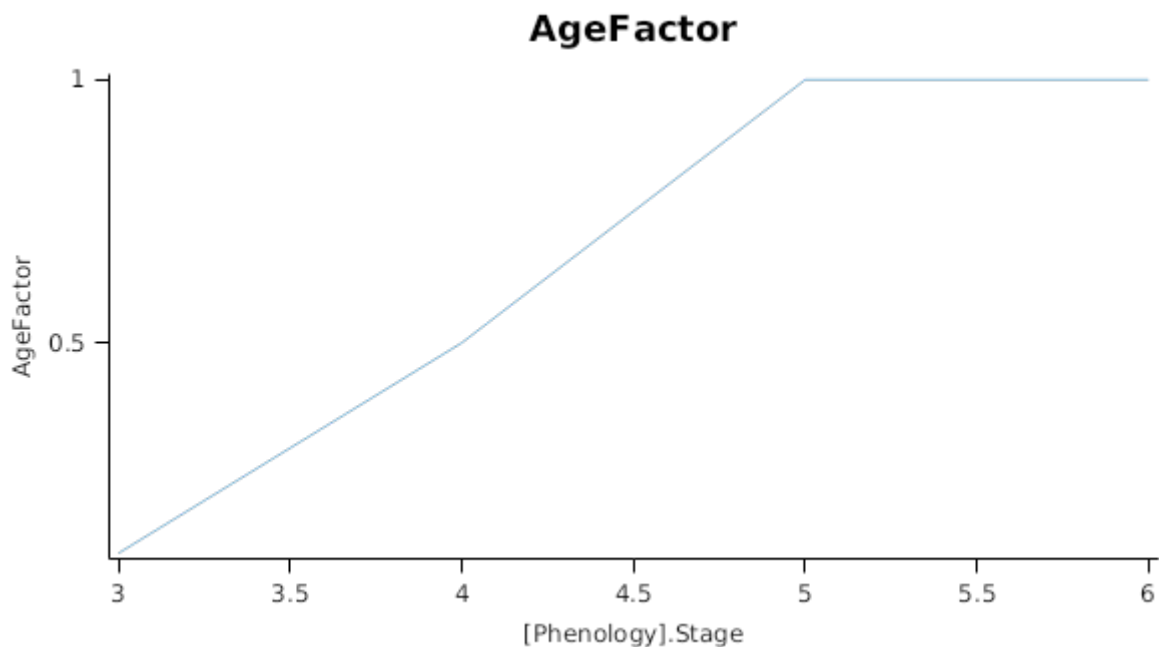
If no stress occurs the leaves will reach a Maximum area (*MaxArea*) at the end of the *GrowthDuration*. The *MaxArea* is defined by:

$$MaxArea = AreaLargestLeaves \times AgeFactor$$

$$AreaLargestLeaves = 2600 \text{ (mm}^2\text{)}$$

AgeFactor is calculated using linear interpolation

[Phenology].Stage	AgeFactor
3.0	0.1
4.0	0.5
5.0	1.0
6.0	1.0

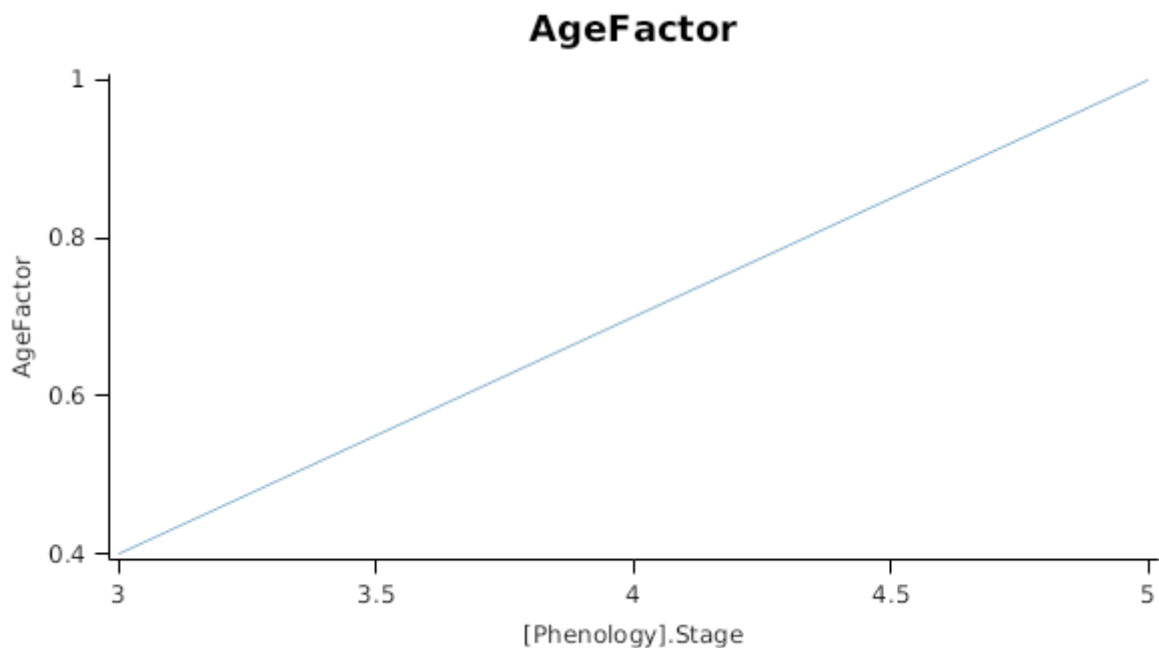


In the absence of stress the leaf will remain at *MaxArea* for a number of degree days set by the *LagDuration* and then area will senesce to zero at the end of the *SenescenceDuration*

$$LagDuration = AgeFactor \times LastLeafDuration$$

AgeFactor is calculated using linear interpolation

[Phenology].Stage	AgeFactor
3.0	0.4
4.0	0.7
5.0	1.0



$$LastLeafDuration = ThermalTimeToRipe - [Leaf].CohortParameters.SenescenceDuration$$

$$ThermalTimeToRipe = [Phenology].HeadEmergence.Target + [Phenology].EarlyFlowering.Target + [Phenology].GrainDevelopment.Target + [Phenology].GrainFilling.Target + [Phenology].Maturing.Target + [Phenology].Ripening.Target$$

$$SenescenceDuration = 3 \times [Phenology].Phyllochron$$

Mutual shading can cause premature senescence of cohorts if the leaf area above them becomes too great. Each cohort models the proportion of its area that is lost to shade induced senescence each day as:

ShadeInducedSenescenceRate = 0

1.6.6.2 Stress effects on Leaf Area Index

Stress reduces leaf area in a number of ways. Firstly, stress occurring prior to the appearance of the cohort can reduce cell division, so reducing the maximum leaf size. Leaf captures this by multiplying the *MaxSize* of each cohort by a *CellDivisionStress* factor which is calculated as:

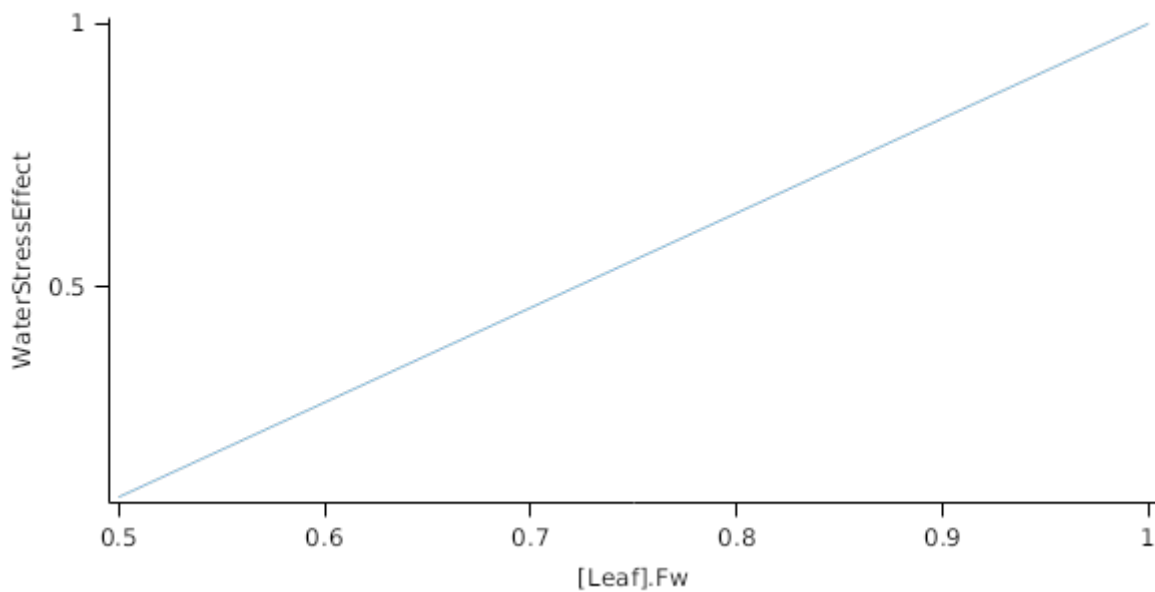
$CellDivisionStress = \text{Min}(WaterStressEffect, NitrogenStressEffect)$

Where:

WaterStressEffect is calculated using linear interpolation

[Leaf].Fw	WaterStressEffect
0.5	0.1
1.0	1.0

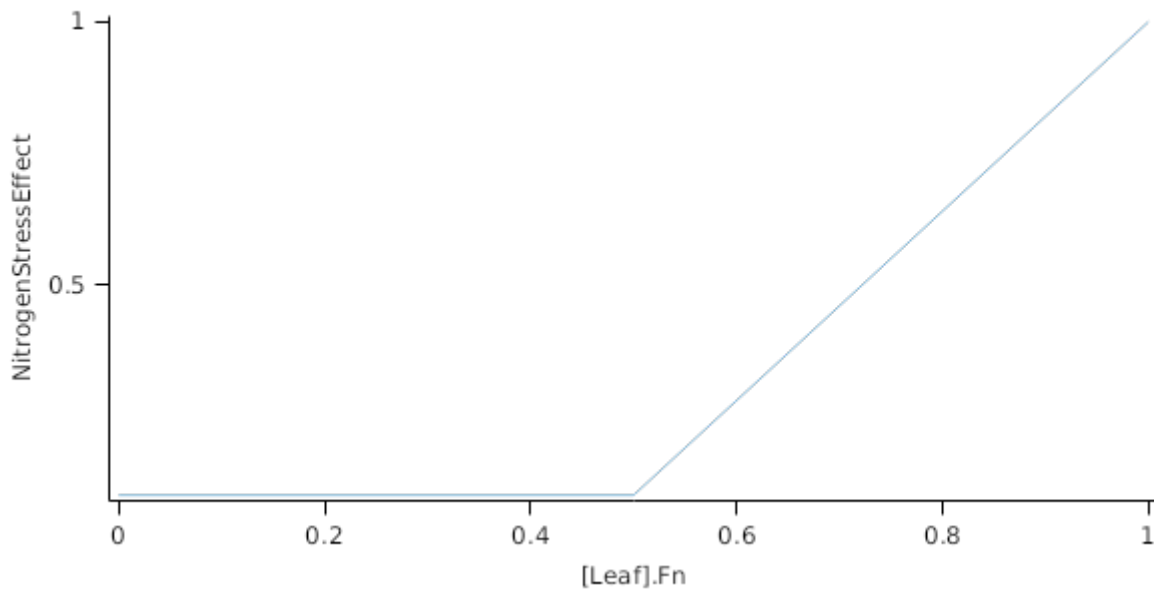
WaterStressEffect



NitrogenStressEffect is calculated using linear interpolation

[Leaf].Fn	NitrogenStressEffect
0.0	0.1
0.5	0.1
1.0	1.0

NitrogenStressEffect



Leaf.FN quantifies the N stress status of the plant and represents the concentration of metabolic N relative the maximum potential metabolic N content of the leaf calculated as $(Leaf.NConc - MinimumNConc) / (CriticalNConc - MinimumNConc)$.

Leaf.FW quantifies water stress and is calculated as $Leaf.Transpiration / Leaf.WaterDemand$, where *Leaf.Transpiration* is the minimum of *Leaf.WaterDemand* and *Root.WaterUptake*

Stress during the *GrowthDuration** of the cohort reduces the size increase of the cohort by multiplying the potential increase by a *ExpansionStress* factor:

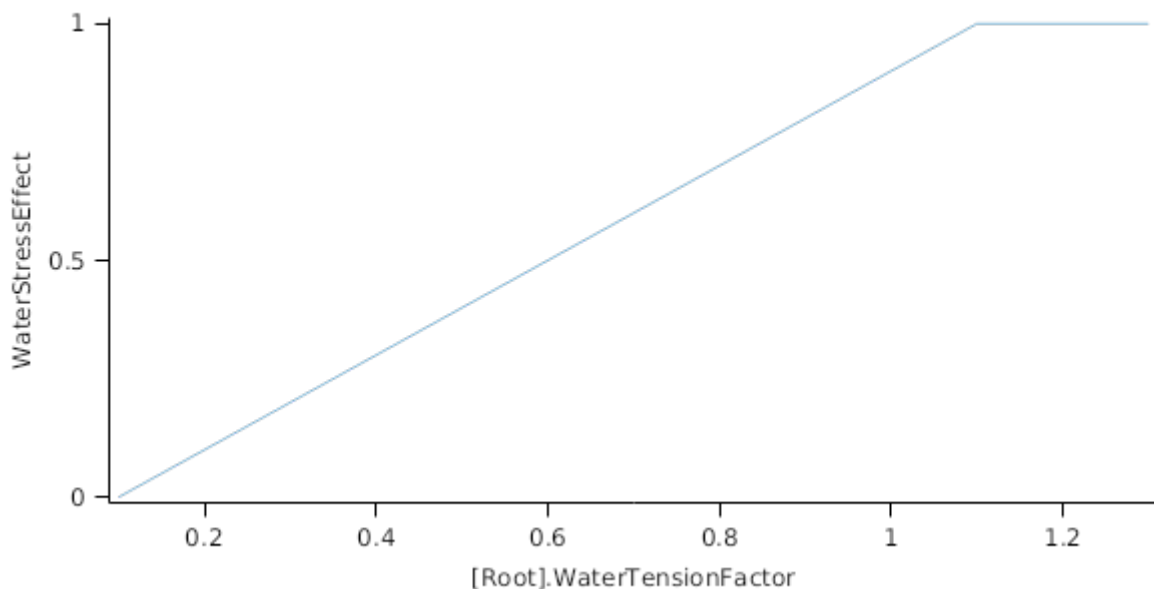
$$ExpansionStress = \text{Min}(WaterStressEffect, TemperatureEffect, NitrogenStressEffect)$$

Where:

WaterStressEffect is calculated using linear interpolation

[Root].WaterTensionFactor	WaterStressEffect
0.1	0.0
1.1	1.0
1.3	1.0

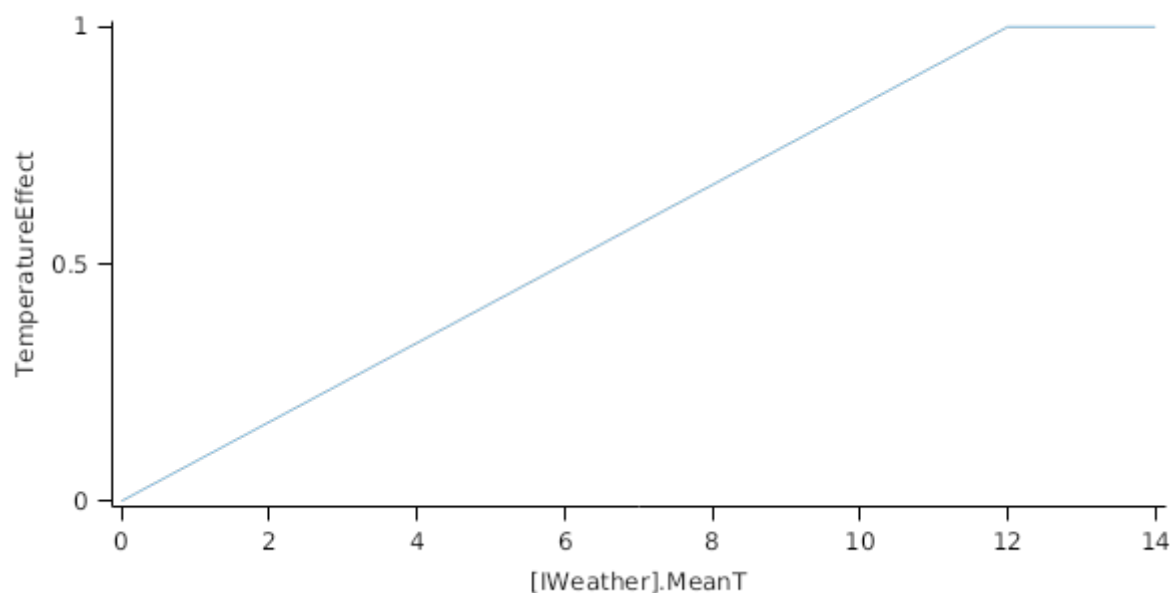
WaterStressEffect



TemperatureEffect is calculated using linear interpolation

[IWeather].MeanT	TemperatureEffect
0.0	0.0
12.0	1.0
14.0	1.0

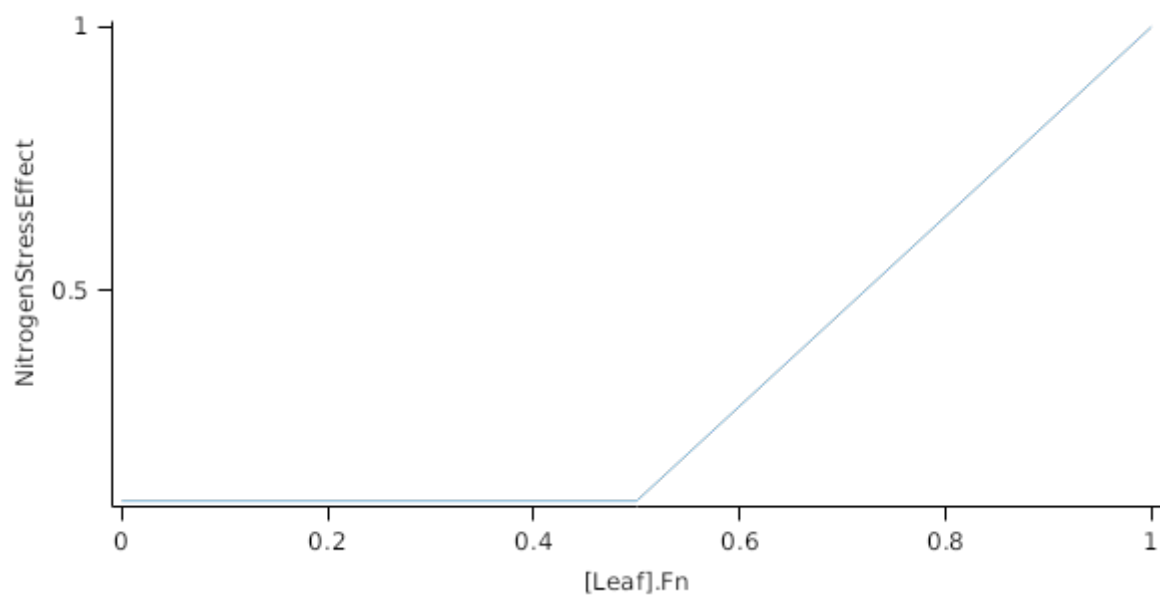
TemperatureEffect



NitrogenStressEffect is calculated using linear interpolation

[Leaf].Fn	NitrogenStressEffect
0.0	0.1
0.5	0.1
1.0	1.0

NitrogenStressEffect



Stresses can also accelerate the onset and rate of senescence in a number of ways. Nitrogen shortage will cause N to be retranslocated out of lower order leaves to support the expansion of higher order leaves and other organs. When this

happens the lower order cohorts will have their area reduced in proportion to the amount of N that is remobilised out of them.

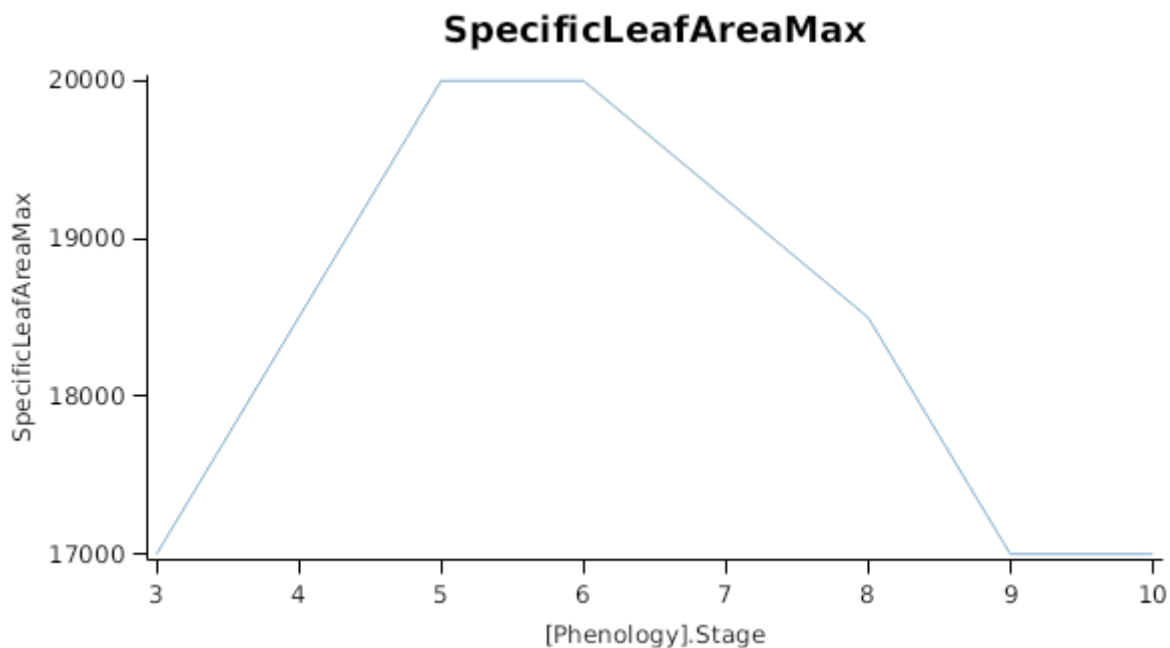
Water stress hastens senescence by increasing the rate of thermal time accumulation in the lag and senescence phases. This is done by multiplying thermal time accumulation by *DroughtInducedLagAcceleration* and *DroughtInducedSenescenceAcceleration* factors, respectively

1.6.6.3 Dry matter Demand

Leaf calculates the DM demand from each cohort as a function of the potential size increment (*DeltaPotentialArea*) an specific leaf area bounds. Under non stressed conditions the demand for non-storage DM is calculated as *DeltaPotentialArea* divided by the mean of *SpecificLeafAreaMax* and *SpecificLeafAreaMin*. Under stressed conditions it is calculated as *DeltaWaterConstrainedArea* divided by *SpecificLeafAreaMin*.

SpecificLeafAreaMax is calculated using linear interpolation

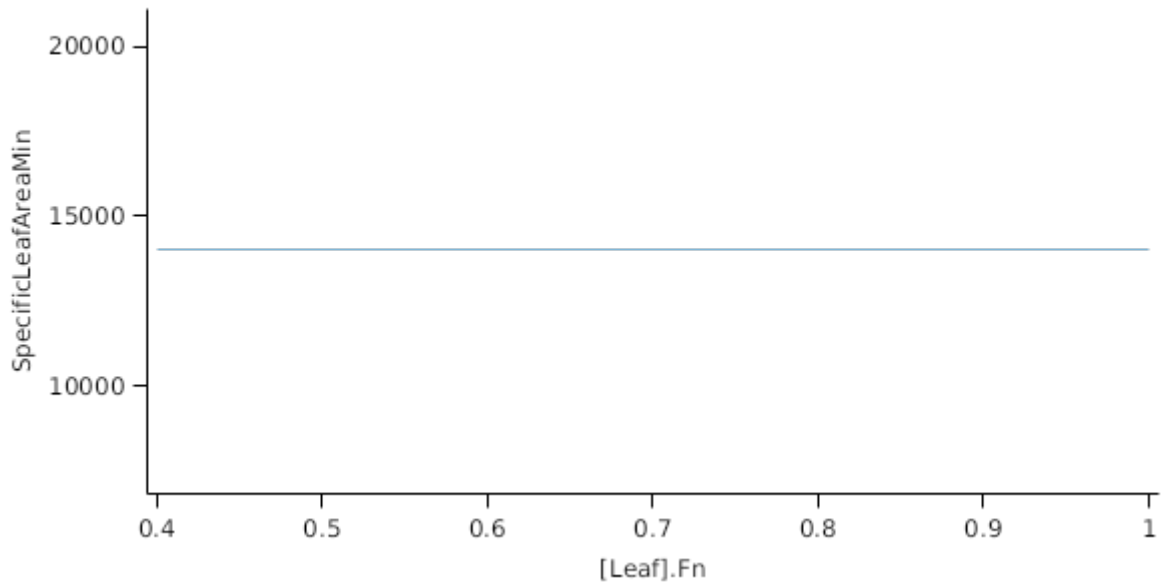
[Phenology].Stage	SpecificLeafAreaMax
3.0	17000.0
5.0	20000.0
6.0	20000.0
8.0	18500.0
9.0	17000.0
10.0	17000.0



SpecificLeafAreaMin is calculated using linear interpolation

[Leaf].Fn	SpecificLeafAreaMin
0.4	14000.0
1.0	14000.0

SpecificLeafAreaMin



Non-storage DM Demand is then separated into structural and metabolic DM demands using the *StructuralFraction*:

$\text{StructuralFraction} = 0.5$

The storage DM demand is calculated from the sum of metabolic and structural DM (including today's demands) multiplied by a *NonStructuralFraction*

1.6.6.4 Nitrogen Demand

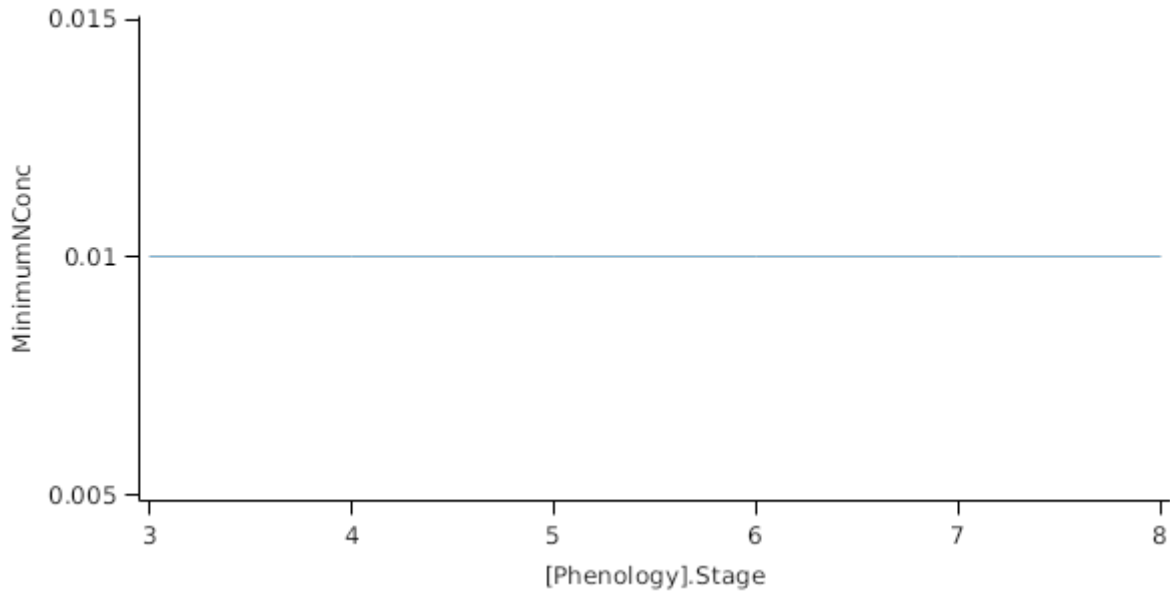
Leaf calculates the N demand from each cohort as a function of the potential DM increment and N concentration bounds.

Structural N demand = $\text{PotentialStructuralDMAAllocation} * \text{MinimumNConc}$ where:

MinimumNConc is calculated using linear interpolation

[Phenology].Stage	MinimumNConc
3.0	0.01
4.0	0.01
5.0	0.01
6.0	0.01
7.0	0.01
8.0	0.01

MinimumNConc



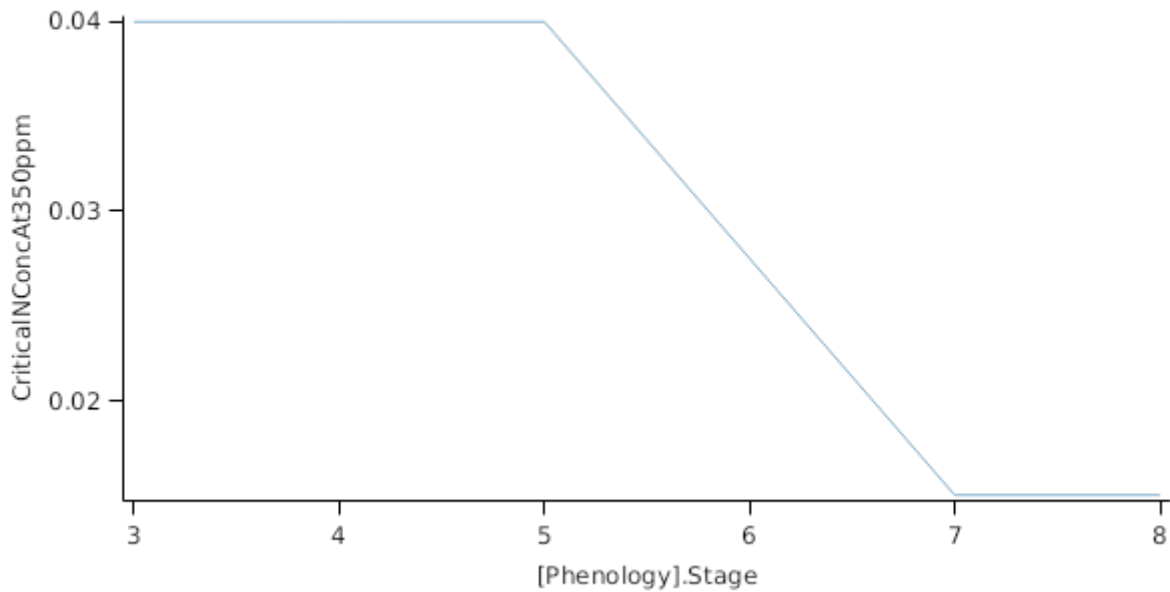
Metabolic N demand is calculated as $PotentialMetabolicDMAAllocation * (CriticalNConc - MinimumNConc)$ where:

$CriticalNConc = CriticalNConcAt350ppm \times CO2Factor$

$CriticalNConcAt350ppm$ is calculated using linear interpolation

[Phenology].Stage	CriticalNConcAt350ppm
3.0	0.04
4.0	0.04
5.0	0.04
6.0	0.0275
7.0	0.015
8.0	0.015

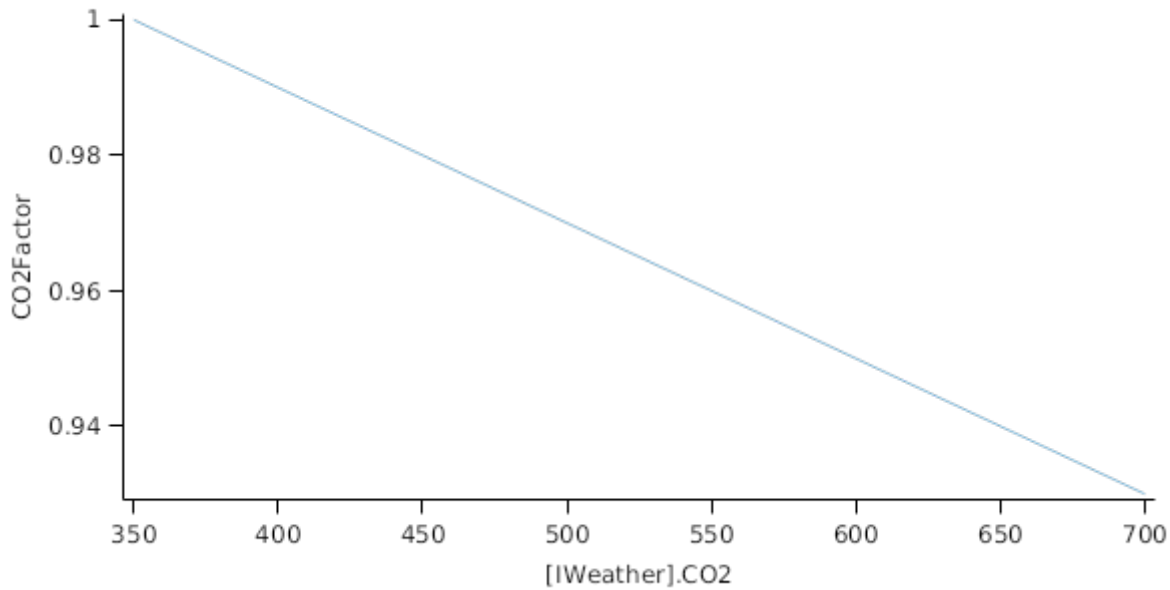
CriticalNConcAt350ppm



$CO2Factor$ is calculated using linear interpolation

[IWeather].CO2	CO2Factor
350.0	1.0
700.0	0.93

CO2Factor

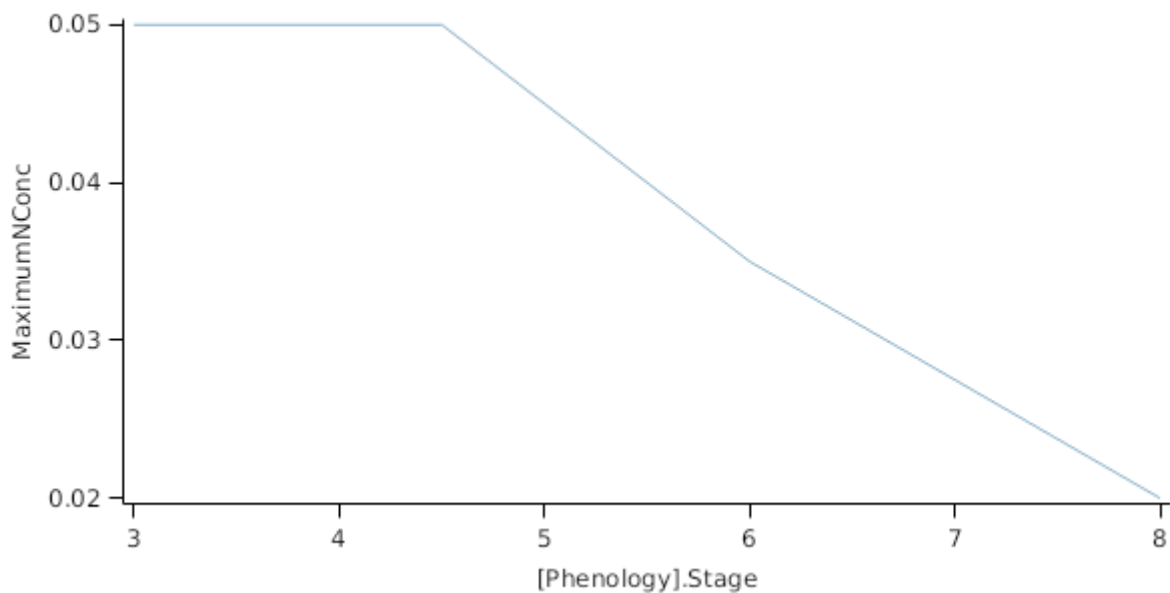


Storage N demand is calculated as the sum of metabolic and structural wt (including todays demands) multiplied by *LuxuryNconc* (*MaximumNConc* - *CriticalNConc*) less the amount of storage N already present. *MaximumNConc* is given by:

MaximumNConc is calculated using linear interpolation

[Phenology].Stage	MaximumNConc
3.0	0.05
4.5	0.05
6.0	0.035
8.0	0.02

MaximumNConc



1.6.6.5 Drymatter supply

In addition to photosynthesis, the leaf can also supply DM by reallocation of senescing DM and retranslocation of storage DM: Reallocation supply is a proportion of the metabolic and non-structural DM that would be senesced each day where the proportion is set by:

DMReallocationFactor = 1

Retranslocation supply is calculated as a proportion of the amount of storage DM in each cohort where the proportion is set by :

DMRetranslocationFactor = 1

1.6.6.6 Nitrogen supply

Nitrogen supply from the leaf comes from the reallocation of metabolic and storage N in senescing material and the retranslocation of metabolic and storage N. Reallocation supply is a proportion of the Metabolic and Storage DM that would be senesced each day where the proportion is set by:

NReallocationFactor = 1

Retranslocation supply is calculated as a proportion of the amount of storage and metabolic N in each cohort where the proportion is set by :

NRetranslocationFactor = 0.03

1.6.6.7 Constants

NReallocationFactor = 1

RemobilisationCost = 0

MaintenanceRespirationFunction = 0

NRetranslocationFactor = 0.03

DMReallocationFactor = 1

DMRetranslocationFactor = 1

DetachmentLagDuration = 1000000

DetachmentDuration = 1000000

RelativeBranchLeafSize = 1

InitialNConc = 0

StructuralFraction = 0.5

StorageFraction = 0.3

LeafSizeShapeParameter = 0.3

SenescingLeafRelativeSize = 1 (0-1)

ShadeInducedSenescenceRate = 0

1.6.7 ThermalTime

ThermalTime = [Phenology].ThermalTime

1.6.8 FRGRFunction

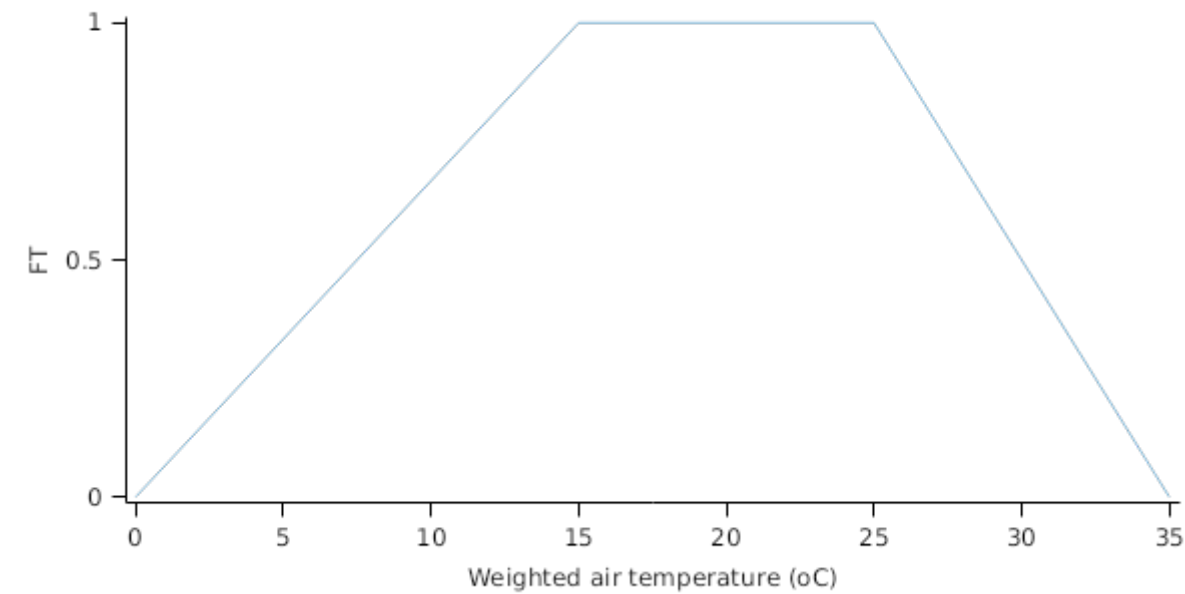
FRGRFunction = Min(*FT*, *FN*, *FVPD*)

Where:

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

MaximumTemperatureWeighting = 0.75

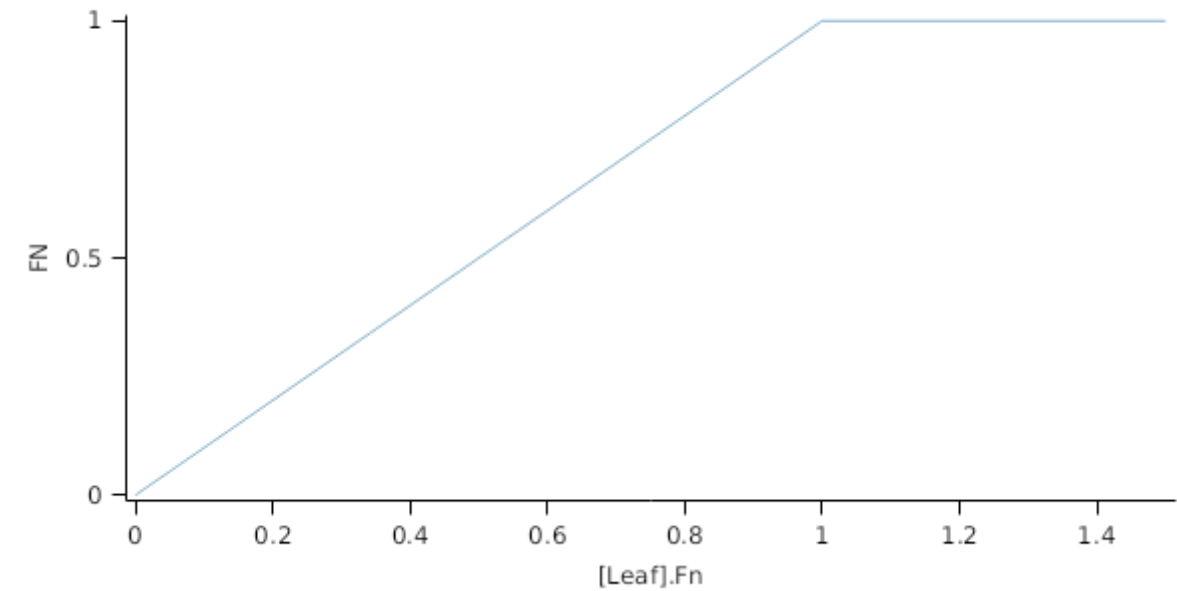
FT



FN is calculated using linear interpolation

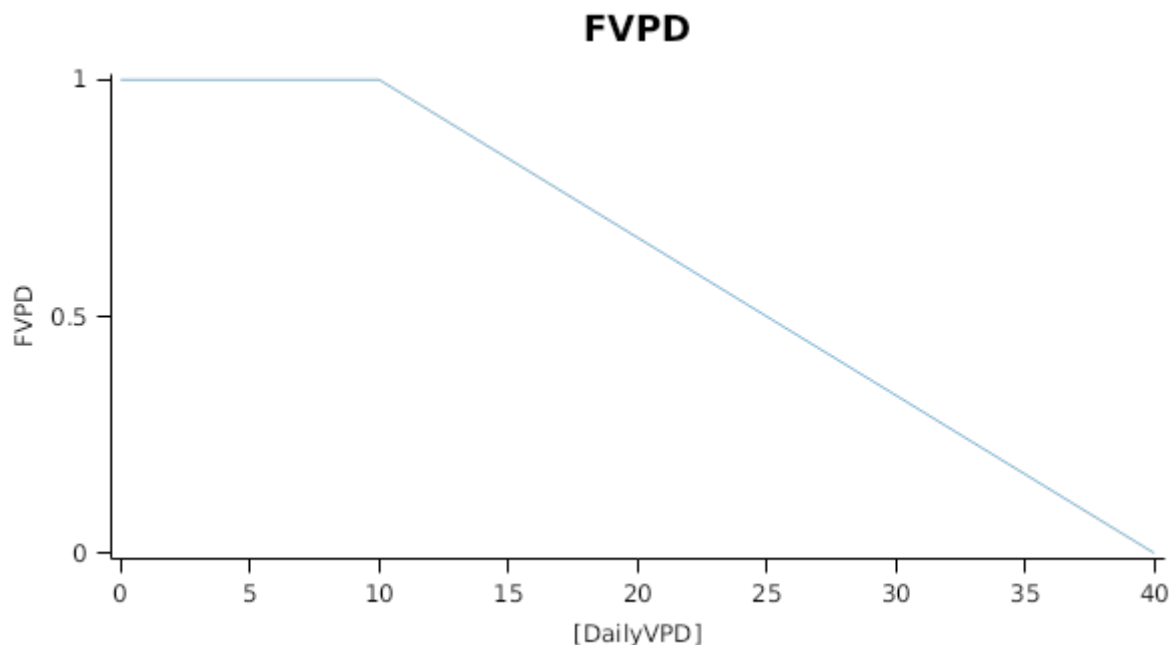
[Leaf].Fn	FN
0.0	0.0
1.0	1.0
1.5	1.0

FN



FVPD is calculated using linear interpolation

[DailyVPD]	FVPD
0.0	1.0
10.0	1.0
40.0	0.0



1.6.9 BiomassRemovalDefaults

1.6.9.1 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.

1.6.10 DepthFunction

$DepthFunction = [Leaf].Height$

1.6.11 DMDemandPriorityFactors

1.6.11.1 DMDemandPriorityFactors

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

1.6.12 NDemandPriorityFactors

1.6.12.1 NDemandPriorityFactors

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

1.7 Spike

1.7.1 Spike

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.

1.7.2 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.

1.7.2.1 DMDemands

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

1.7.3 Nitrogen Demand

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

1.7.3.1 NDemands

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

1.7.4 N Concentration Thresholds

MinimumNConc = 0.004

$CriticalNConc = [Spike].MinimumNConc + MetabolicNconc$

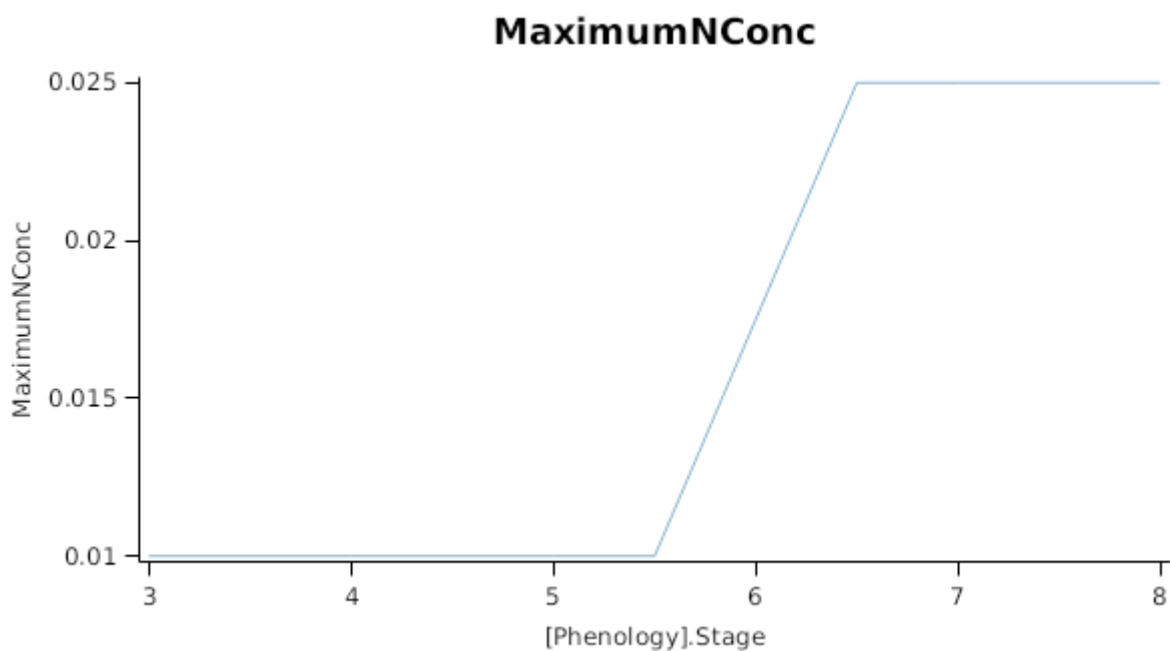
$MetabolicNconc = NonStructuralN \times Proportion$

$NonStructuralN = [Spike].MaximumNConc - [Spike].MinimumNConc$

Proportion = 0.8

MaximumNConc is calculated using linear interpolation

[Phenology].Stage	MaximumNConc
3.0	0.01
4.0	0.01
5.0	0.01
5.5	0.01
6.5	0.025
7.0	0.025
8.0	0.025



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

1.7.5 Dry Matter Supply

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

VegetativeGrowth has a value between Emergence and StartGrainFill calculated as:

DMRetranslocationFactor = 0

ReproductiveGrowth has a value between StartGrainFill and EndGrainFill calculated as:

DMRetranslocationFactor = 0.5

1.7.6 Nitrogen Supply

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

EarlyGrowth has a value between Emergence and StartGrainFill calculated as:

ValueDuringEarlyGrowth = 0

ReproductiveGrowth has a value between StartGrainFill and EndGrainFill calculated as:

ValueDuringGrainFill = 0.5

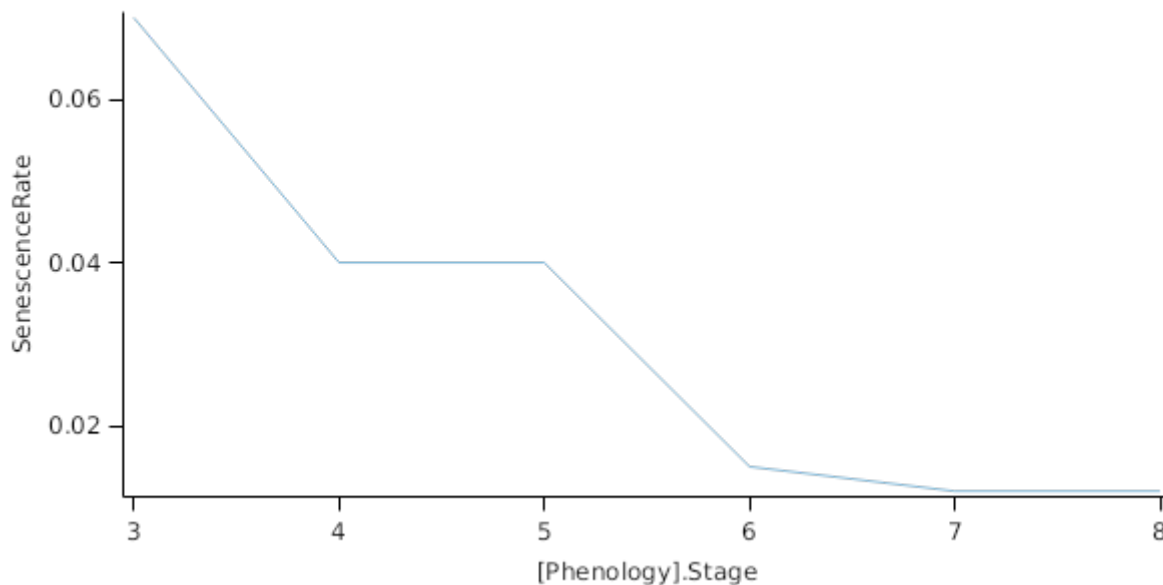
1.7.7 Senescence and Detachment

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

SenescenceRate is calculated using linear interpolation

[Phenology].Stage	SenescenceRate
3.0	0.07
4.0	0.04
5.0	0.04
6.0	0.015
7.0	0.012
8.0	0.012

SenescenceRate



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

1.7.8 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.

1.8 Stem

1.8.1 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.

1.8.2 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.

1.8.2.1 DMDemands

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

1.8.3 Nitrogen Demand

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

1.8.3.1 NDemands

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

1.8.4 N Concentration Thresholds

MinimumNConc = 0.0025

CriticalNConc = [Stem].MinimumNConc + *MetabolicNconc*

MetabolicNconc = *NonStructuralN* x *Proportion*

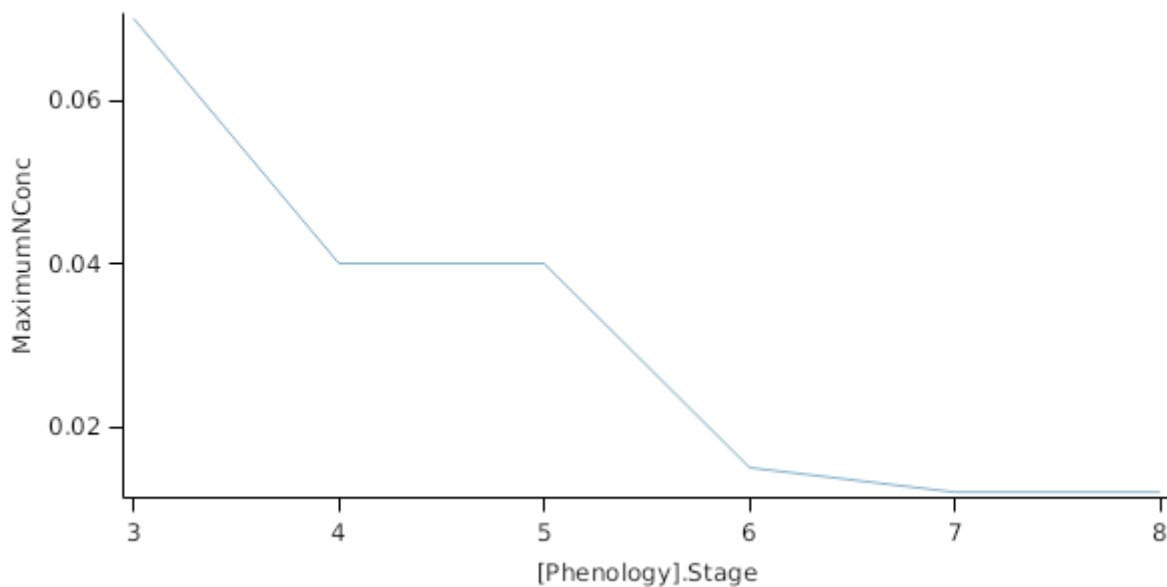
NonStructuralN = [Stem].MaximumNConc - [Stem].MinimumNConc

Proportion = 0.5

MaximumNConc is calculated using linear interpolation

[Phenology].Stage	MaximumNConc
3.0	0.07
4.0	0.04
5.0	0.04
6.0	0.015
7.0	0.012
8.0	0.012

MaximumNConc



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

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

VegetativeGrowth has a value between Emergence and StartGrainFill calculated as:

DMRetranslocationFactor = 0

ReproductiveGrowth has a value between StartGrainFill and EndGrainFill calculated as:

DMRetranslocationFactor = 0.5

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

VegetativeGrowth has a value between Sowing and Flowering calculated as:

Fraction = 0

ReproductiveGrowth has a value between Flowering and HarvestRipe calculated as:

Fraction = 0.5

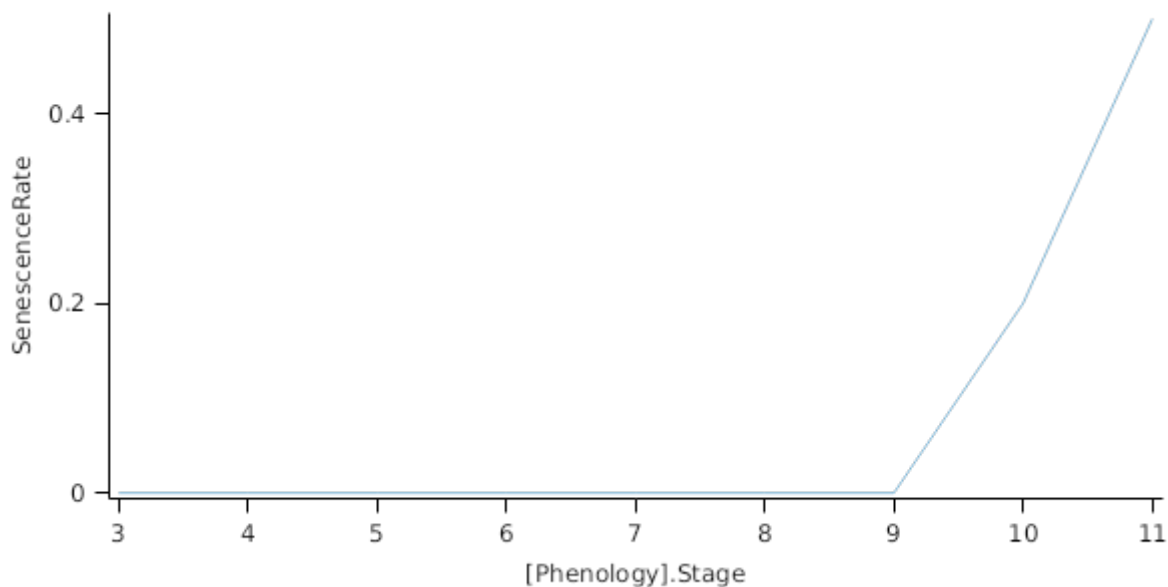
1.8.7 Senescence and Detachment

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

SenescenceRate is calculated using linear interpolation

[Phenology].Stage	SenescenceRate
3.0	0.0
4.0	0.0
5.0	0.0
6.0	0.0
7.0	0.0
8.0	0.0
9.0	0.0
10.0	0.2
11.0	0.5

SenescenceRate



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

1.8.8 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.

1.9 AboveGround

1.9.1 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
- * Spike
- * Grain

1.10 AboveGroundLive

1.10.1 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
- * Spike
- * Grain

1.11 AboveGroundDead

1.11.1 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
- * Spike
- * Grain

1.12 BelowGround

1.12.1 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

1.13 Total

1.13.1 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
- * Spike
- * Grain

1.14 TotalLive

1.14.1 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
- * Spike
- * Grain

1.15 TotalDead

1.15.1 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
- * Spike
- * Grain

1.16 Ear

1.16.1 Ear

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

Ear summarises the following biomass objects:

- * Spike
- * Grain

1.17 StemPlusSpike

1.17.1 StemPlusSpike

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

StemPlusSpike summarises the following biomass objects:

- * Stem
- * Spike

1.18 MortalityRate

MortalityRate = 0

1.19 SeedMortalityRate

SeedMortalityRate = 0

2 The APSIM Wheat Model

Brown, H.E., Huth, N.I. and Holzworth, D.P.

The APSIM wheat 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 wheat model consists of:

- * a phenology model to simulate development through sequential developmental phases
- * a structure model to simulate plant morphology

- * a collection of organs to simulate the various plant parts
- * an arbitrator to allocate resources (N, biomass) to the various plant organs

This work builds upon earlier APSIM Wheat models such as NWheat ([S Asseng et al., 2002](#), [BA Keating, 2001](#)), NWheatS ([S Asseng et al., 1998](#)), Cropmod-Wheat ([Wang et al., 2002](#)), and the earlier versions developed in Plant (<http://www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Wheat.aspx>) APSIM Wheat 7.5") and then within the Plant Modelling Framework ([Brown et al., 2014](#)).

3 Validation

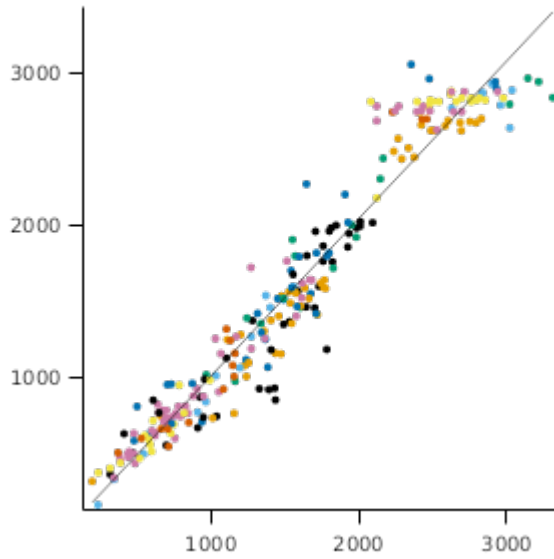
A test dataset has been developed to test the APSIM Wheat model for a range of environmental (soil and climate) conditions, management options (sowing dates, populations, nitrogen rates, row spacing, irrigation), genetic backgrounds (different regions, cultivar types) and for special considerations such as crop damage. These tests have been grouped into various geographical regions to allow the user to evaluate the suitability of the model for their particular region of interest. Graphs of model performance are provided for yield, biomass production, canopy development, phenological development, water and nitrogen uptake, and grain yield components.



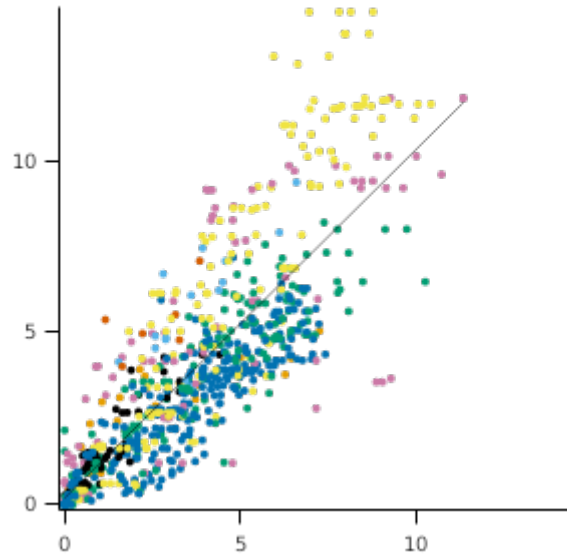
3.1 Combined Results

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).

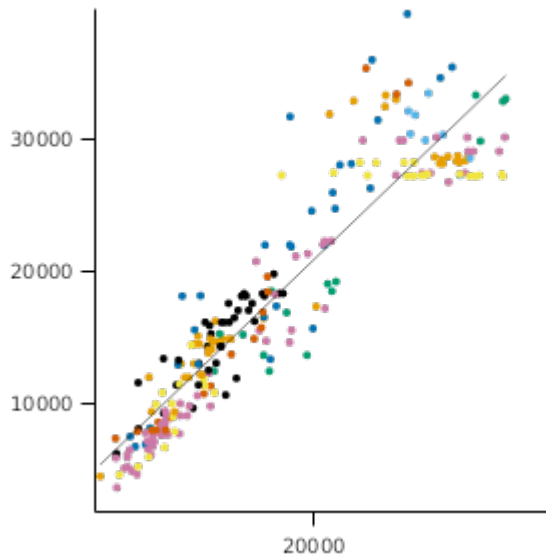
Harvest Biomass



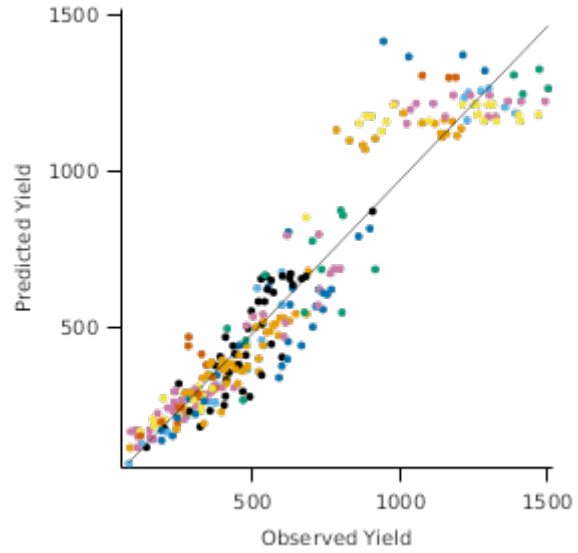
Leaf Area Index



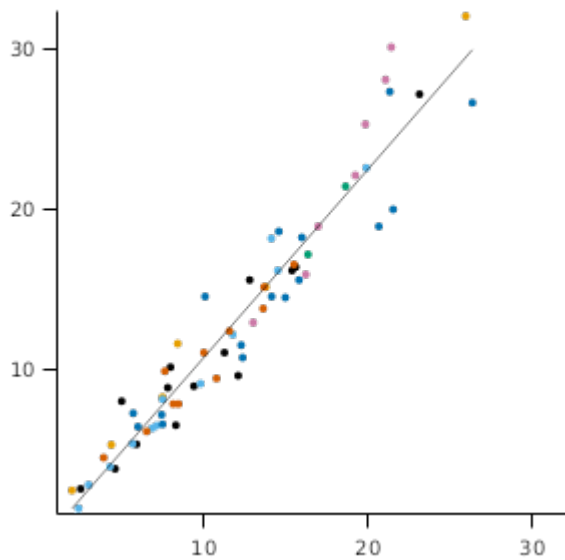
Grain Number



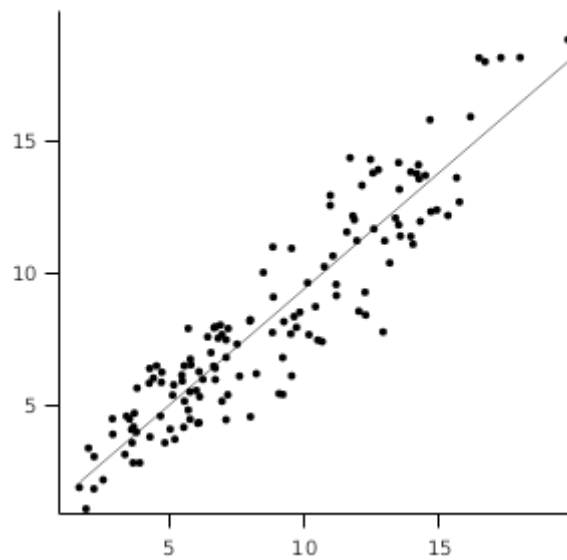
Harvest Yield

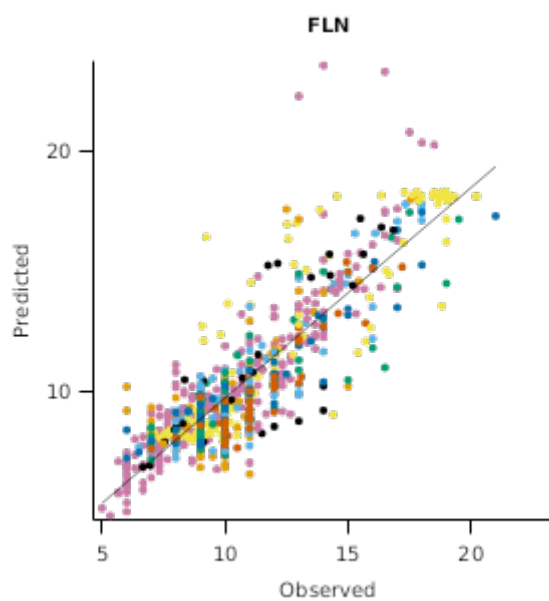
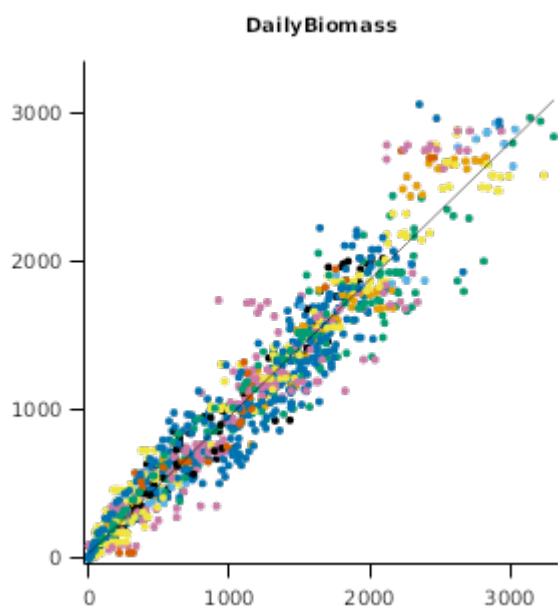
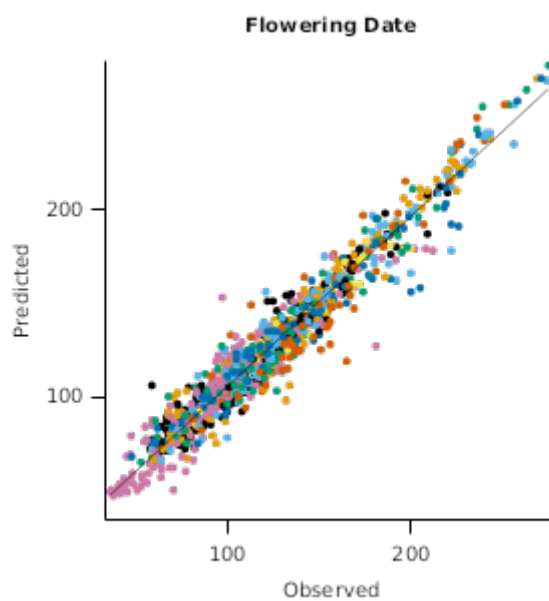
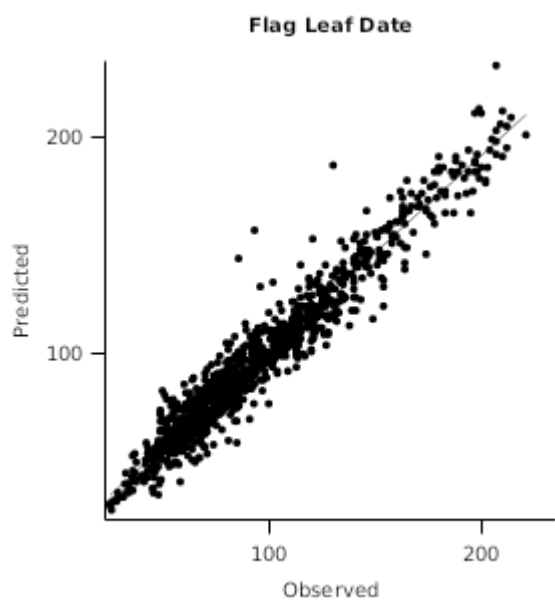
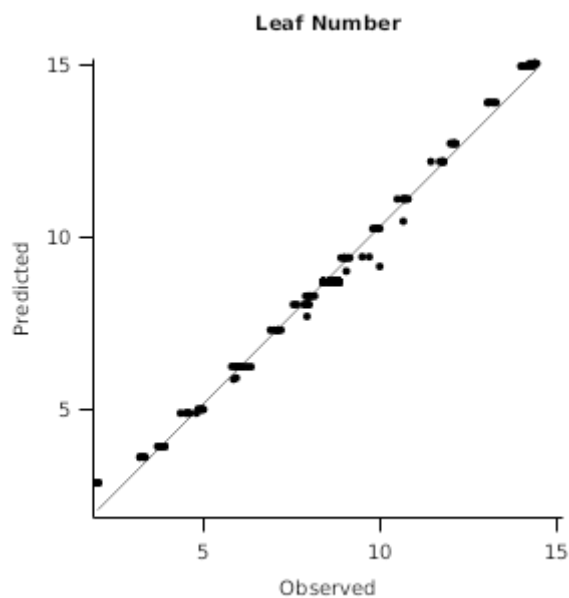
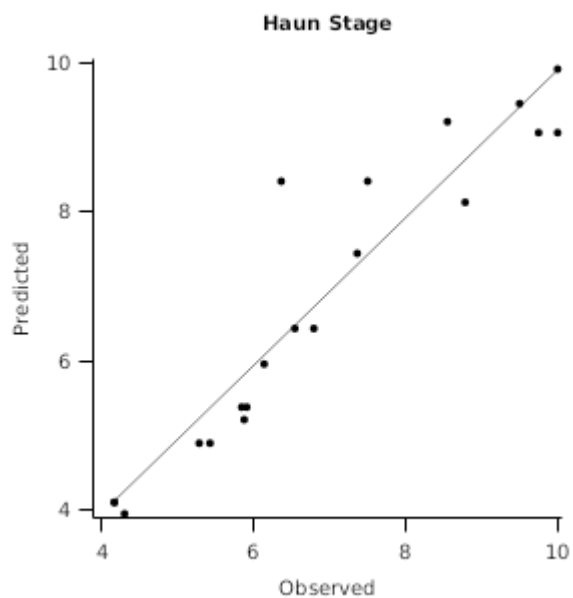


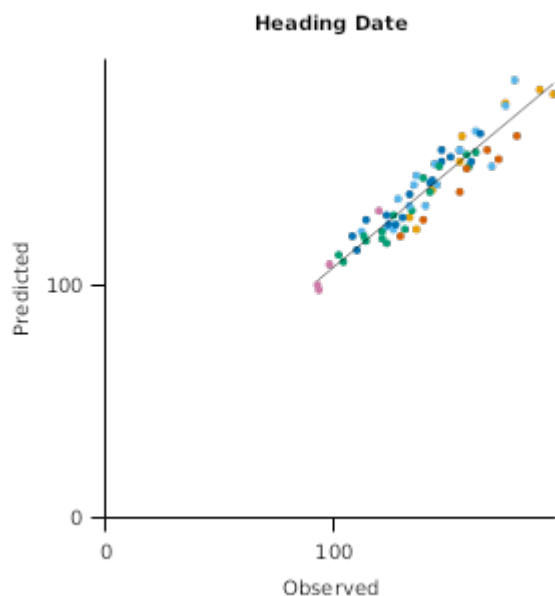
Harvest Biomass N



Harvest Grain N







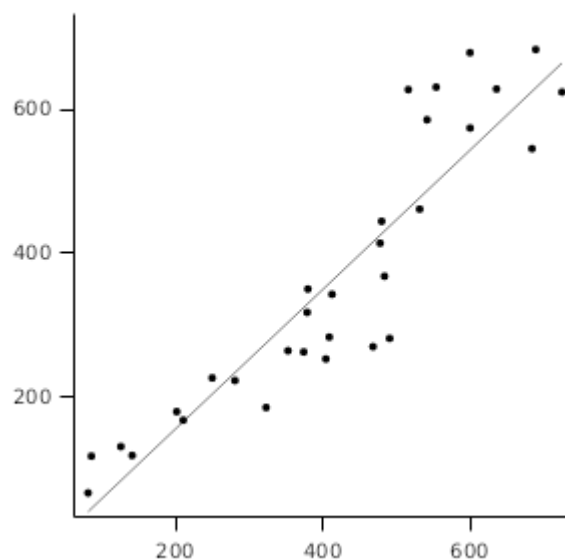
3.2 SE Queensland

South-eastern Queensland has a warm subtropical environment. Daytime temperatures are moderate due to the relatively low latitudes for wheat growing in Australia, but inland continental conditions can provide cool nights with occasional frosts. Many of the datasets used here have been published as part of previous APSIM Wheat model tests. Further datasets have been added to provide information on phenological development of modern cultivars.

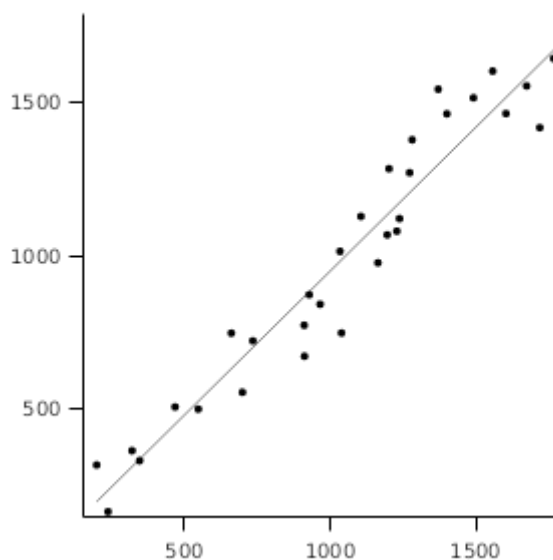
List of experiments.

Experiment Name	Design (Number of Treatments)
APS26	NRate x Water (8)
APS6	NRate (6)
APS14	Stubble x NRate (12)
APS2	TOS (2)
GattonRowSpacing	RowSpace (3)
Gatton94	Cv x TOS (12)
Gatton2009	TOS x Cv (48)
Gatton2011	TOS x Cv (15)
Gatton2014	TOS x Cv (148)
Gatton2014AE	V x P x Cv (148)
TraitMod2015	TOS x Cv (10)
TraitMod2016	TOS x Cv (5)

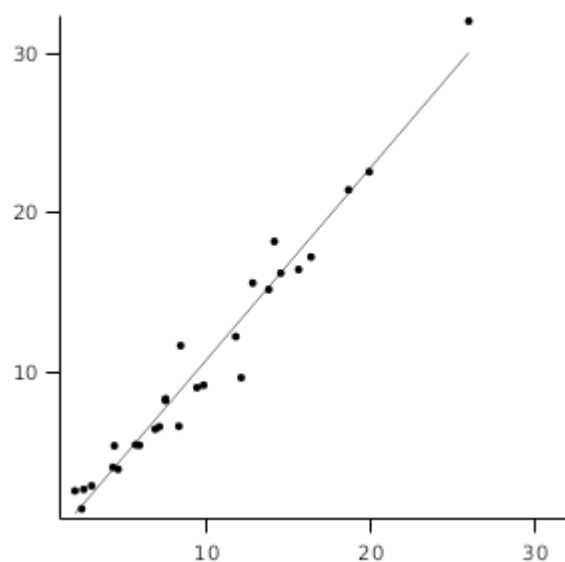
Harvest Yield



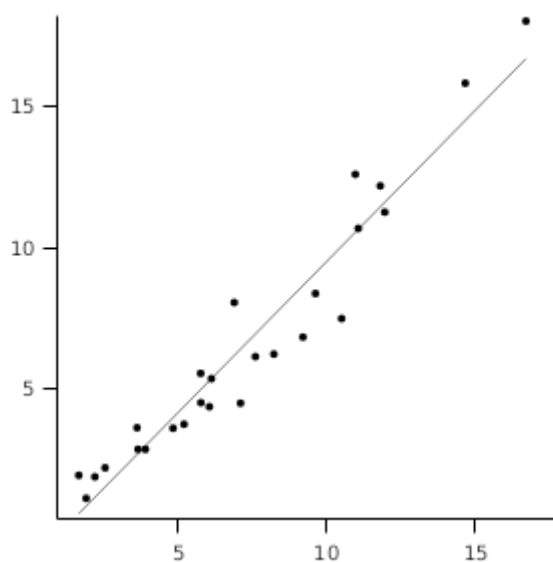
Harvest Biomass



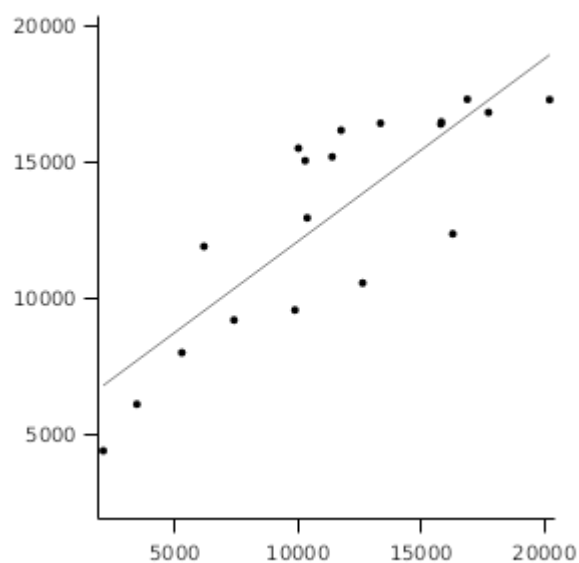
Harvest Biomass N



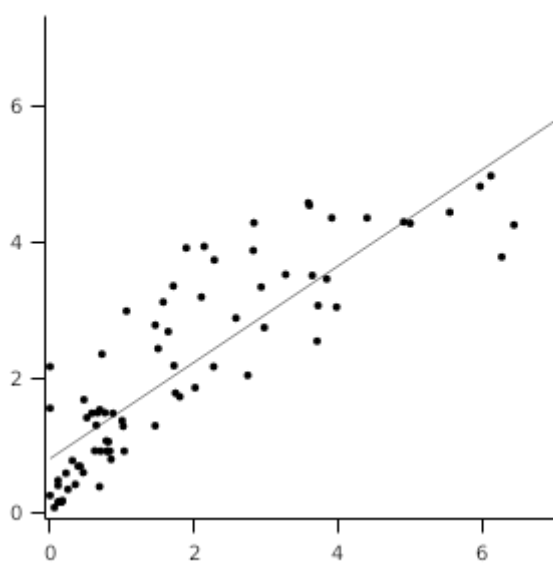
Harvest Grain N

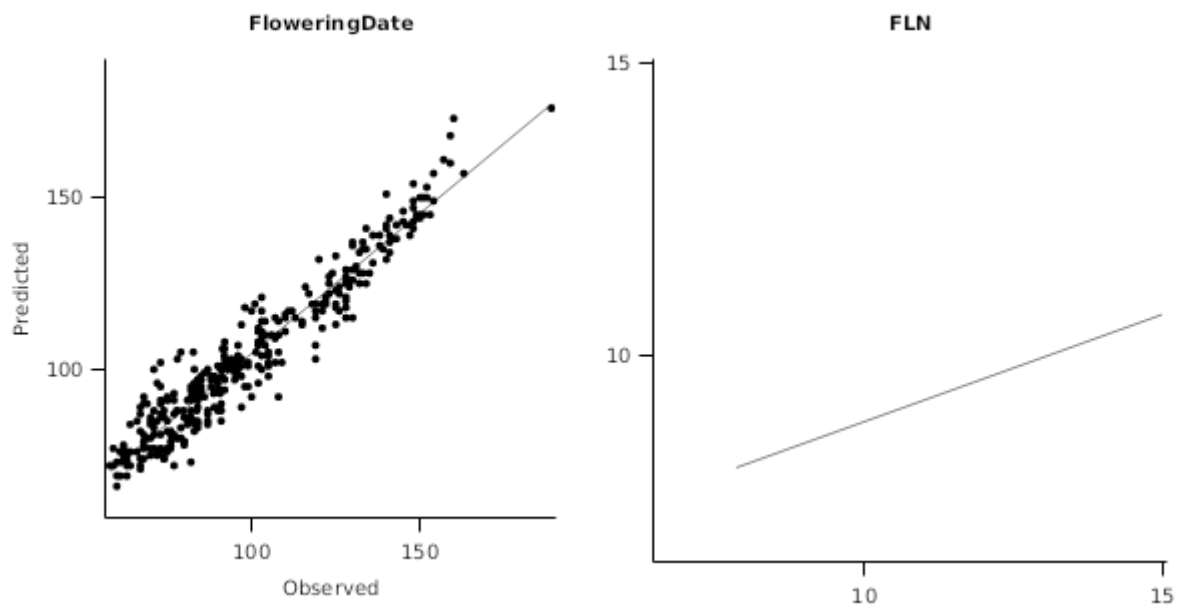


GrainNumber



Leaf Area Index



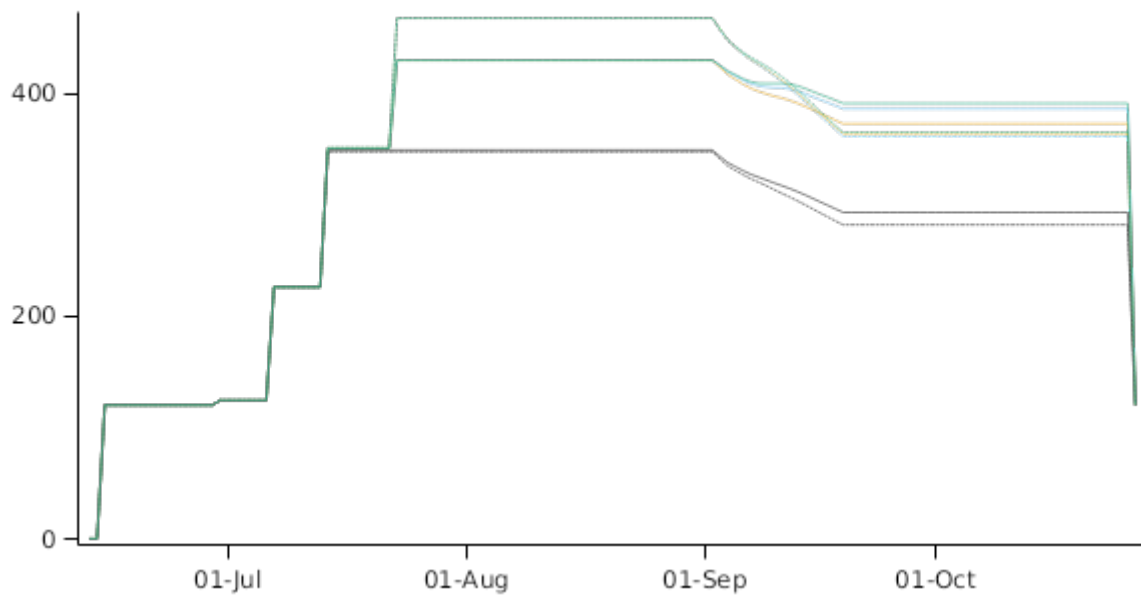


3.2.1 APS26

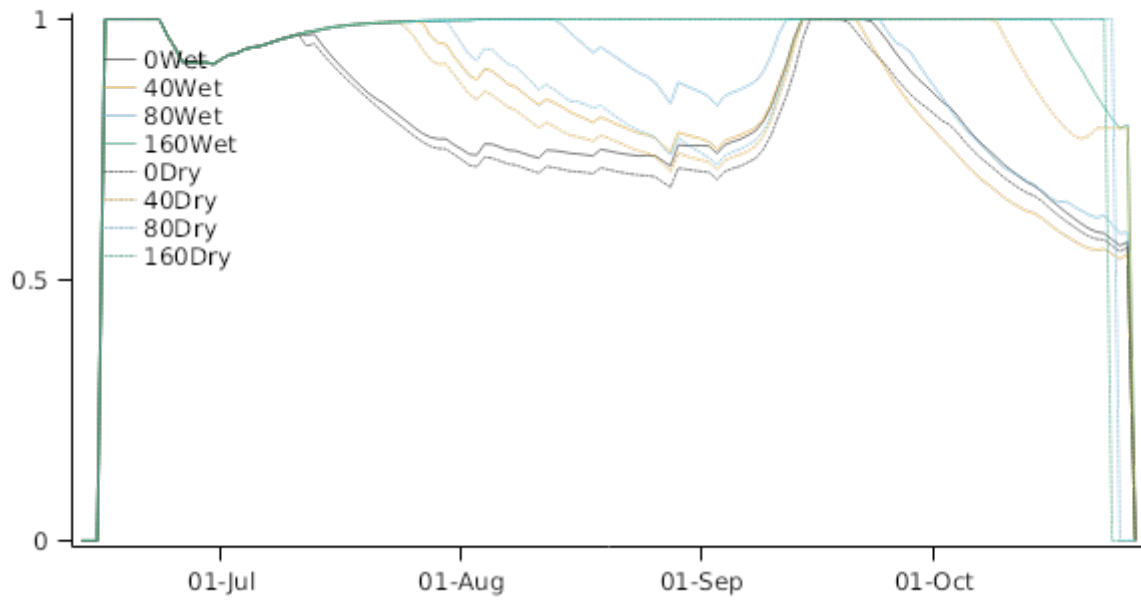
This trial was conducted at Gatton in 1995 using the local variety, Hartog. It consisted of 4 Nitrogen rates (0,40,80,160) with two irrigation rates (minimal amount for establishment, fully irrigated). Yields ranged from 1.4 t/ha to 5.4 t/ha.

FW photo

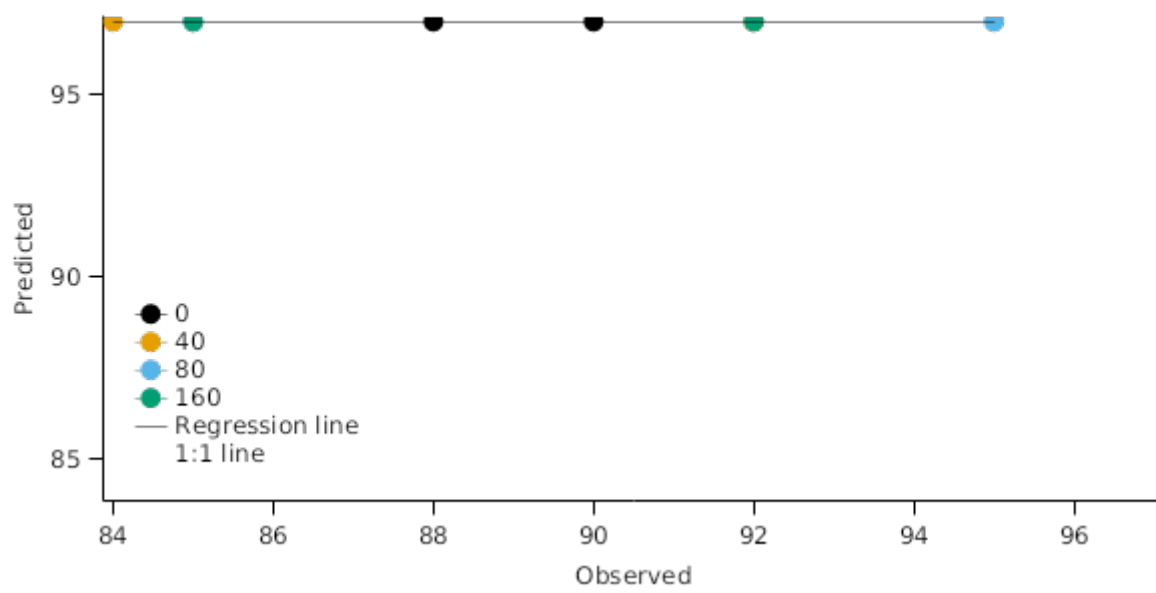
StemNumber



Leaf Fn



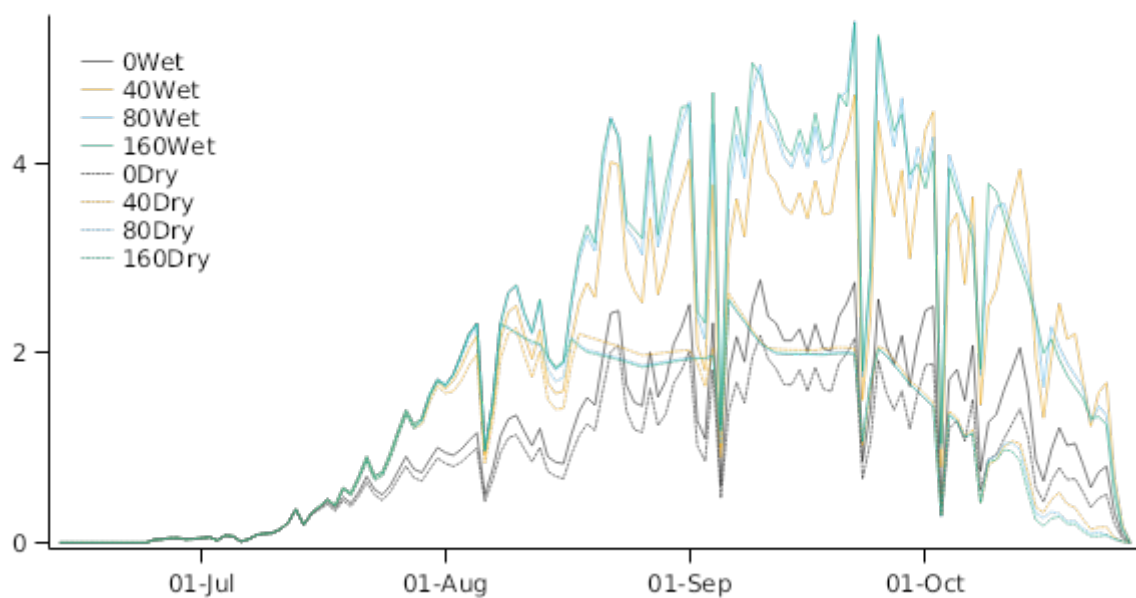
FloweringDate



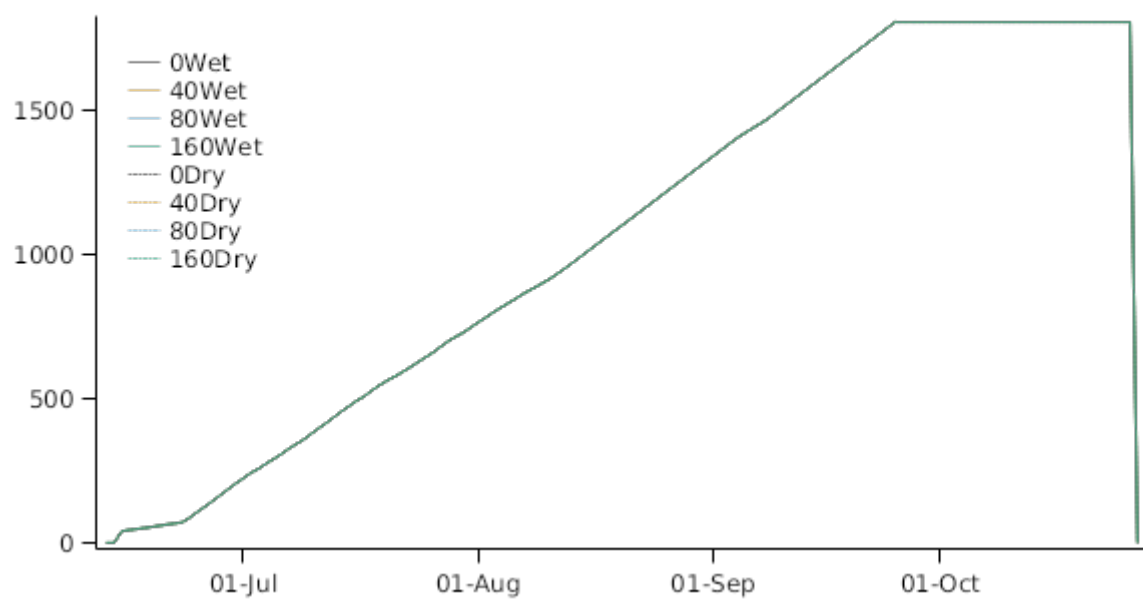
WaterPotential

C Supply and Demand

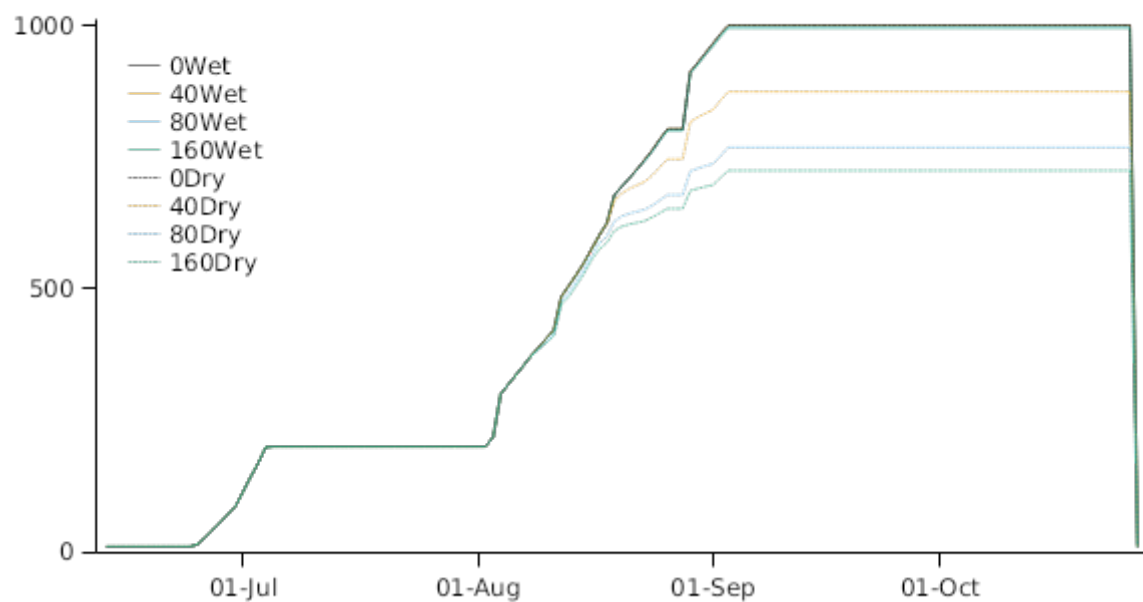
ET



RootDepth



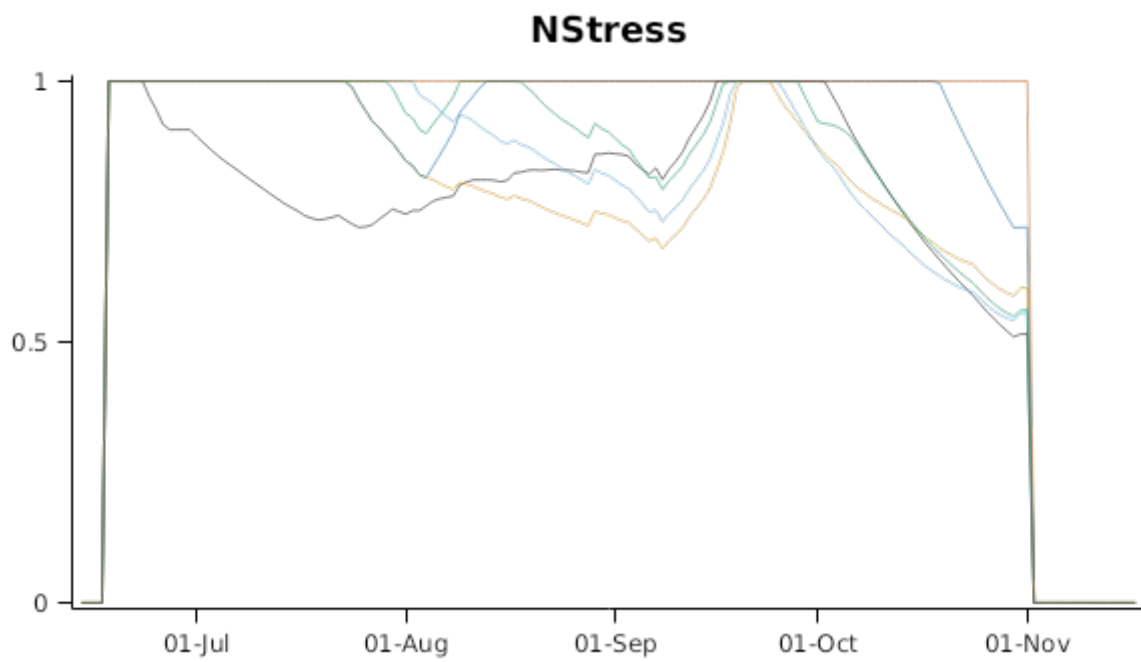
Height



RootLengthDensity

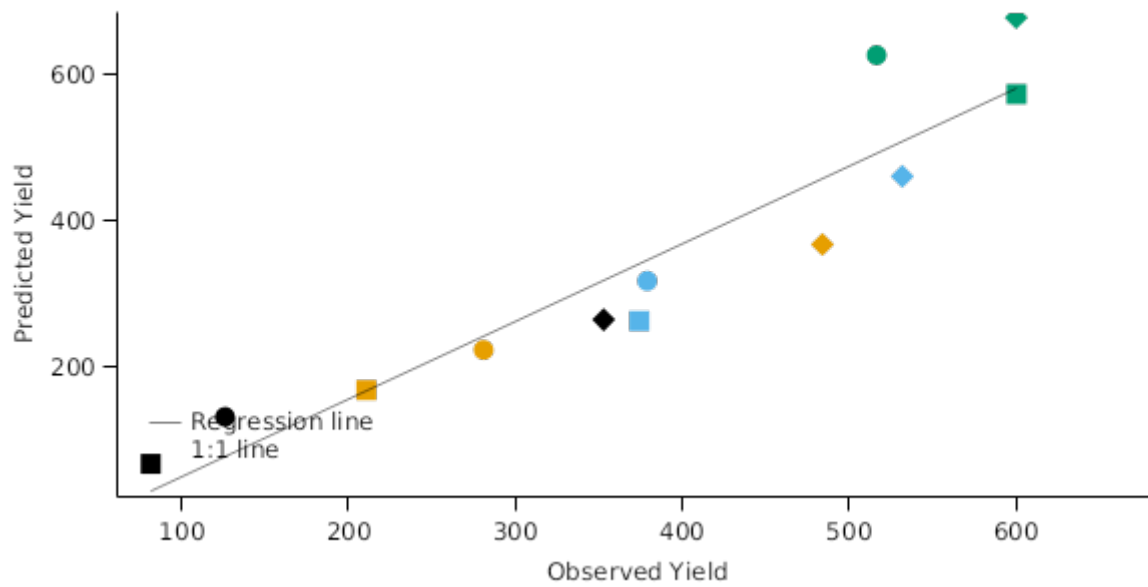
3.2.2 APS6

NOTE: High N treatment logdged. Final grain sizes were less than expected.

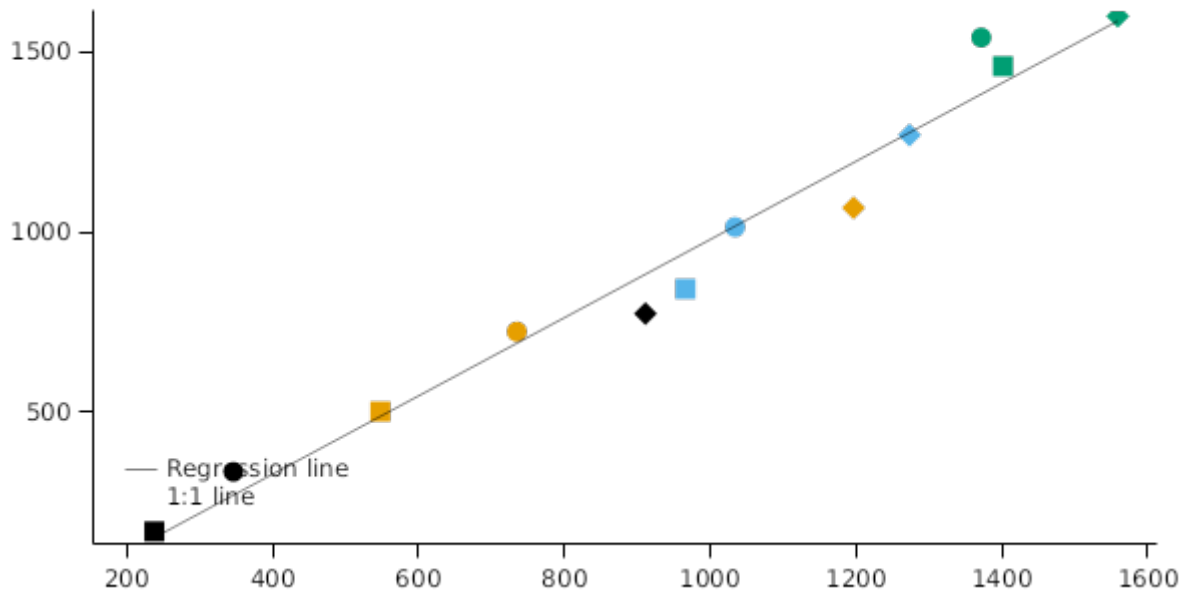


3.2.3 APS14

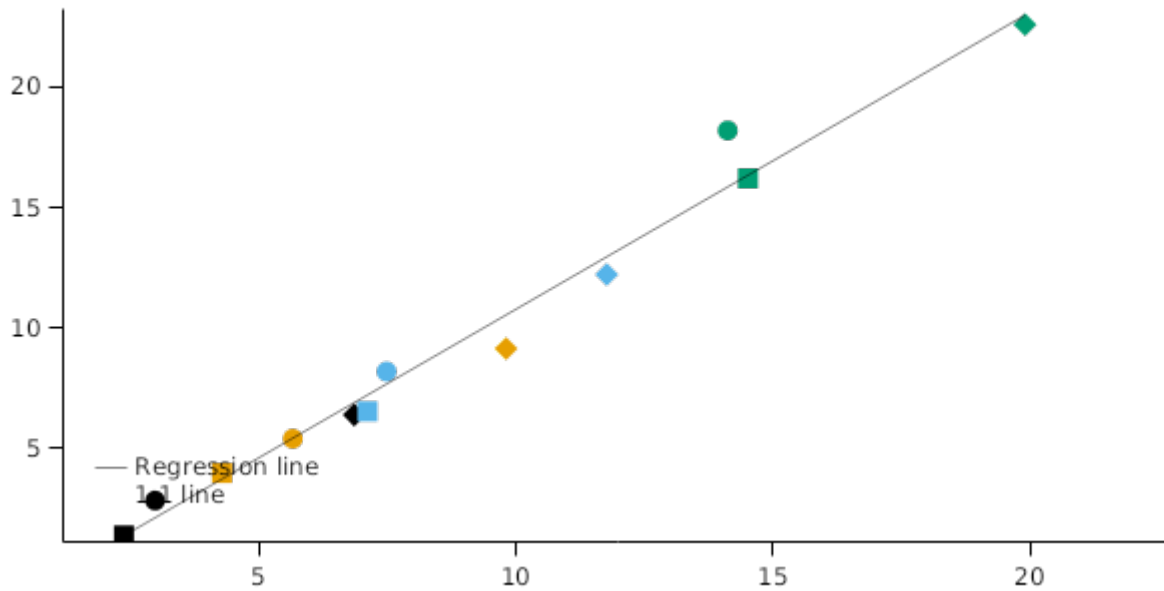
Yield



Biomass



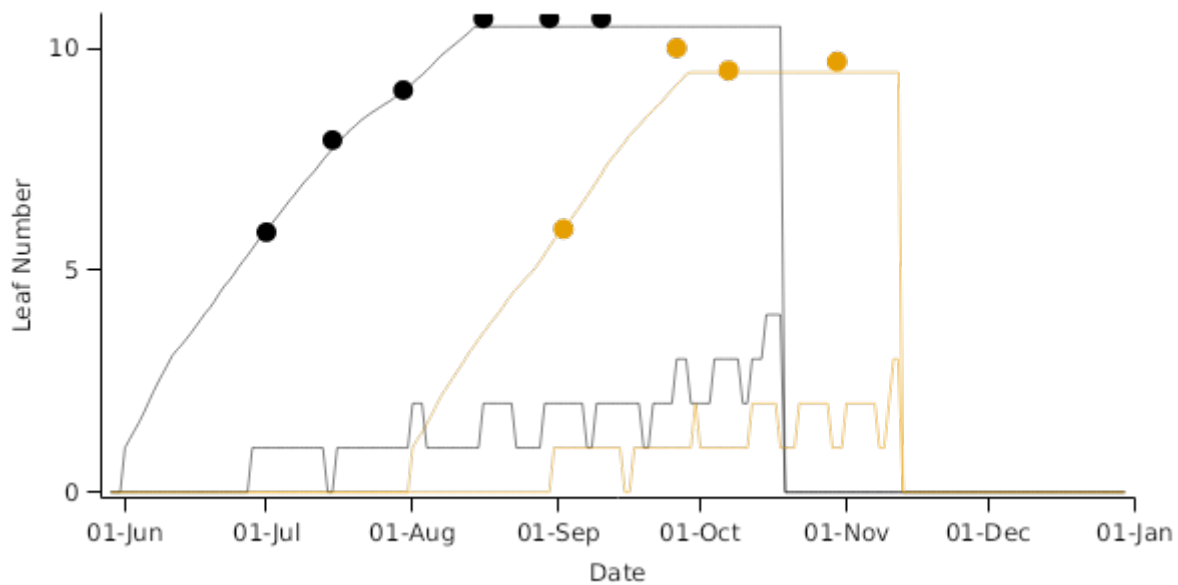
BiomassN



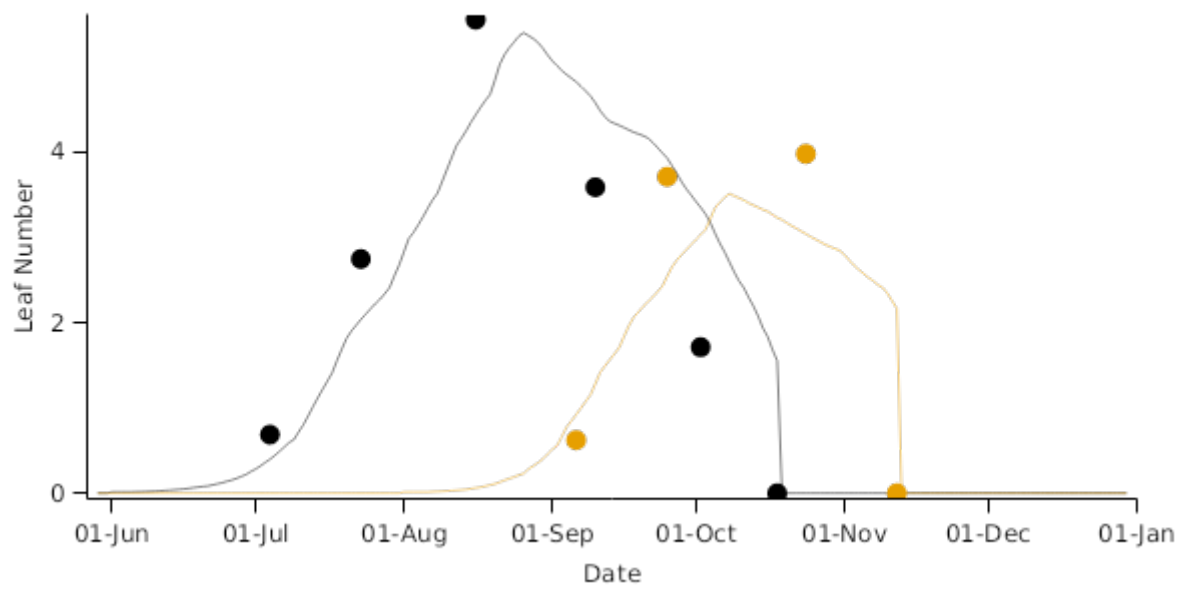
3.2.4 APS2

This simple experiment was conducted to investigate the impact of time of sowing on canopy development and growth of wheat. Wheat (cv. Hartog) was sown at Gatton on 30th of May and 30th of July in 1991. Data were collected on canopy development, biomass accumulation and yield.

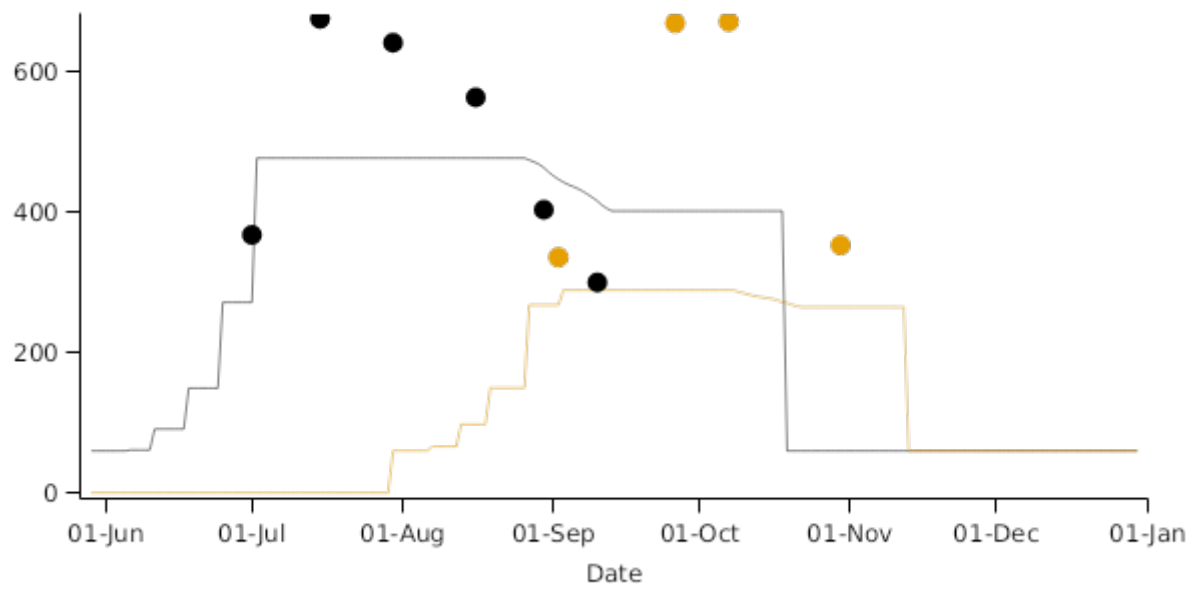
LeafAppearance



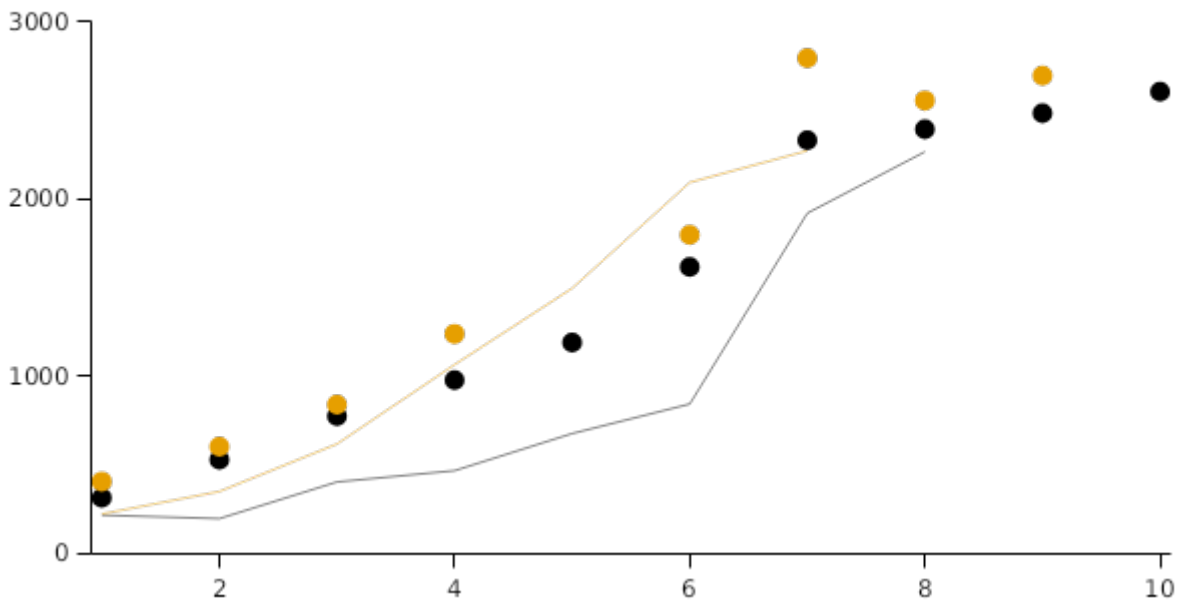
LAI



TillerNumber



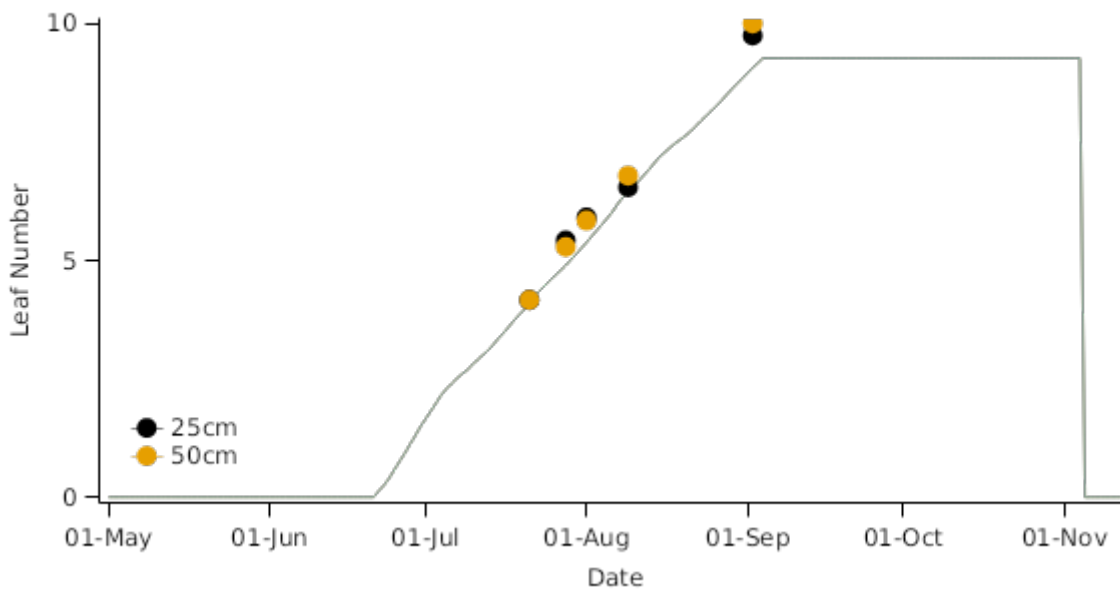
LeafSize



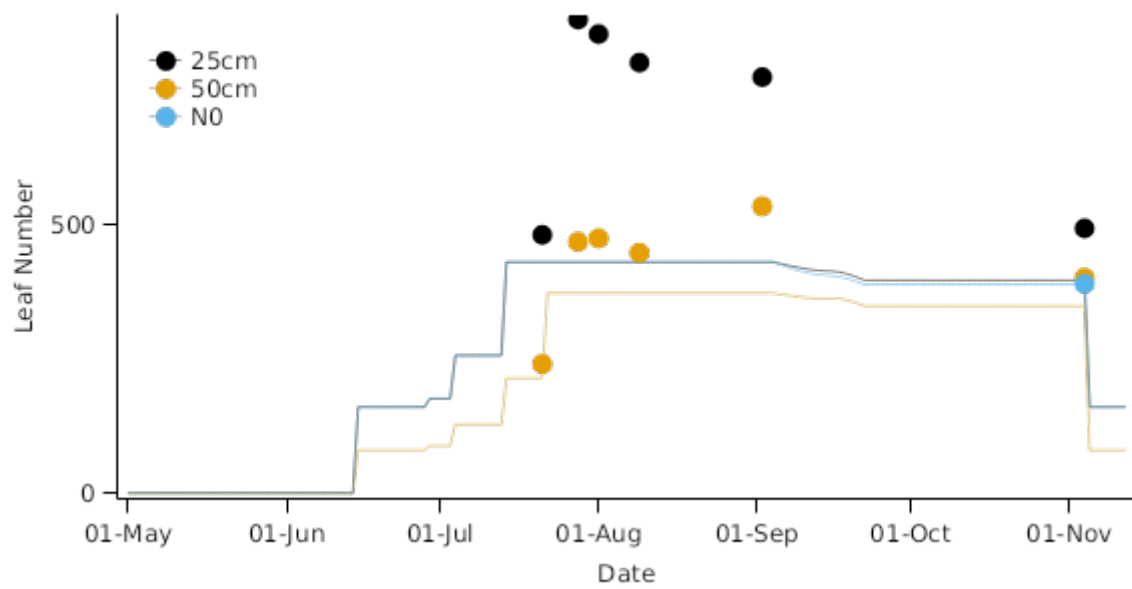
3.2.5 GattonRowSpacing

This simple experiment was conducted to investigate the light interception and subsequent growth of wheat under different populations invoked using row spacing. Wheat was sown at Gatton on 15th of June 2011 at 25cm row spacing. Soon after emergence, alternate rows were removed from selected plots to produce half populations at 50cm row spacing. A zero N treatment was used to identify the inherent fertility of the site to assist in model parameterisation. Data were collected on light interception, canopy development, biomass accumulation and yield.

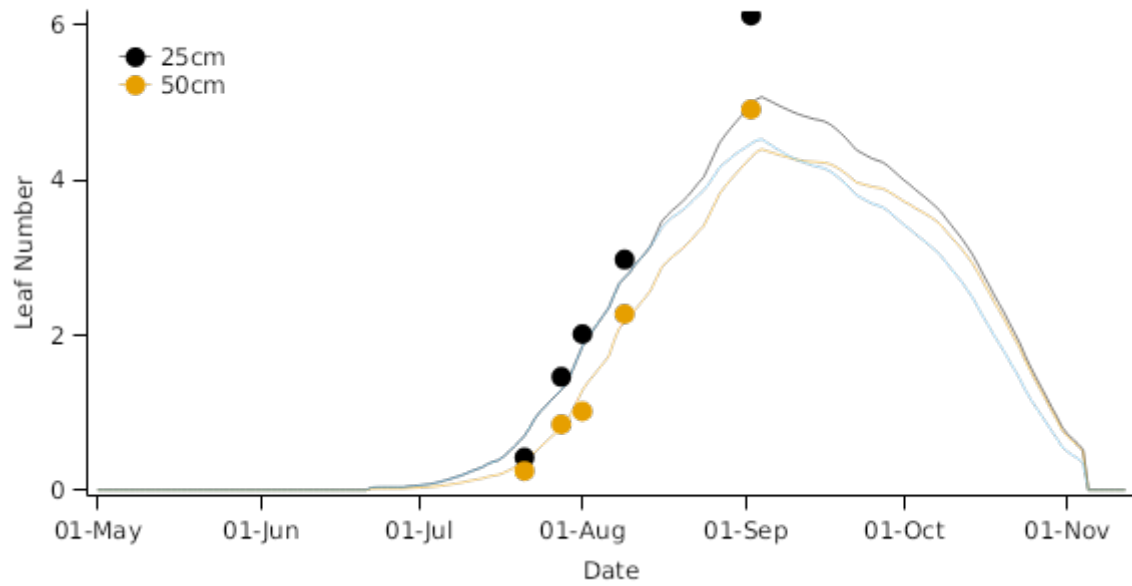
LeafAppearance



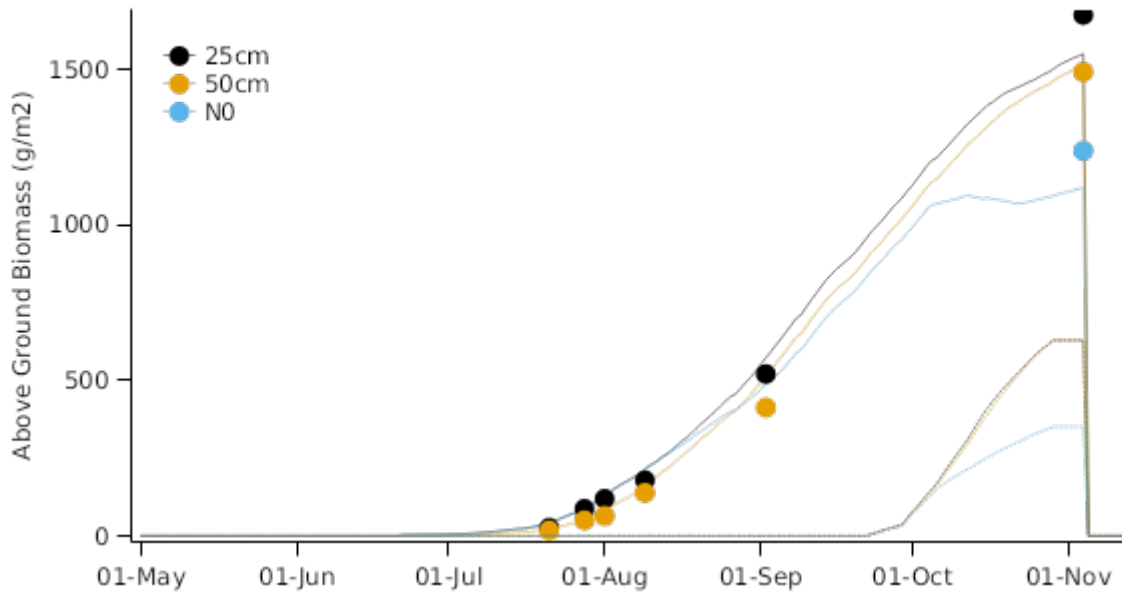
TillerNumber



LAI



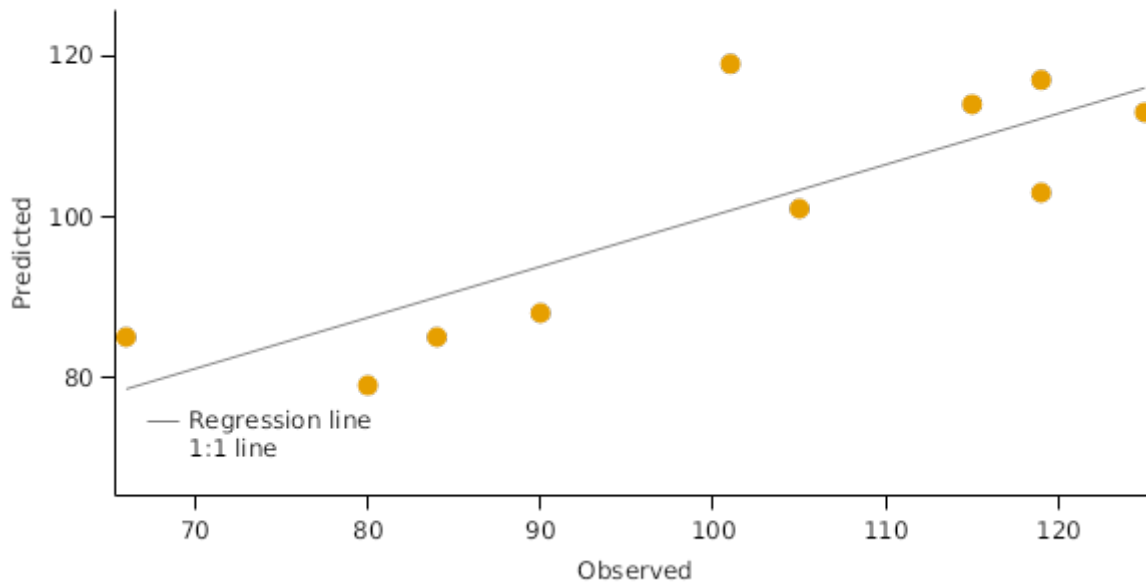
AboveGroundWt



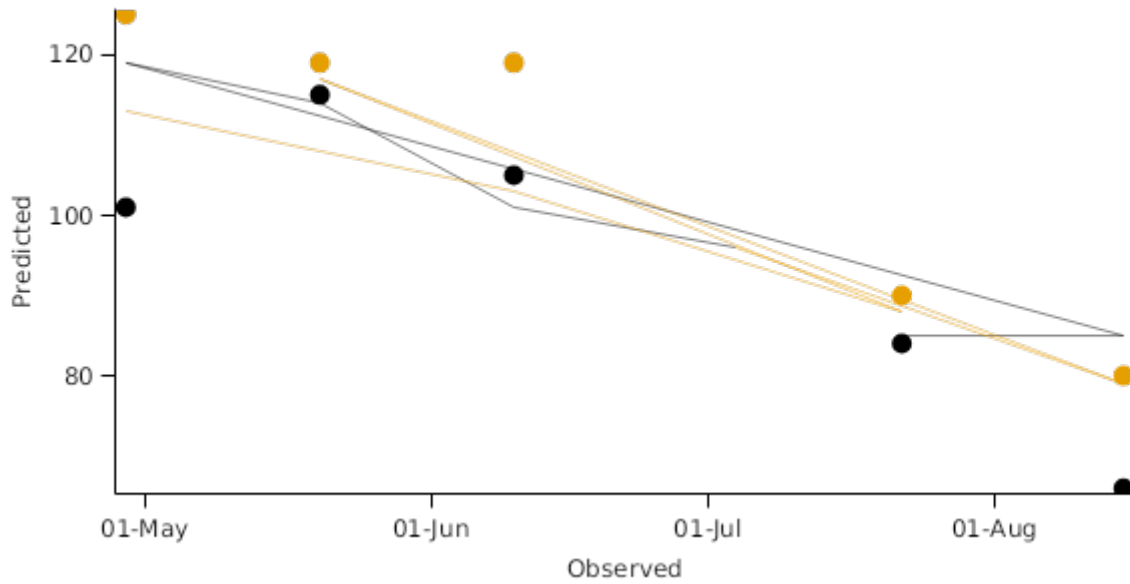
3.2.6 Gatton94

This simple experiment was conducted to investigate the impact of time of sowing on wheat. Wheat (cv. Hartog and Batavia) was sown at Gatton on six dates during 1994. Various data were collected. However final growth data was compromised by mouse damage. The dataset is used here to study the impact of sowing time on phenological development.

FloweringDate

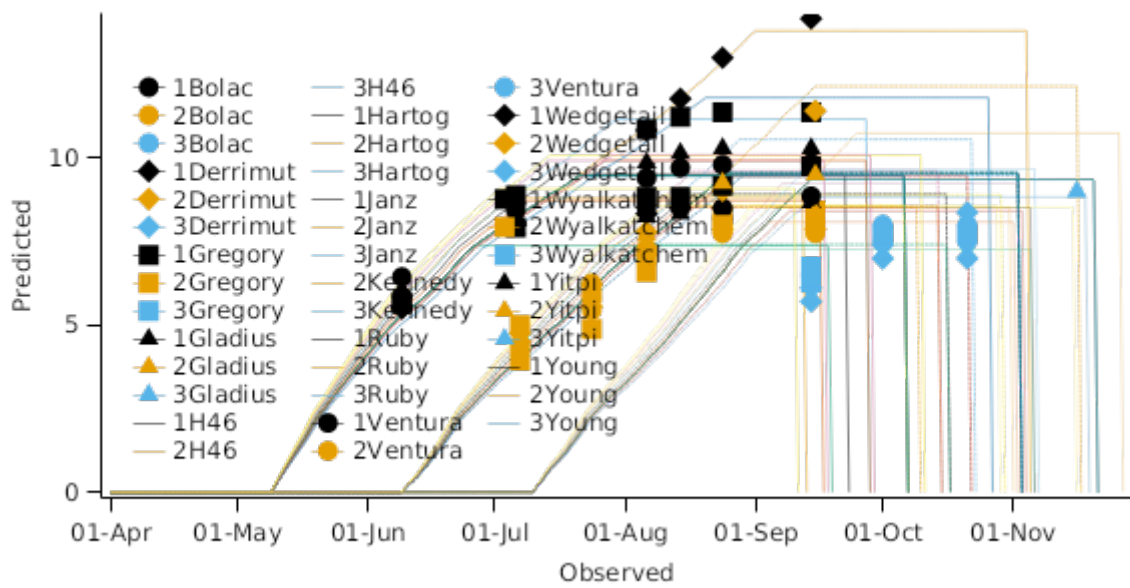


FloweringDate vs TOS

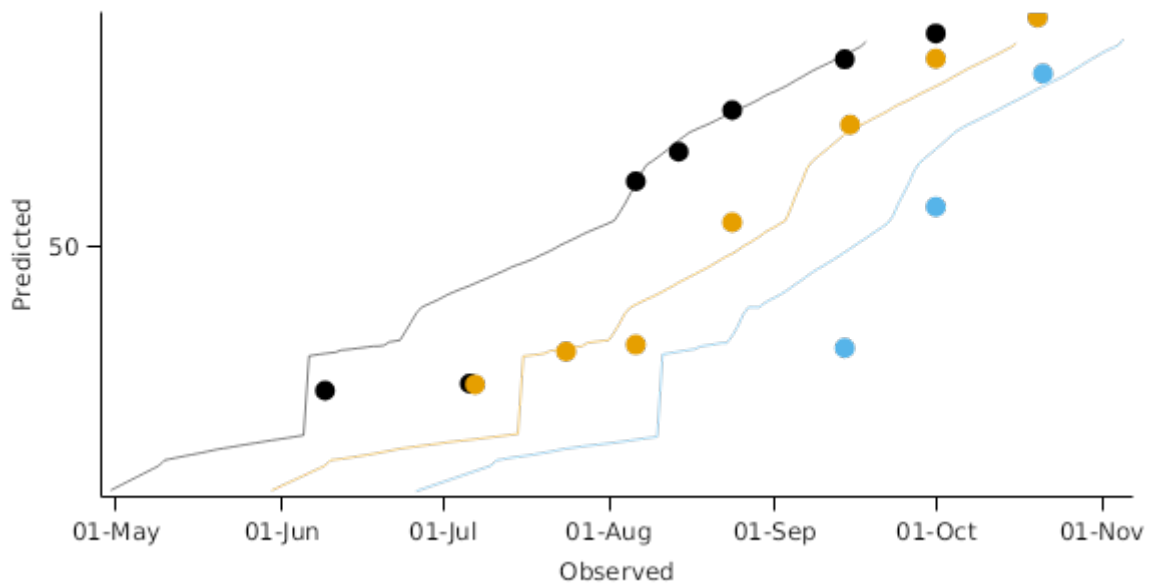


3.2.7 Gatton2009

LeafNumberTimeSeries

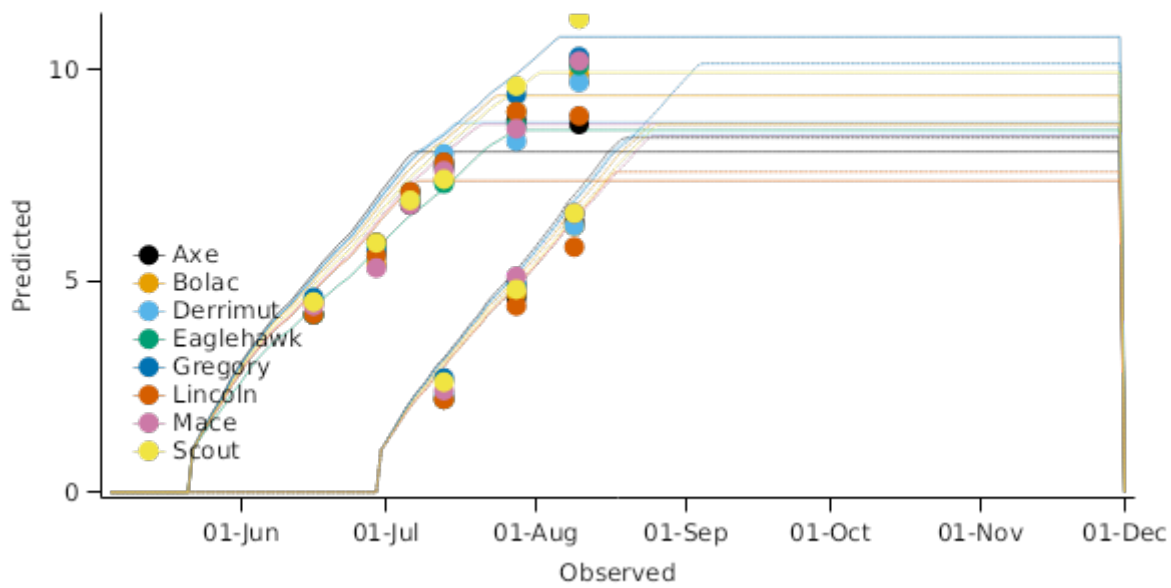


ZadokTimeSeries

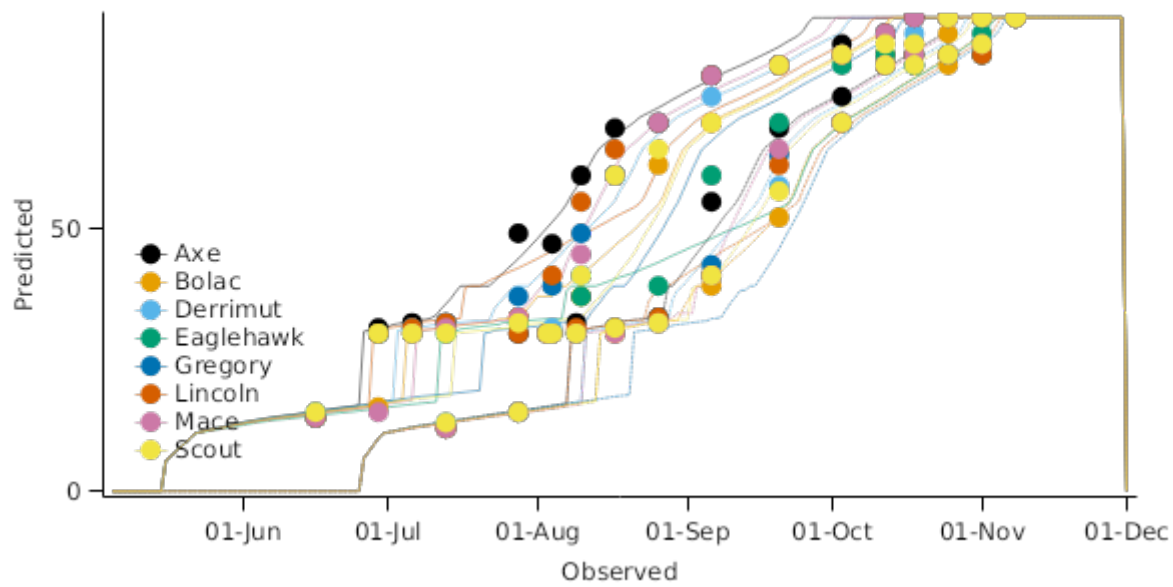


3.2.8 Gatton2011

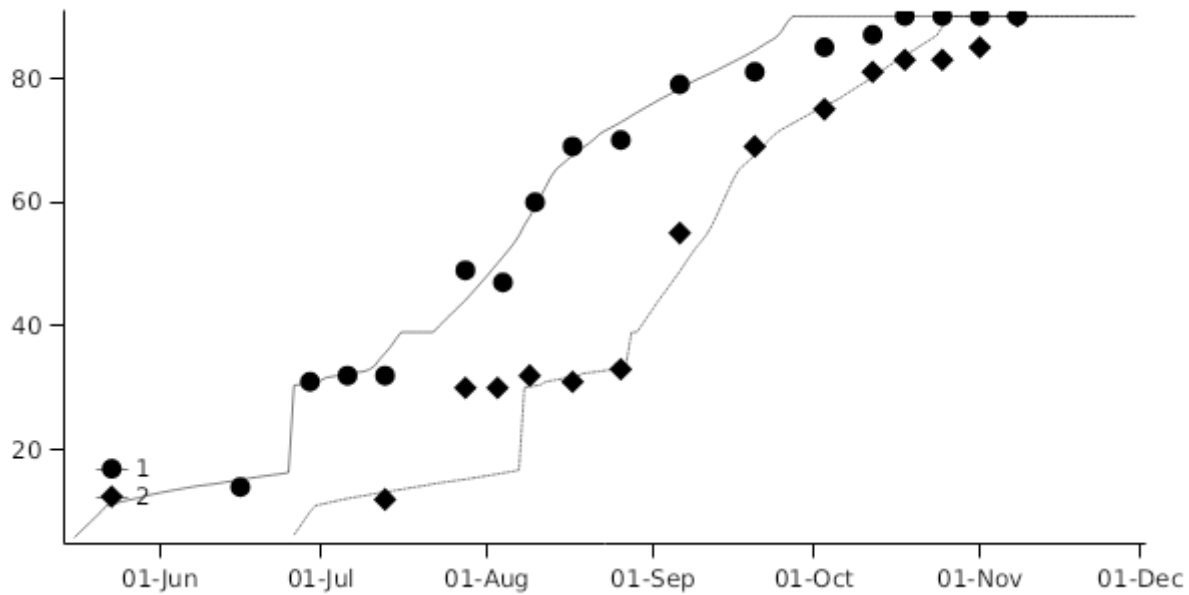
LeafNumberTimeSeries



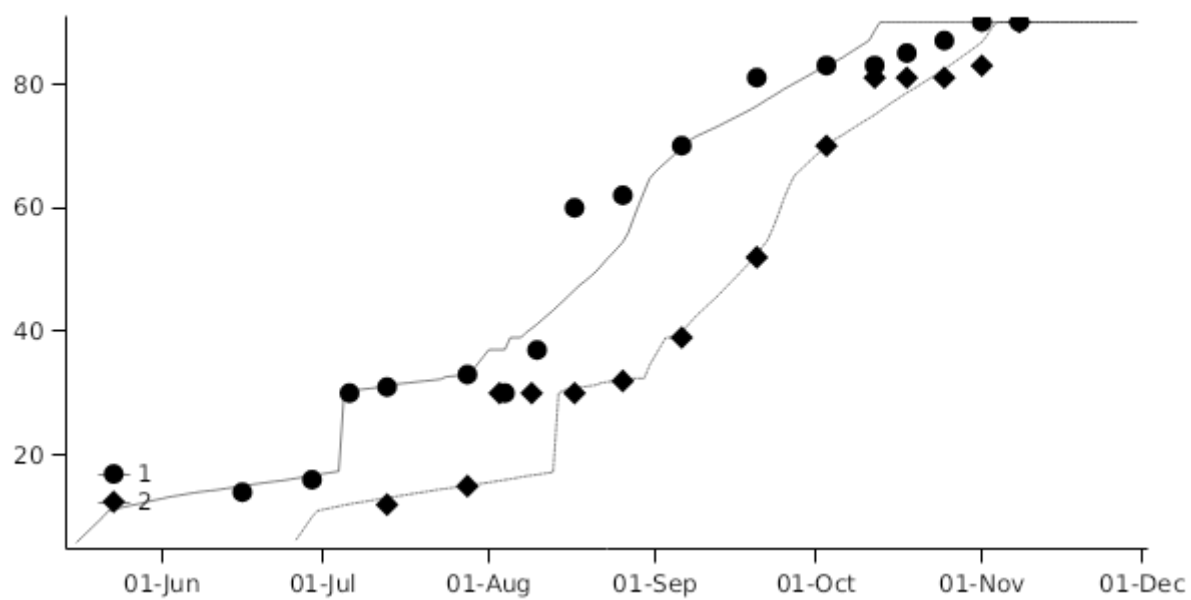
ZadokTimeSeries



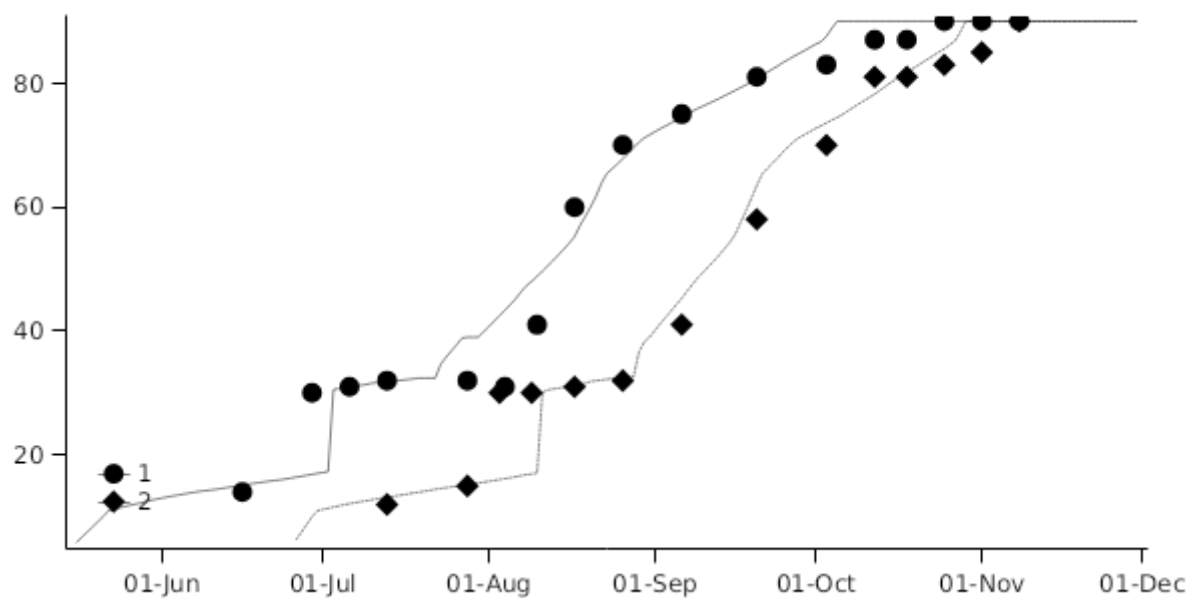
Axe



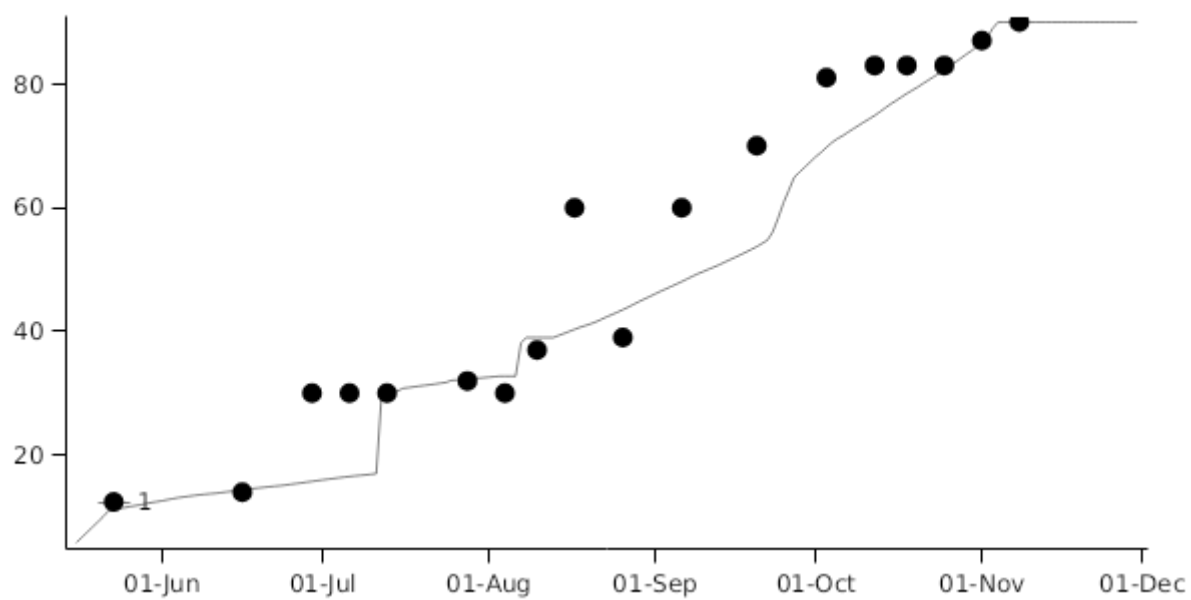
Bolac



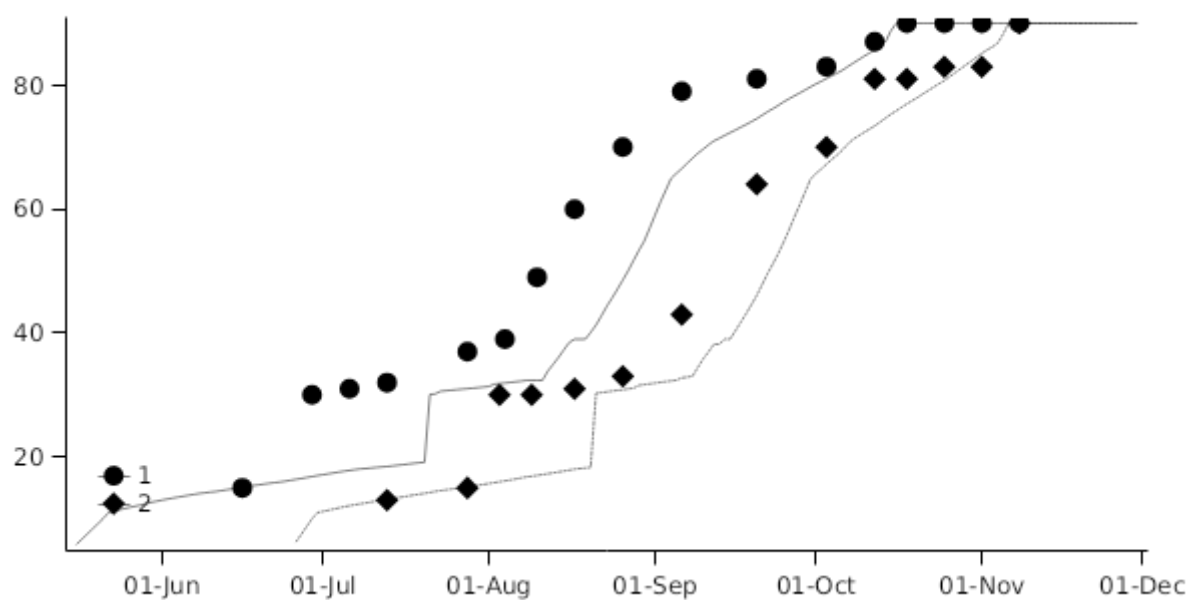
Derrimut



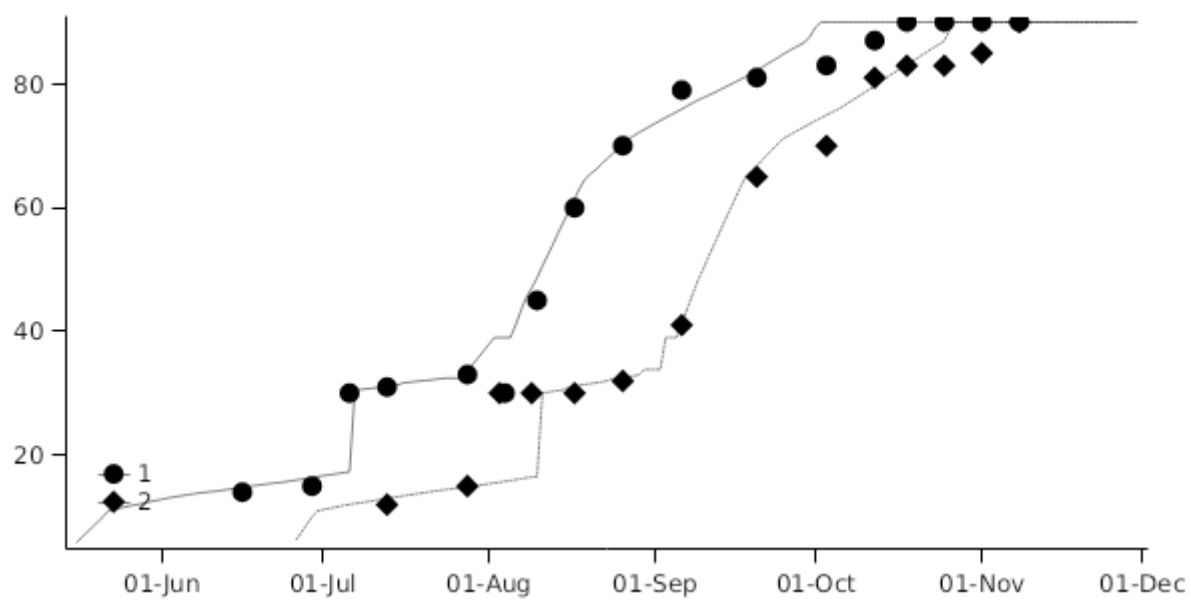
EagleHawk



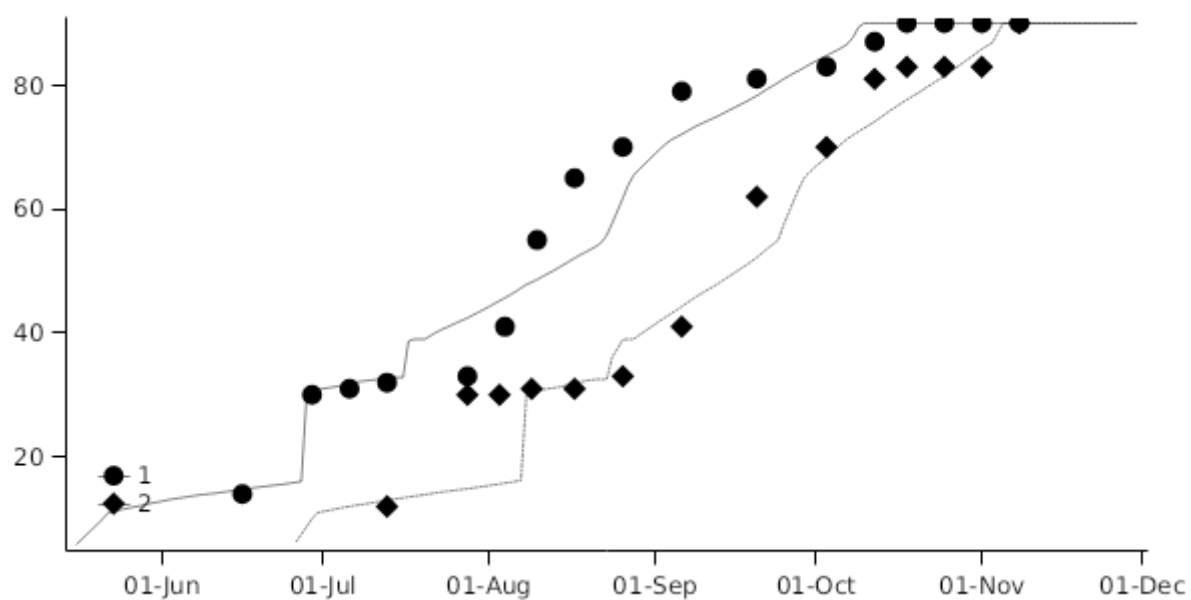
Gregory



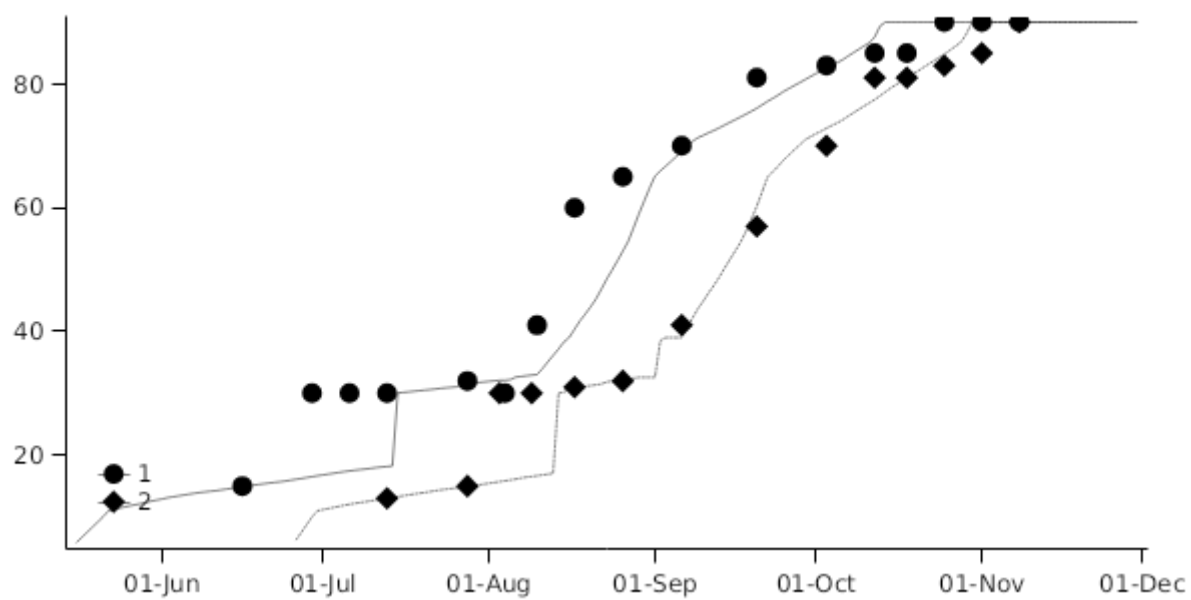
Mace



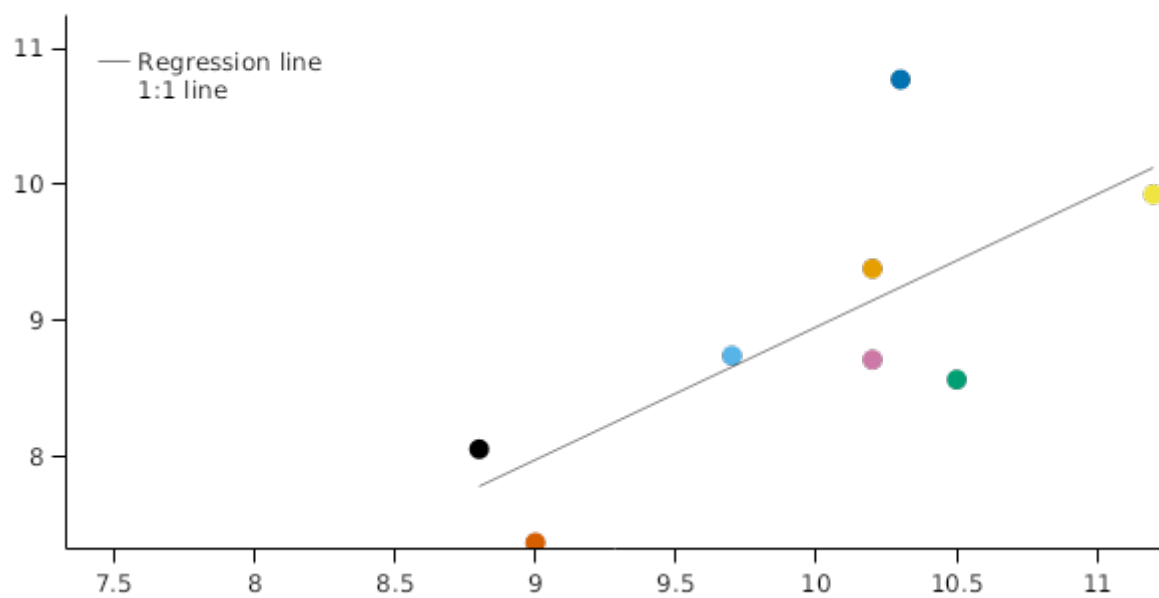
Lincoln



Scout



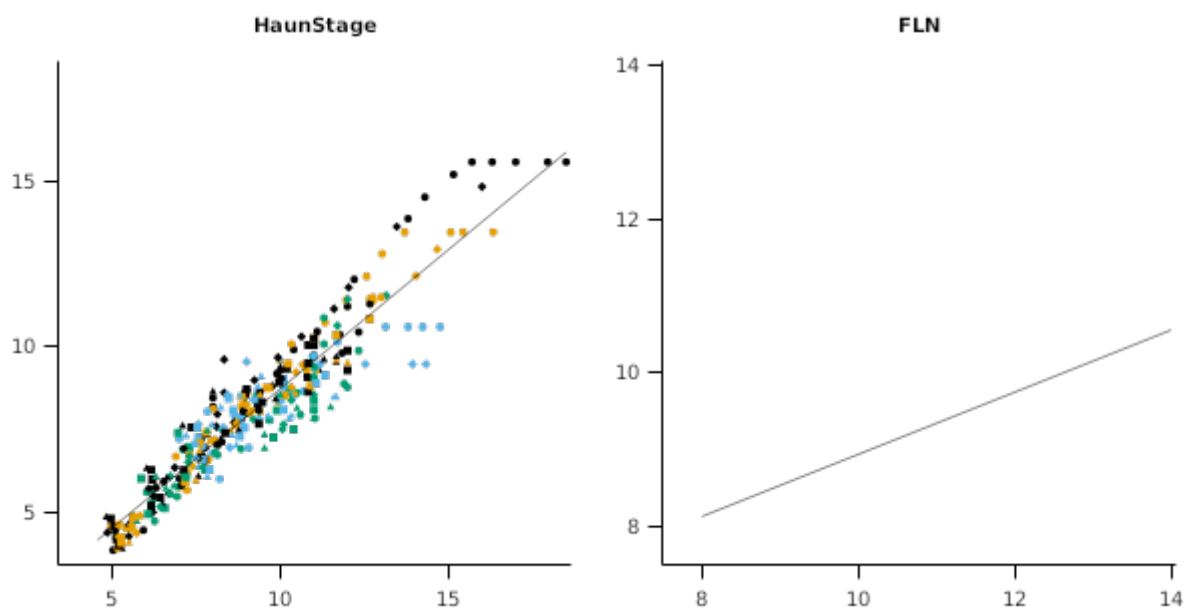
FLN



ZadokTimeSeries1

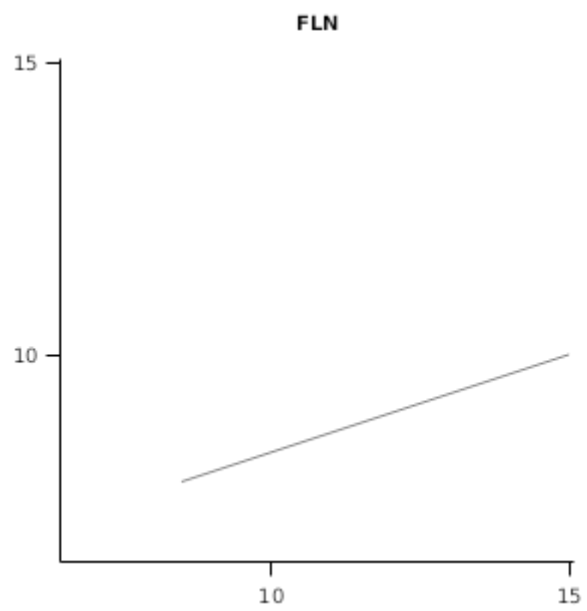
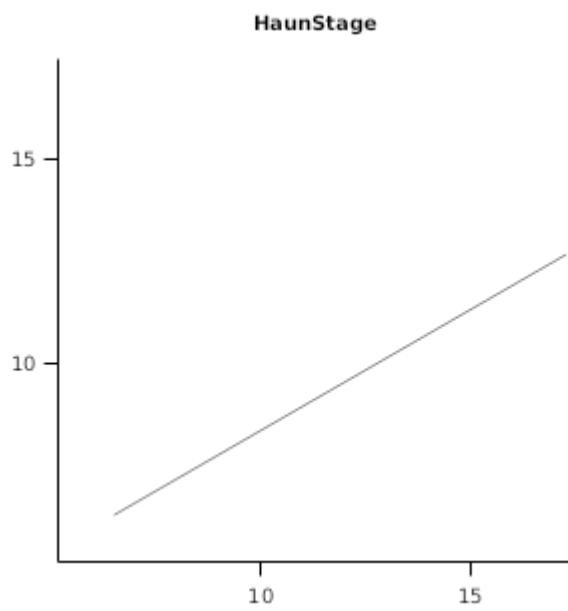
3.2.9 Gatton2014

3.2.9.1 PredObs



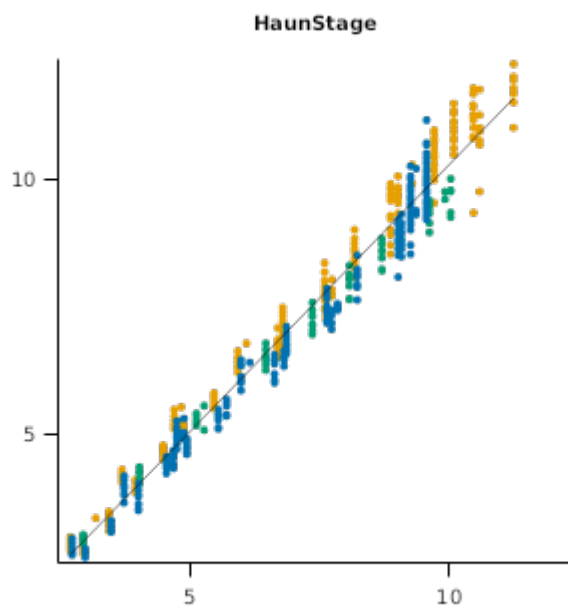
3.2.10 Gatton2014AE

3.2.10.1 PredObs



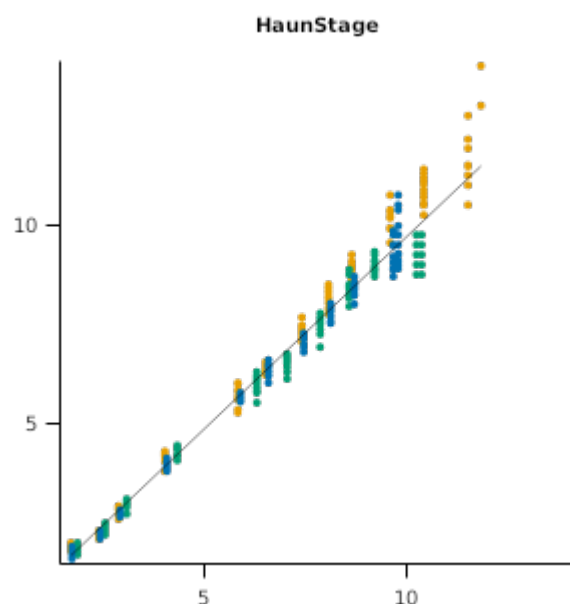
3.2.11 TraitMod2015

3.2.11.1 PredObs



3.2.12 TraitMod2016

3.2.12.1 PredObs



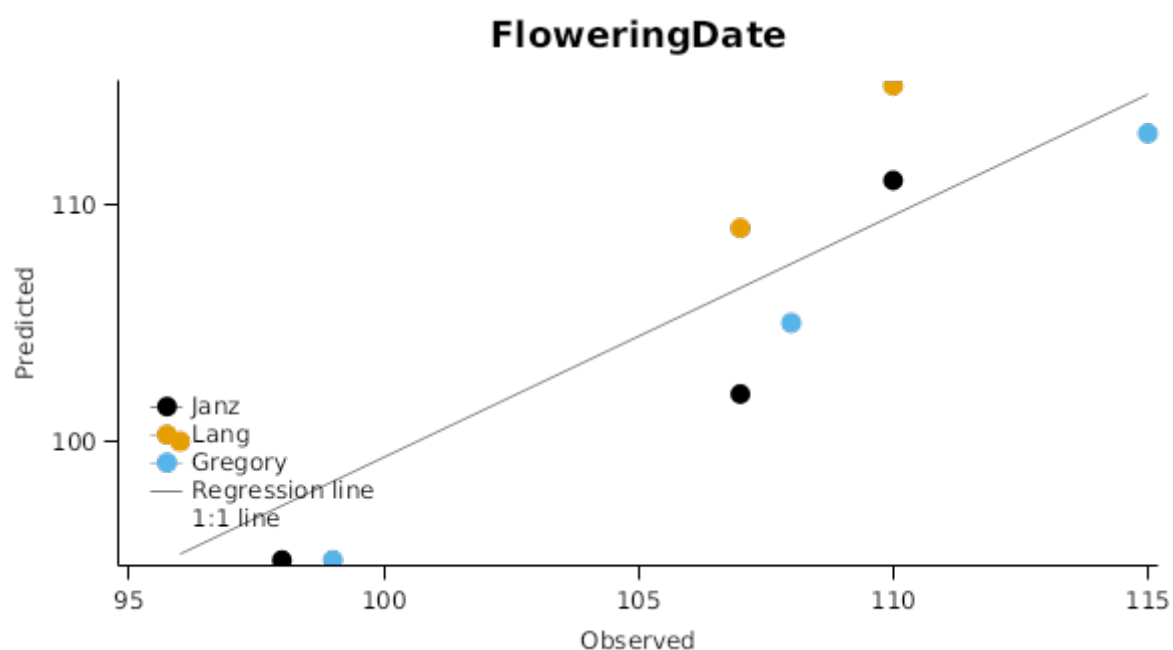
3.2.13 AddingValueToNVT

The "Adding Value to the National Variety Trials" project aimed to use measurement and modelling to explain GeneXEnvironmentXManagement interactions for Australian Wheat cultivars. A description of this national trial can be found in [R.A. Lawes et al., 2016](#). Here we include some of the data from south-eastern Queensland.

List of experiments.

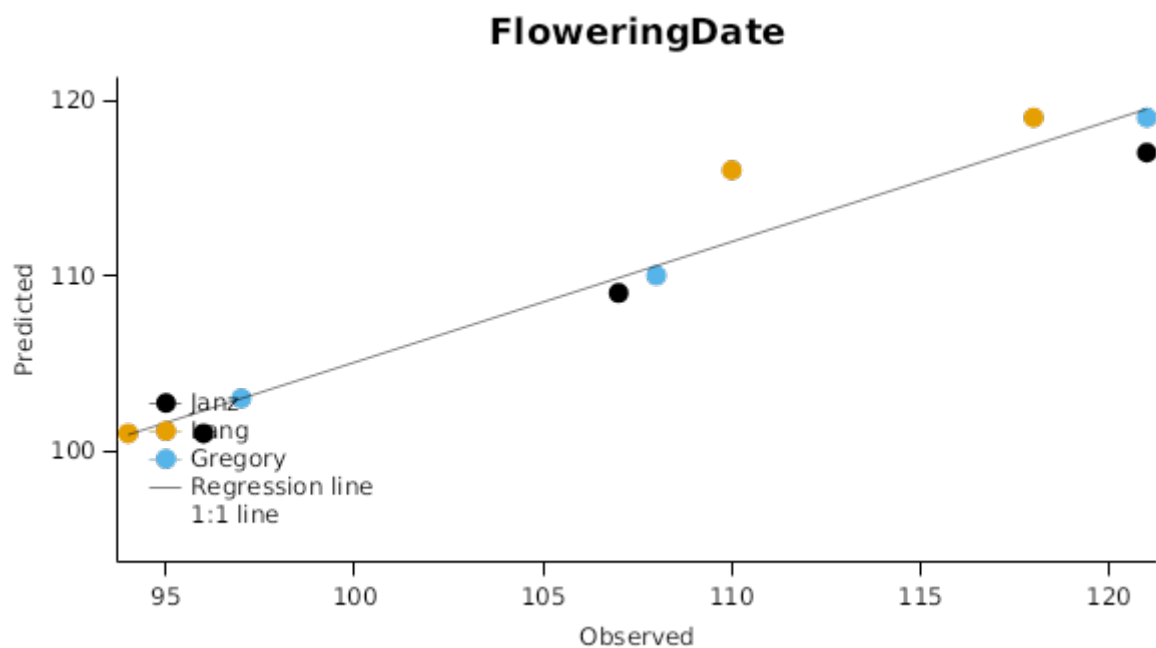
Experiment Name	Design (Number of Treatments)
Goondiwindi2011	Cv x TOS (9)
Nagwee2012	Cv x TOS (9)
Bungunya2012	Cv x TOS (9)

3.2.13.1 Goondiwindi2011



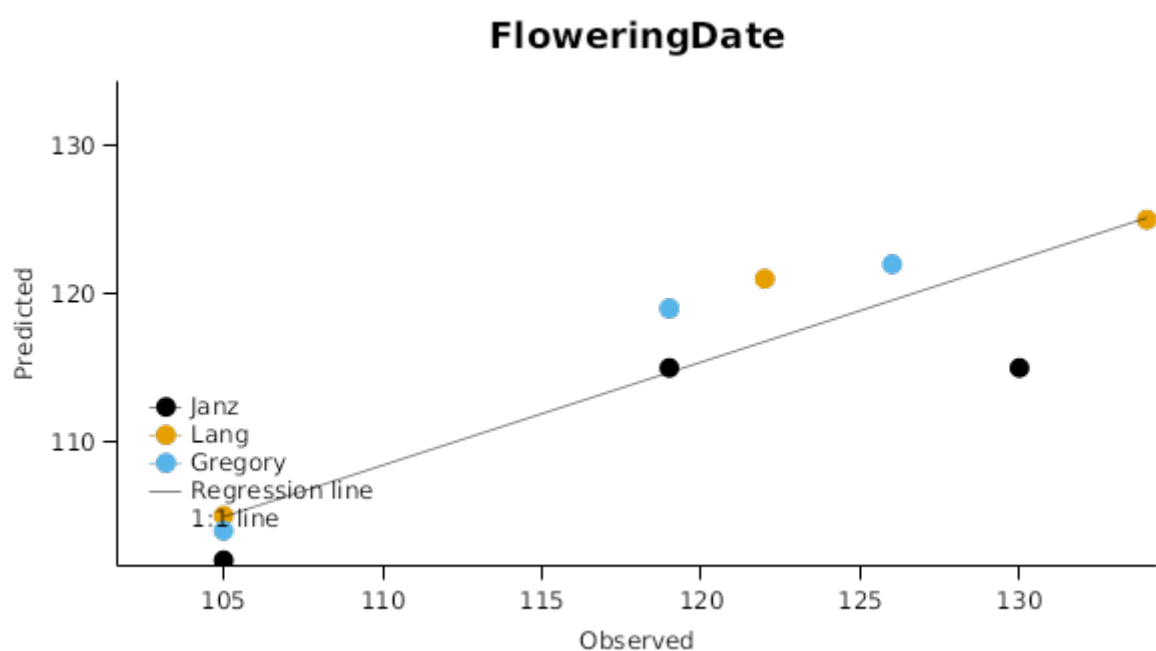
3.2.13.2 Nagwee2012

INSERT TEXT HERE



3.2.13.3 Bungunya2012

INSERT TEXT HERE



3.2.14 Phenology1996

This dataset includes observed heading date for six cultivars (Batavia, Cunningham, Hartog, Janz, Sunbri, Suneca) for a range of locations and planting dates in the northern grain-growing region of Australia.

List of experiments.

Experiment Name	Design (Number of Treatments)
Goondiwindi1996	Cv x TOS (18)
Miles1996	Cv x TOS (30)
Emerald1996	Cv x TOS (24)
Biloela1996	Cv x TOS (30)

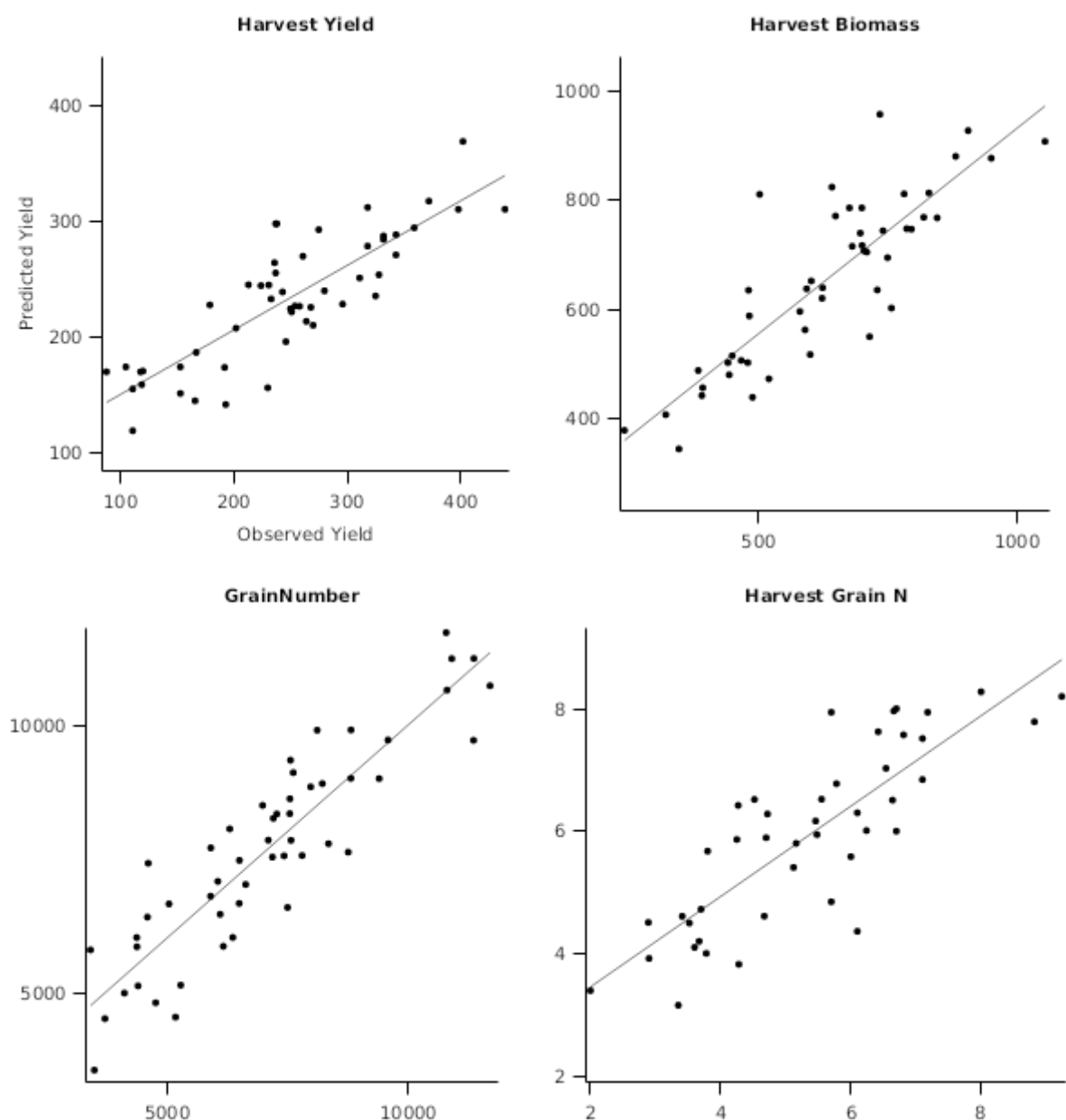
Experiment Name	Design (Number of Treatments)
Moree1996	Cv x TOS (18)

3.3 Western Australia

The wheat belt of Western Australia has a Mediterranean climate (winter dominant rainfall patterns) with mostly sandy soils. Data from [S Asseng et al., 1998](#). and some more recent studies have been included to extend the range of conditions studied and to include more modern cultivars.

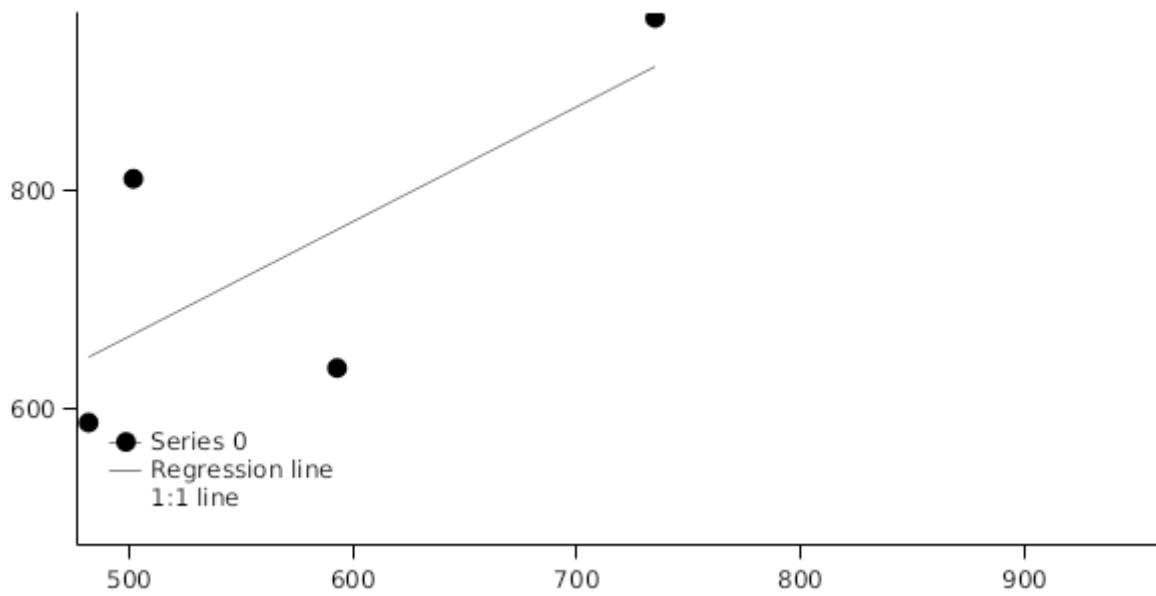
List of experiments.

Experiment Name	Design (Number of Treatments)
Mer86	NRate x Water (4)
Mer73	NRate x Water (6)
Cunderdin97	Sow x SowN x TopN x Irr (40)
Wongan83	Soil x N (10)



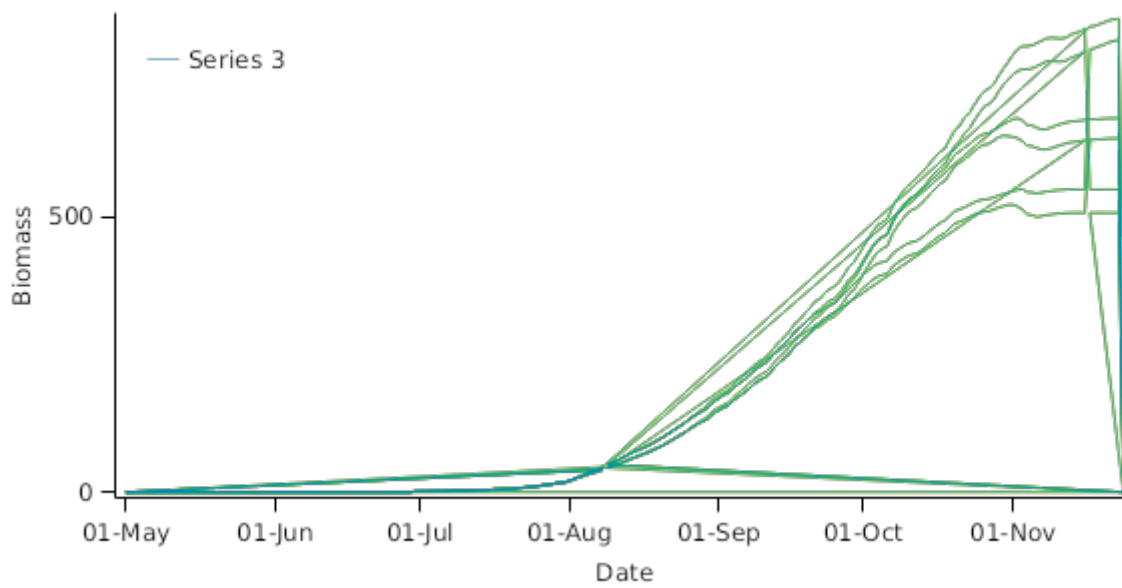
3.3.1 Mer86

Harvest Biomass

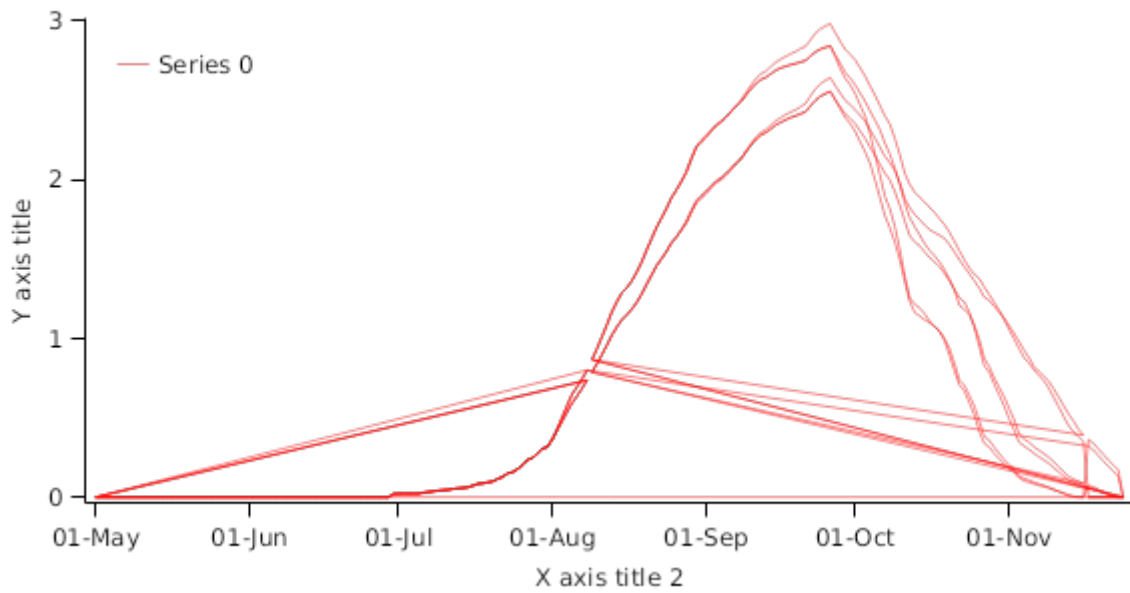


3.3.2 Mer73

Biomass

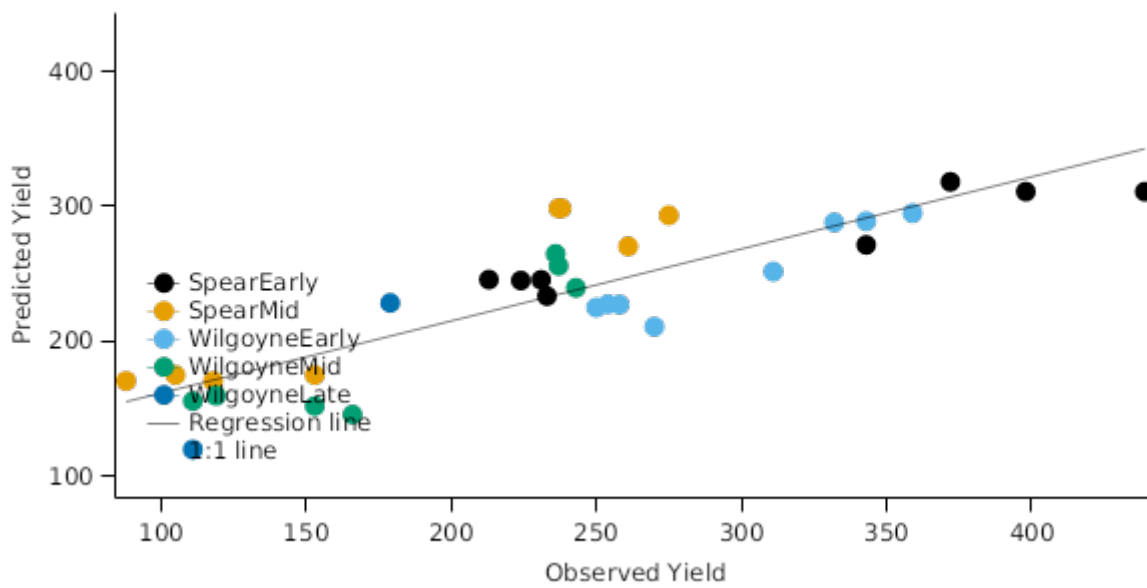


LAI

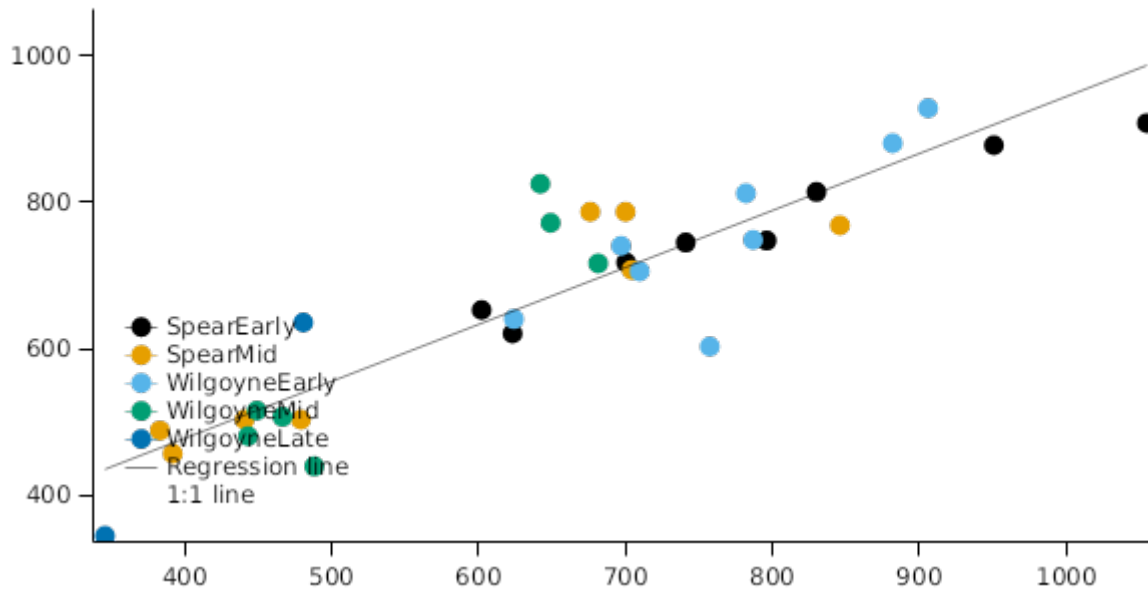


3.3.3 Cunderdin97

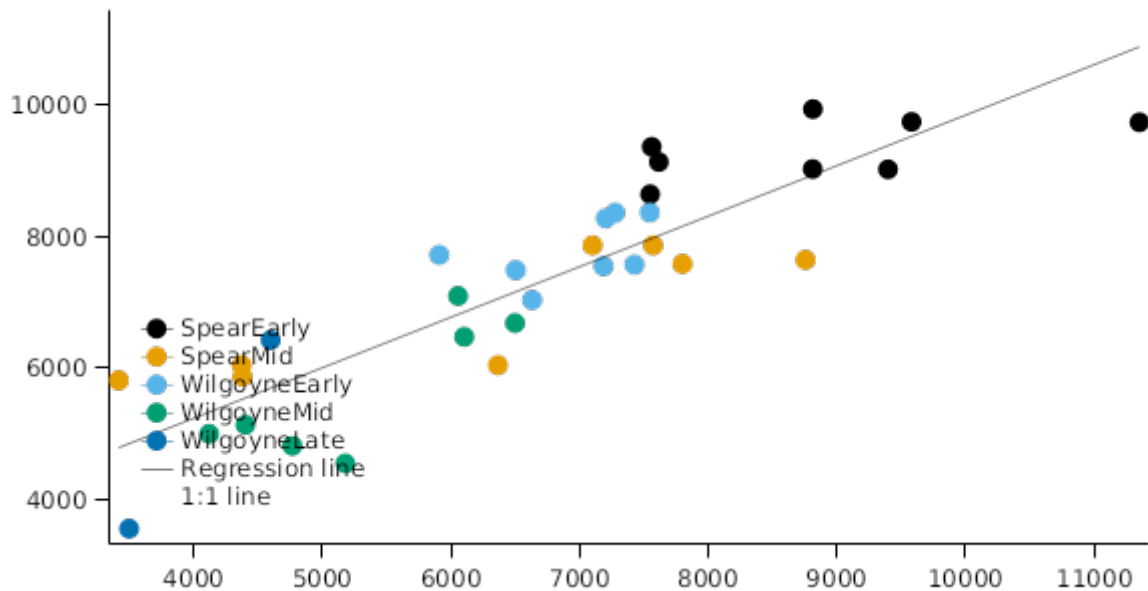
Harvest Yield



Harvest Biomass

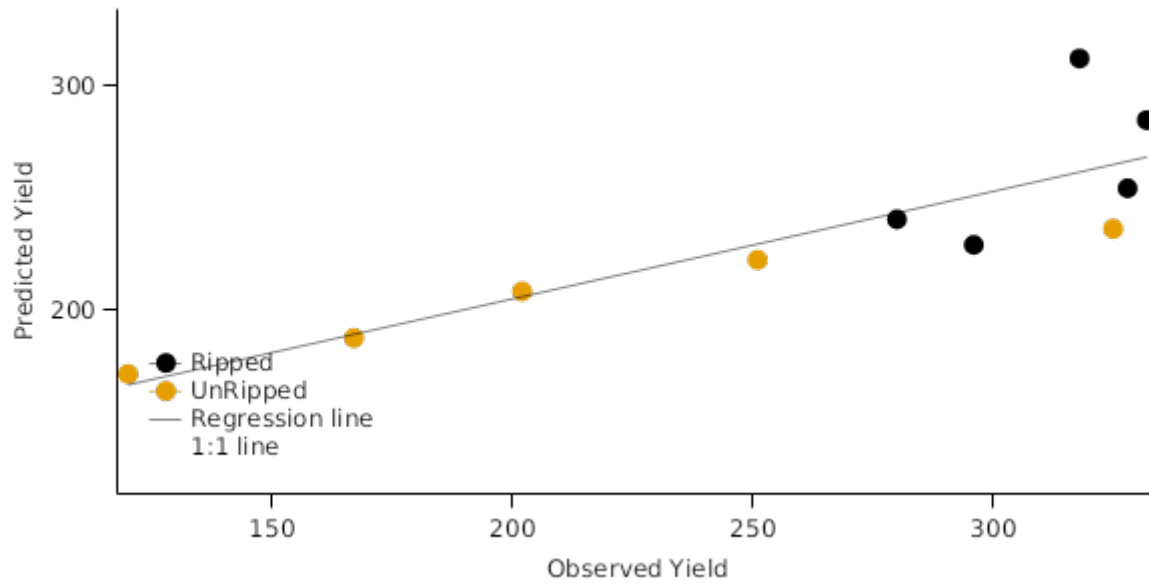


GrainNumber

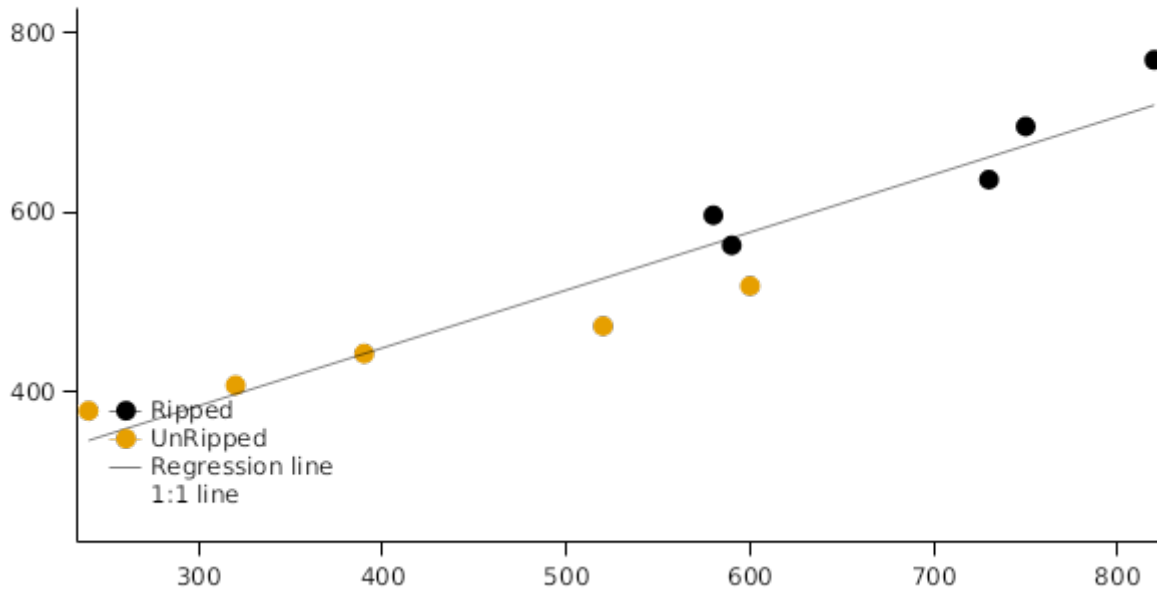


3.3.4 Wongan83

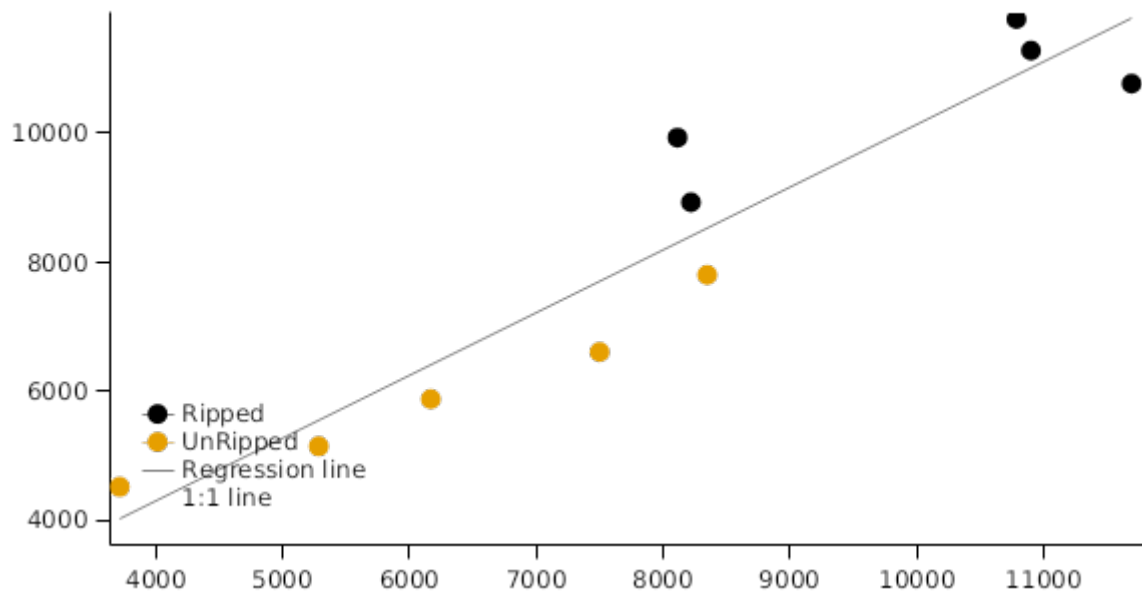
Harvest Yield



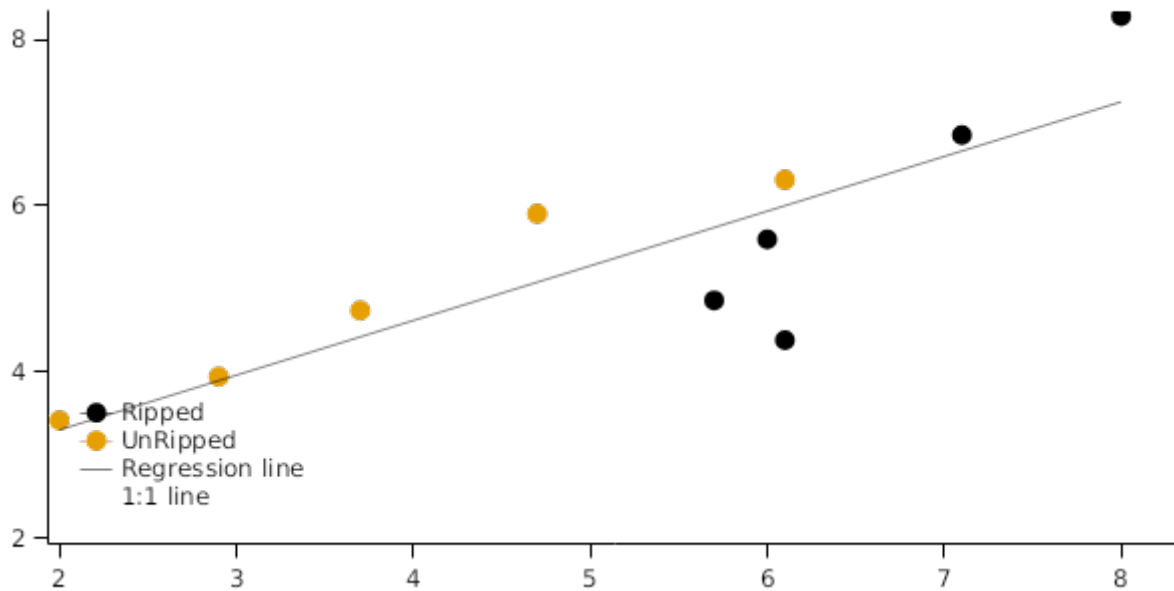
Harvest Biomass



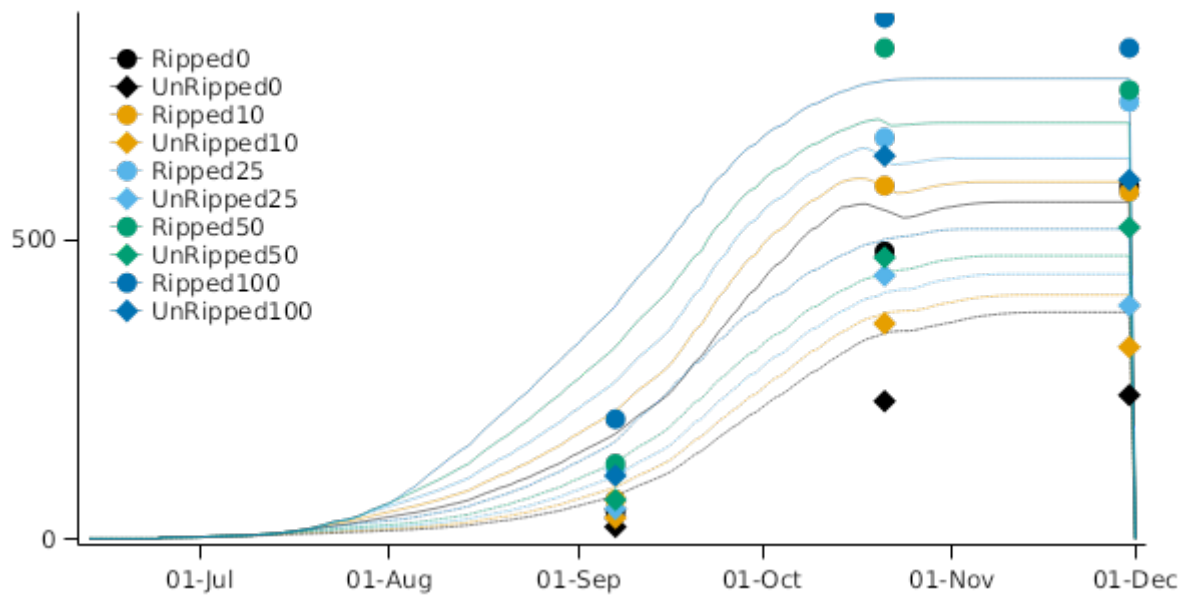
GrainNumber



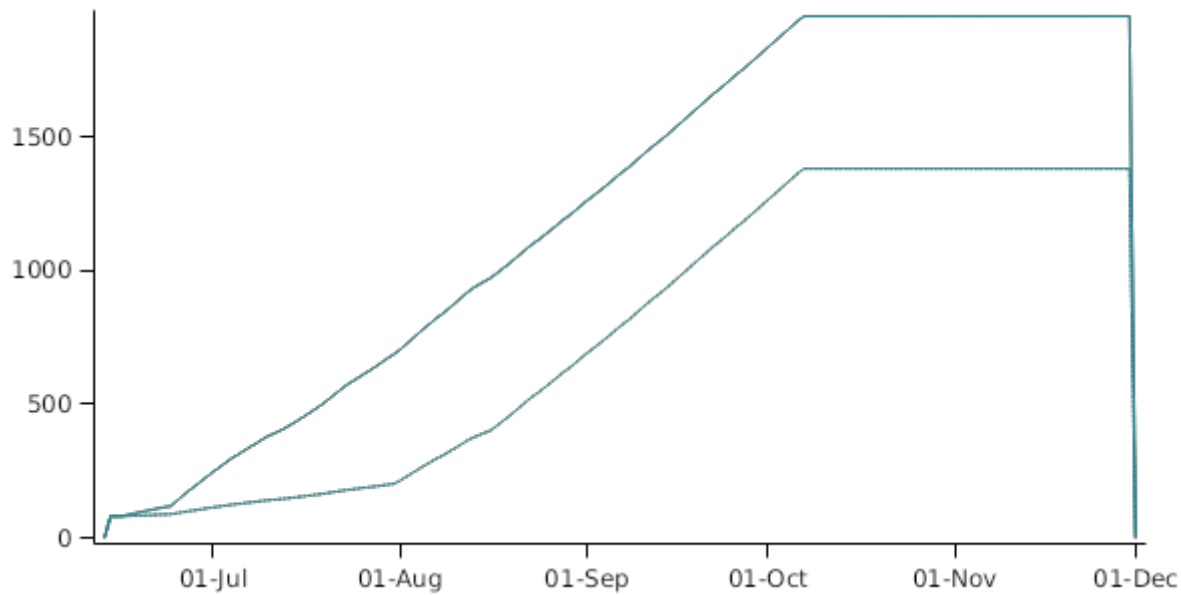
GrainN



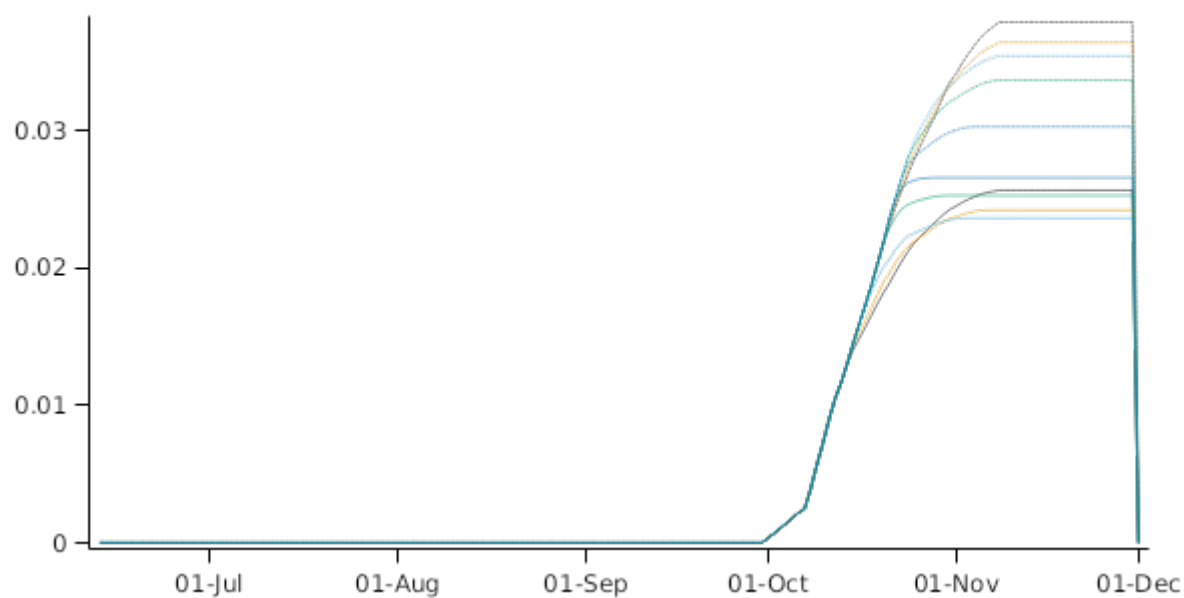
Biomass



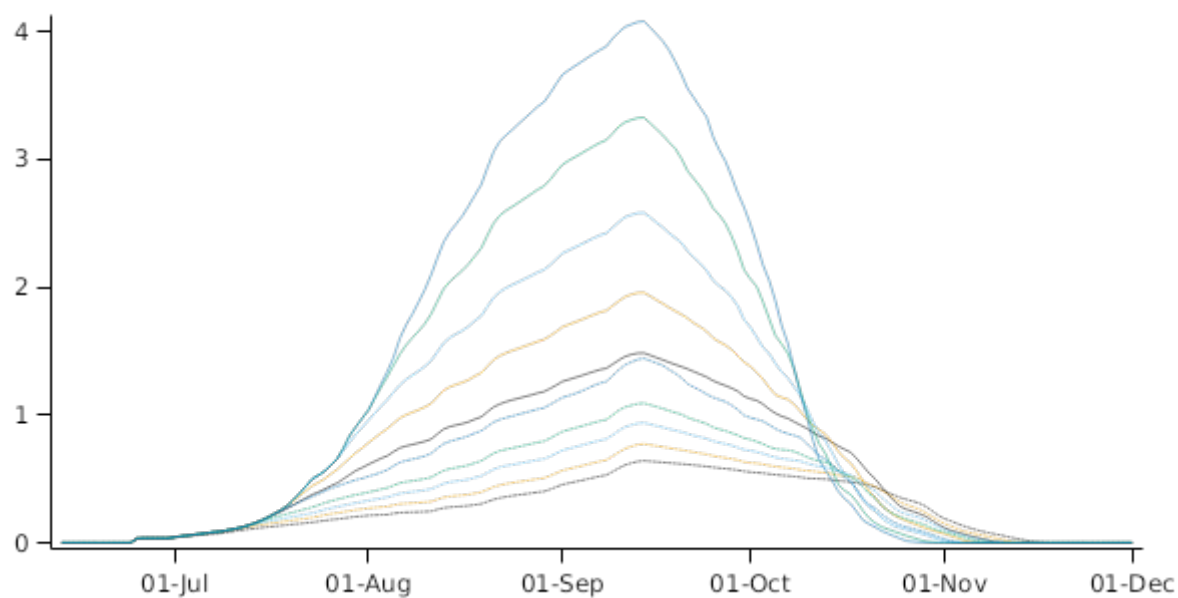
RootDepth



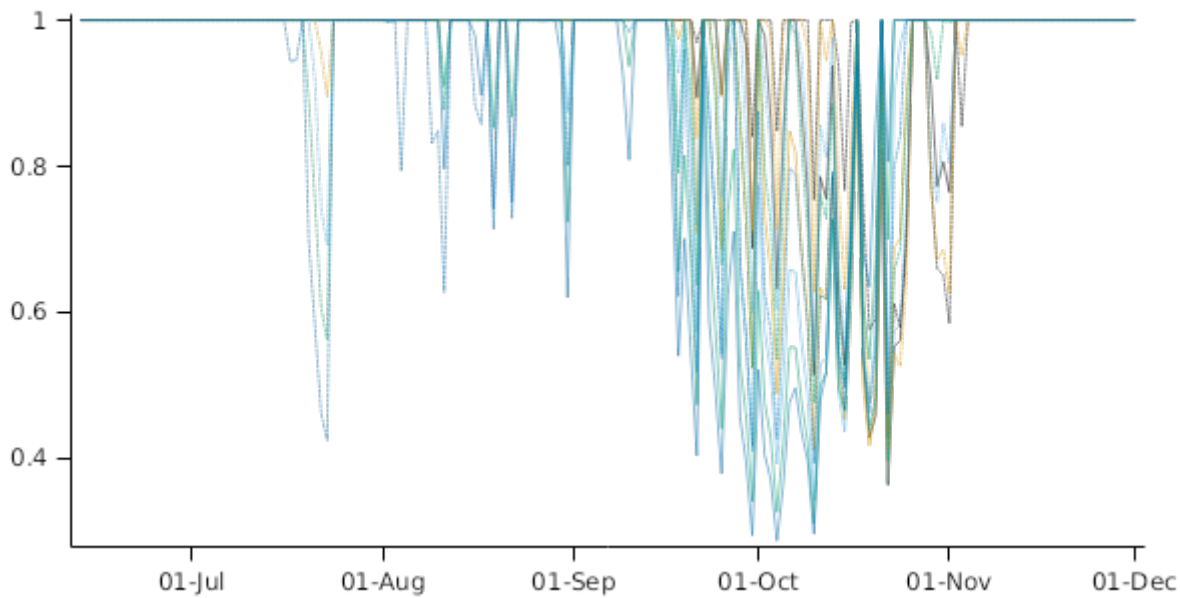
GrainSize



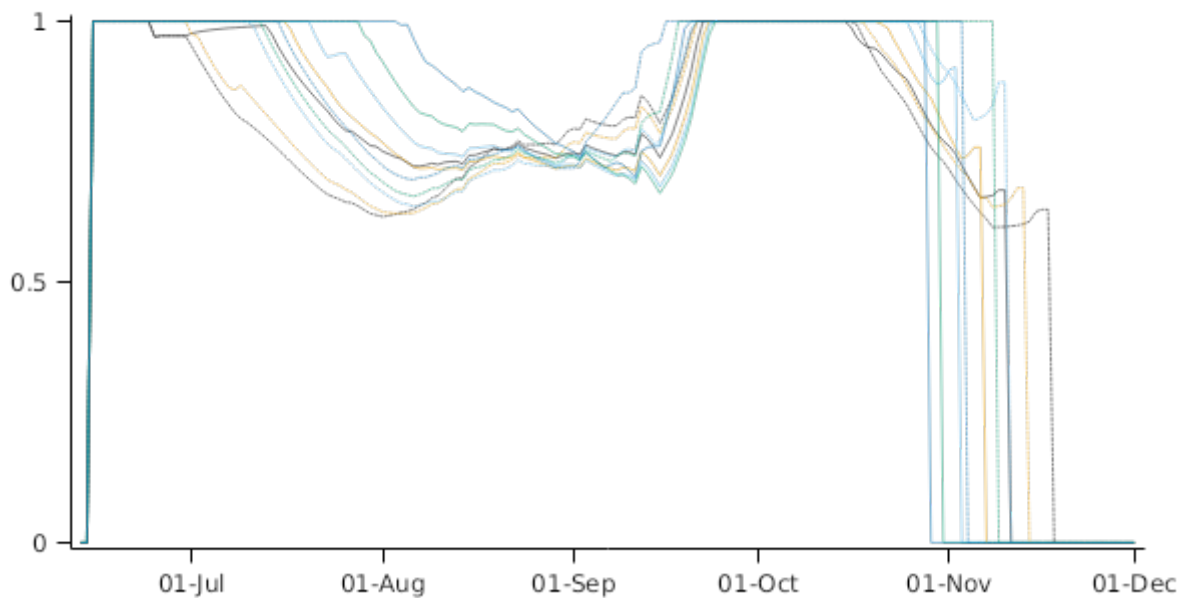
LAI



WaterStress



NStress

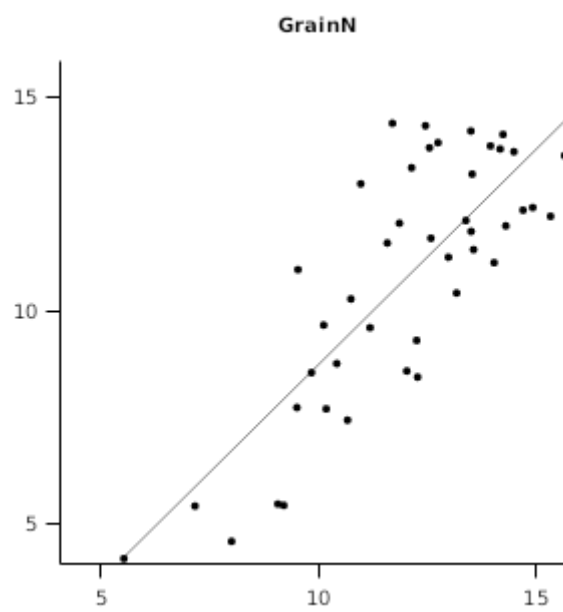
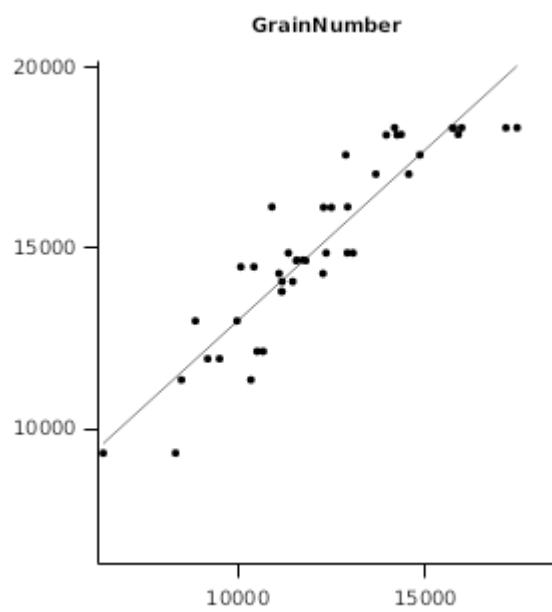
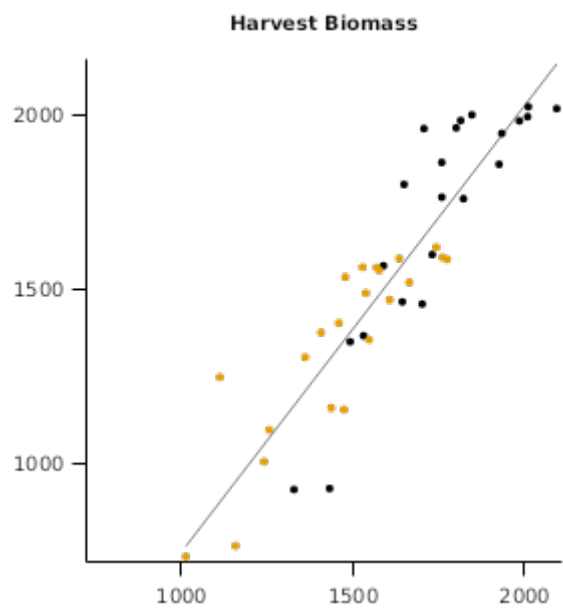
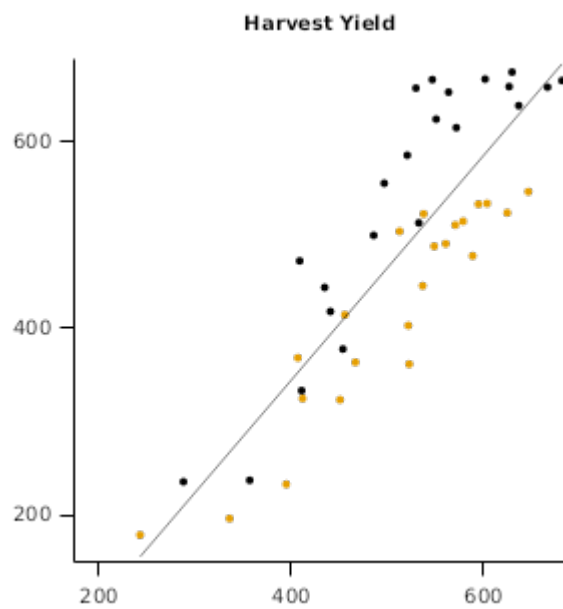


3.4 Turkey

The dataset of [Ali Fuat Tari, 2016](#) includes 4 irrigation deficit treatments applied at each of 3 plant growth stages. The experiment was conducted at Konya in the Central Anatolia region of Turkey. Yields ranged from 2.88 t/ha to 6.82 t/ha. These treatments were reproduced over two growing seasons, resulting in 44 individual wheat crops including differing levels of water stress at different stages of development. Soil data have been estimated from that provided within the original publication.

List of experiments.

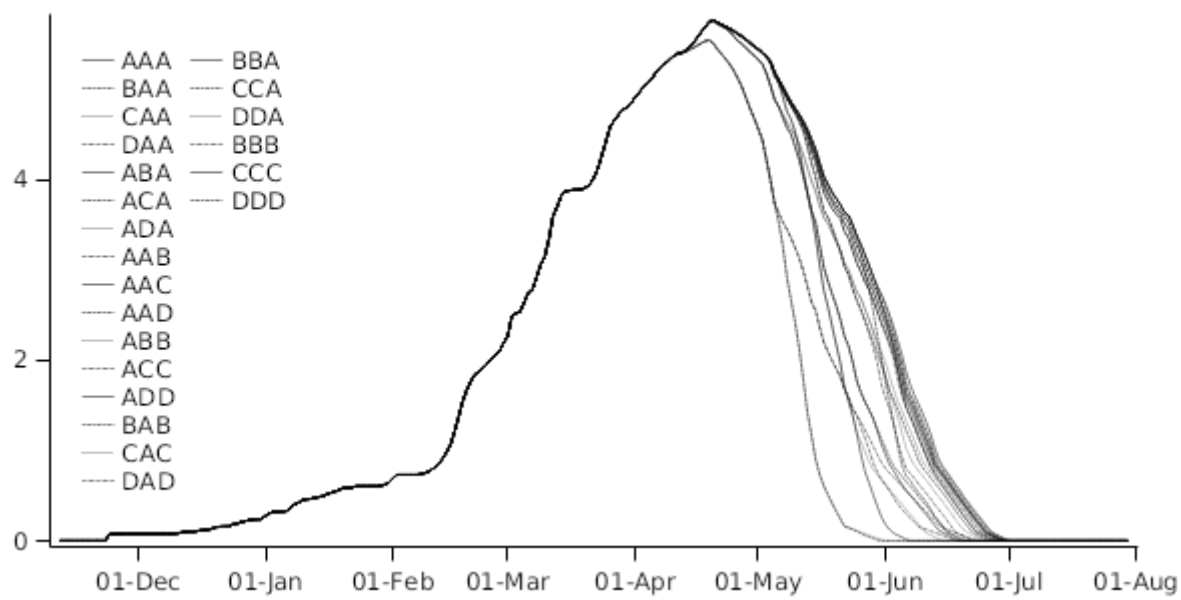
Experiment Name	Design (Number of Treatments)
Konya09	Water (22)
Konya11	Water (22)



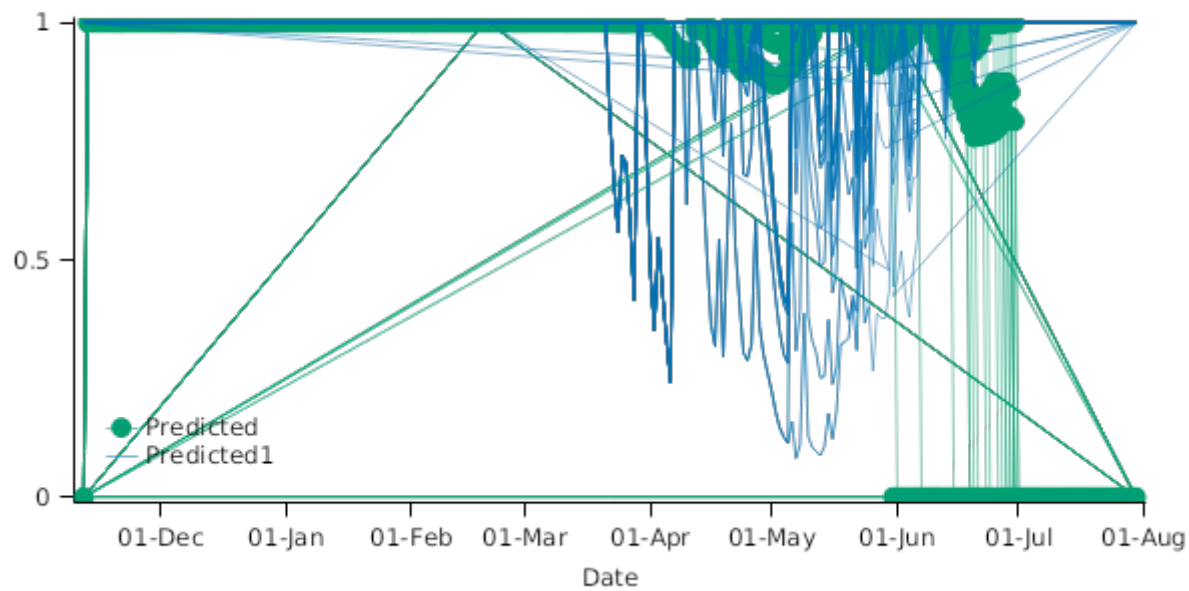
3.4.1 Konya09

TotalSW

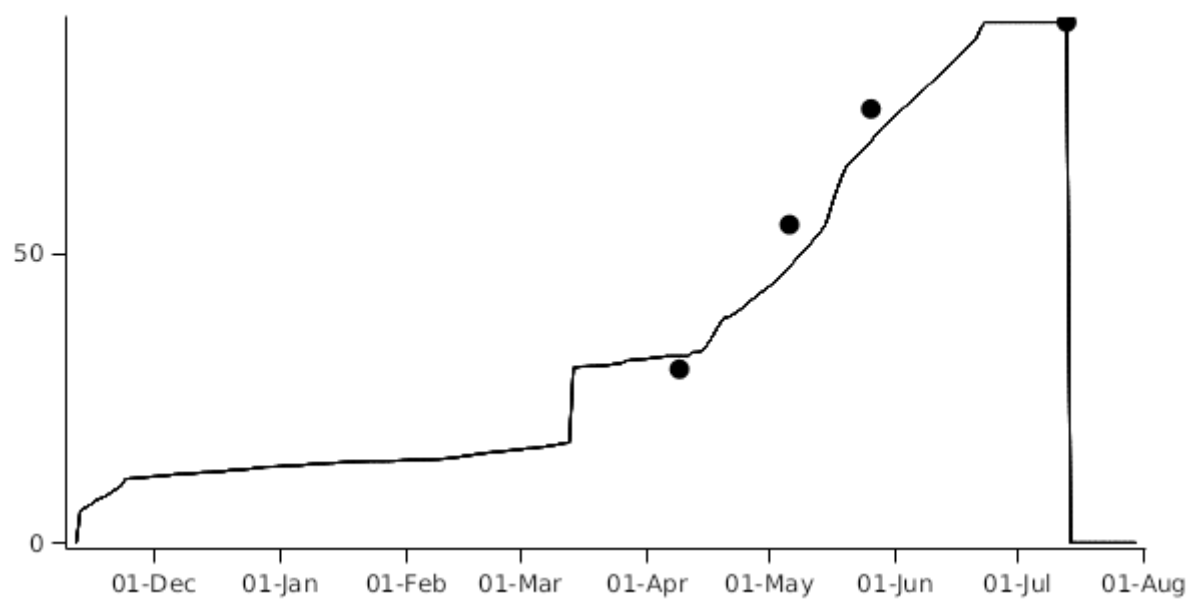
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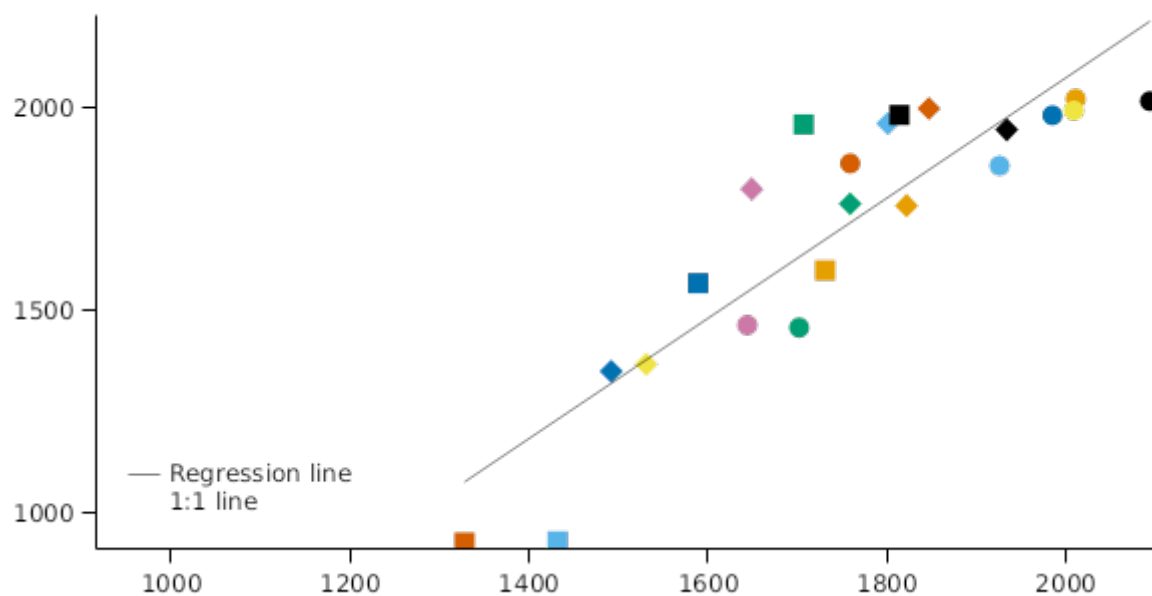
Stress



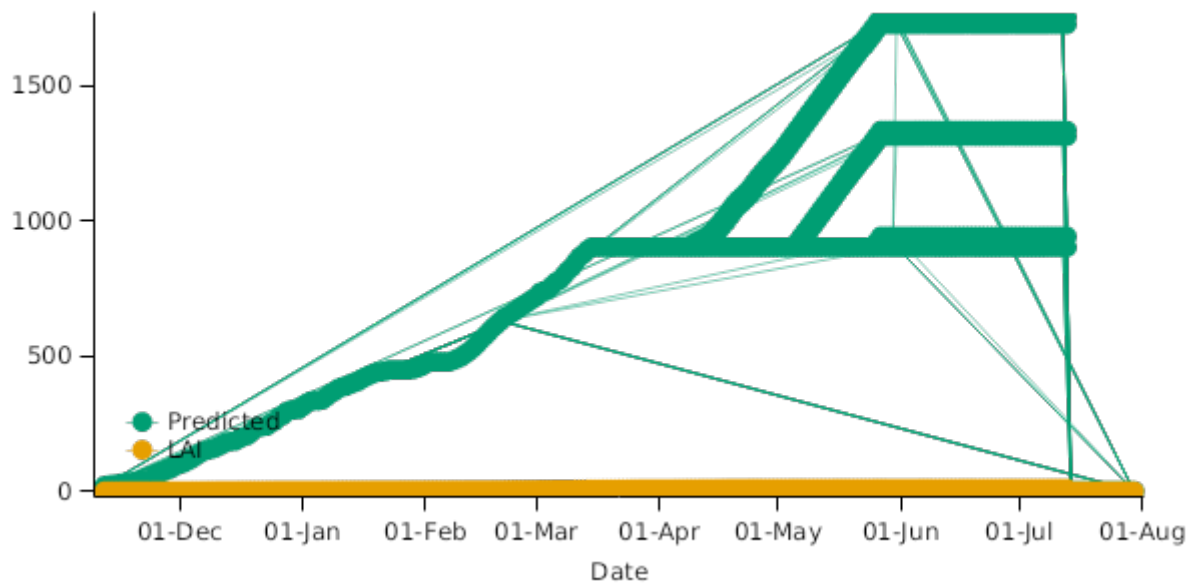
ZadokStage



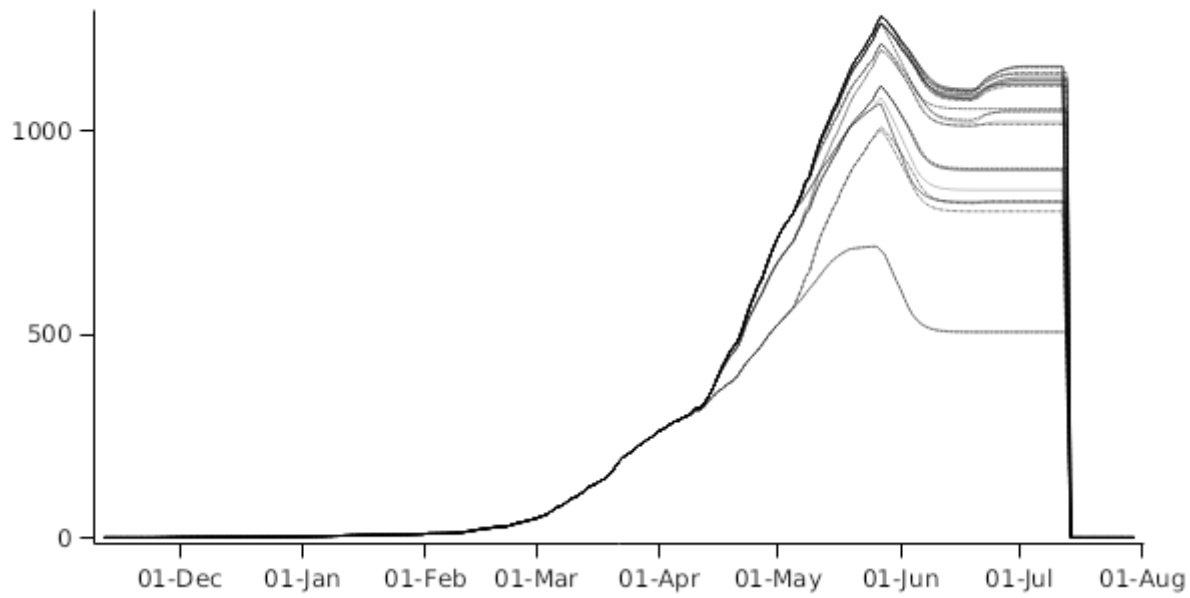
Harvest Biomass



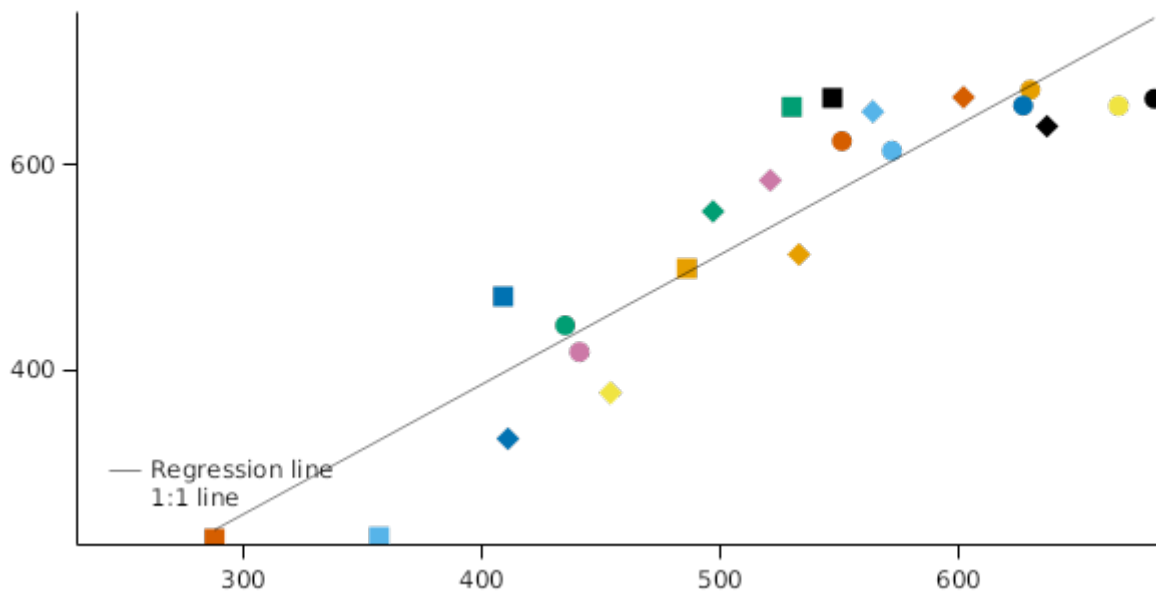
RootDepth



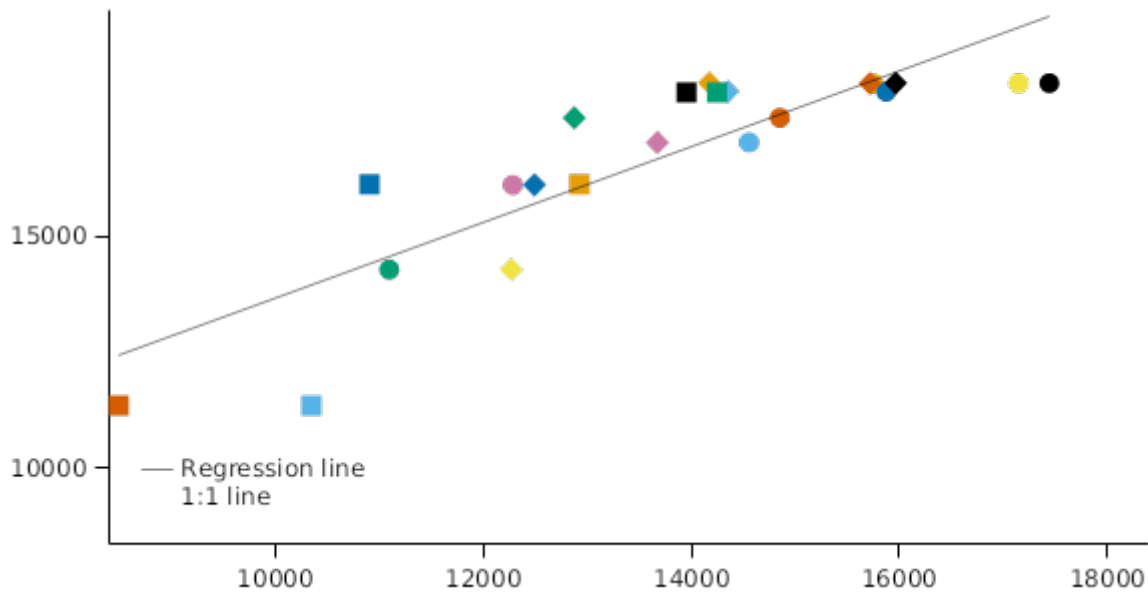
StemWt



Harvest Grain



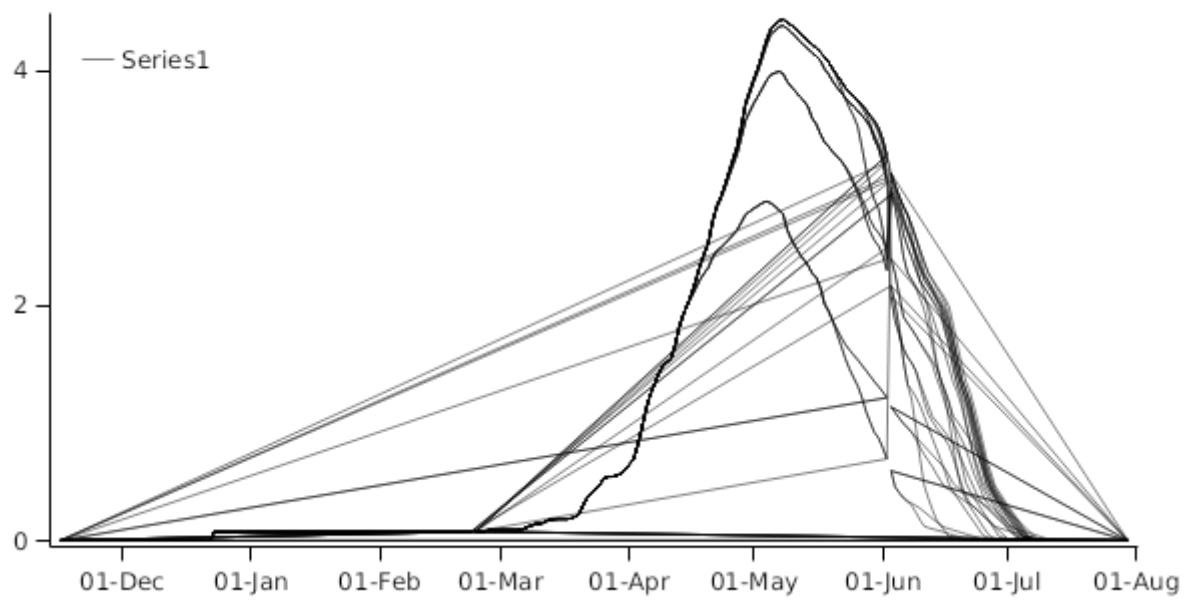
GrainNumber



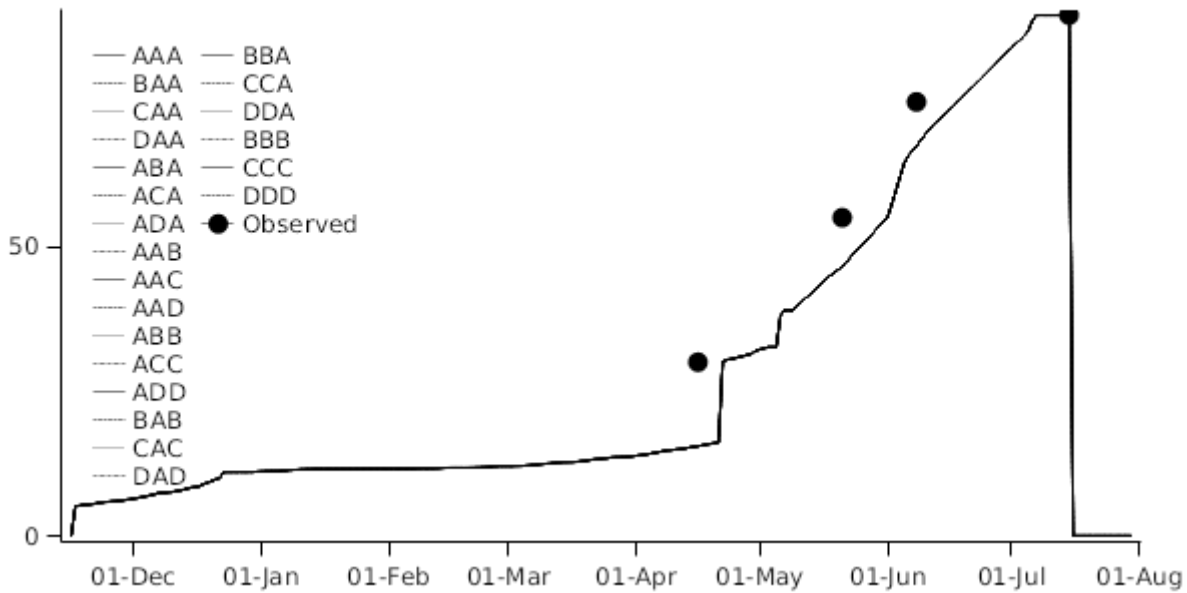
3.4.2 Konya11

TotalSW

LAI



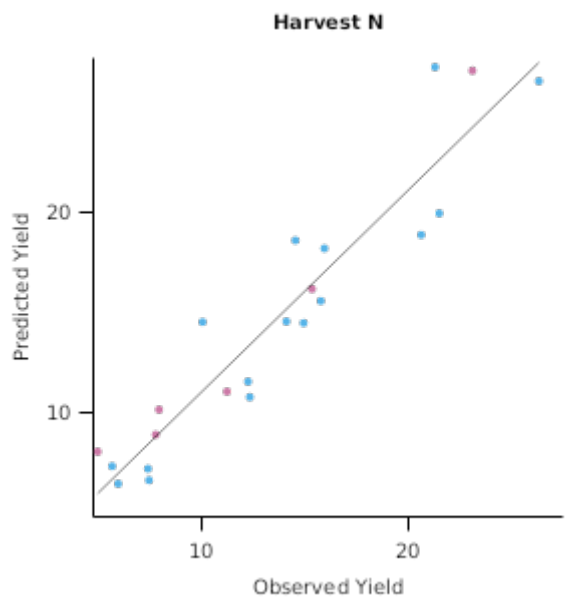
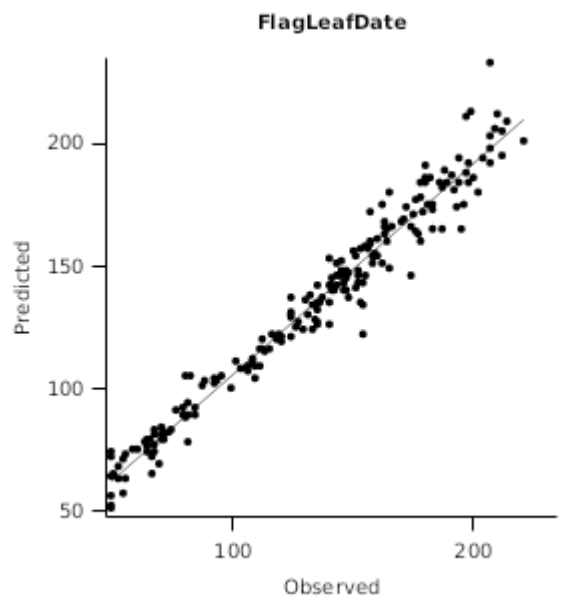
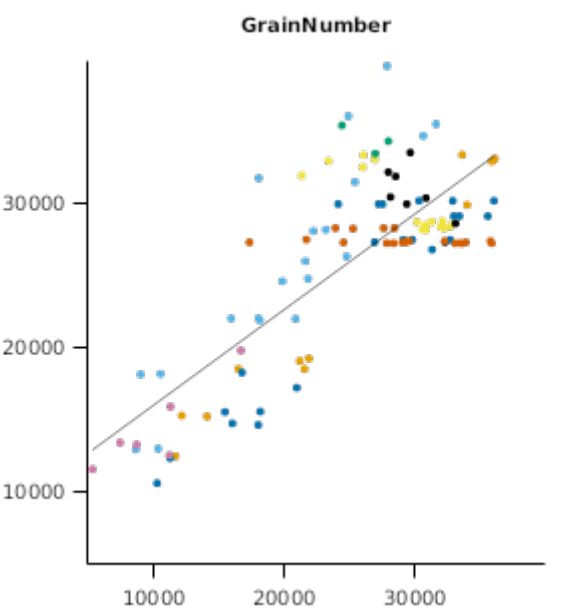
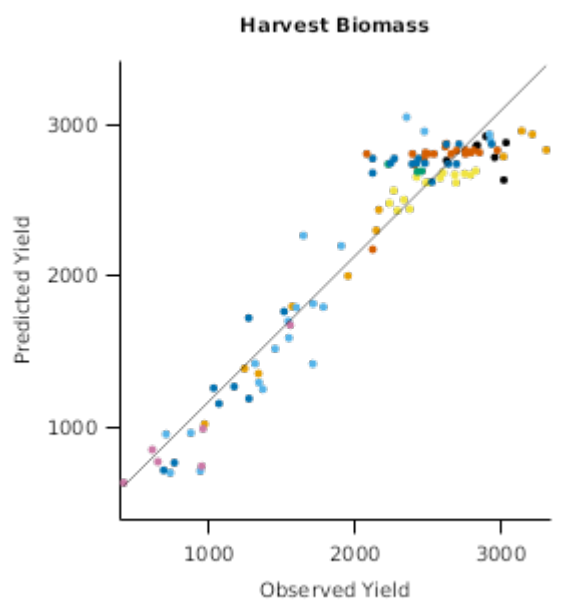
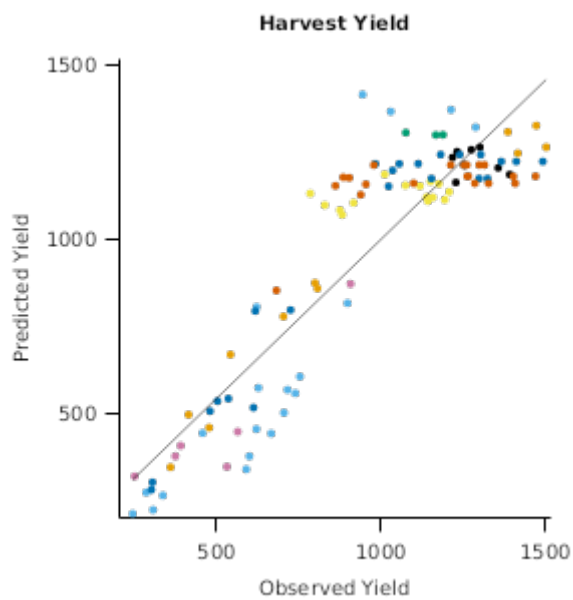
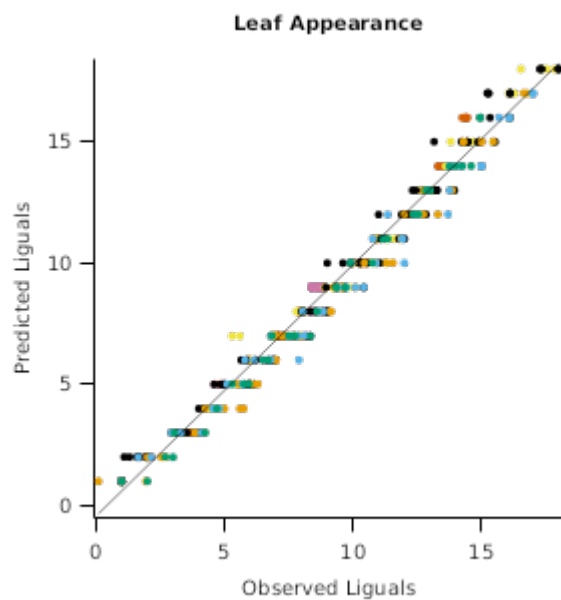
ZadokStage

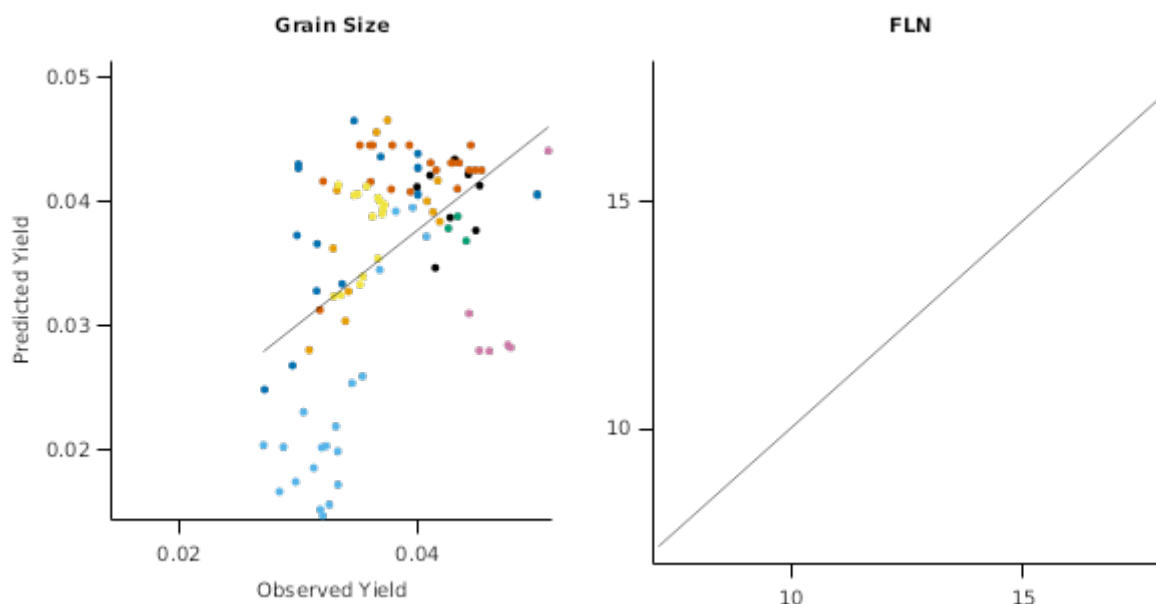


3.5 New Zealand

List of experiments.

Experiment Name	Design (Number of Treatments)
PalmerstonNorth1989	Sow x Cv (18)
Lincoln9192	Irrig (7)
Lincoln1992	Sow x Irr x Nit (16)
Lincoln1994	Sow x Cv (10)
Lincoln2010	Sow x Irr (8)
Lincoln2014	Irrig (6)
Lincoln2015	Nit x Irr (6)
Leeston2013	Sow x Popn (15)
Leeston2014	Sow x Popn (8)
Wakanui2015	Sow x Cm (4)
Wakanui2016	Sow x Cm (4)
Wakanui2017	Sow x Cm (3)
Lincoln2021	SD x CV (14)
Lincoln2023	SD x CV (18)





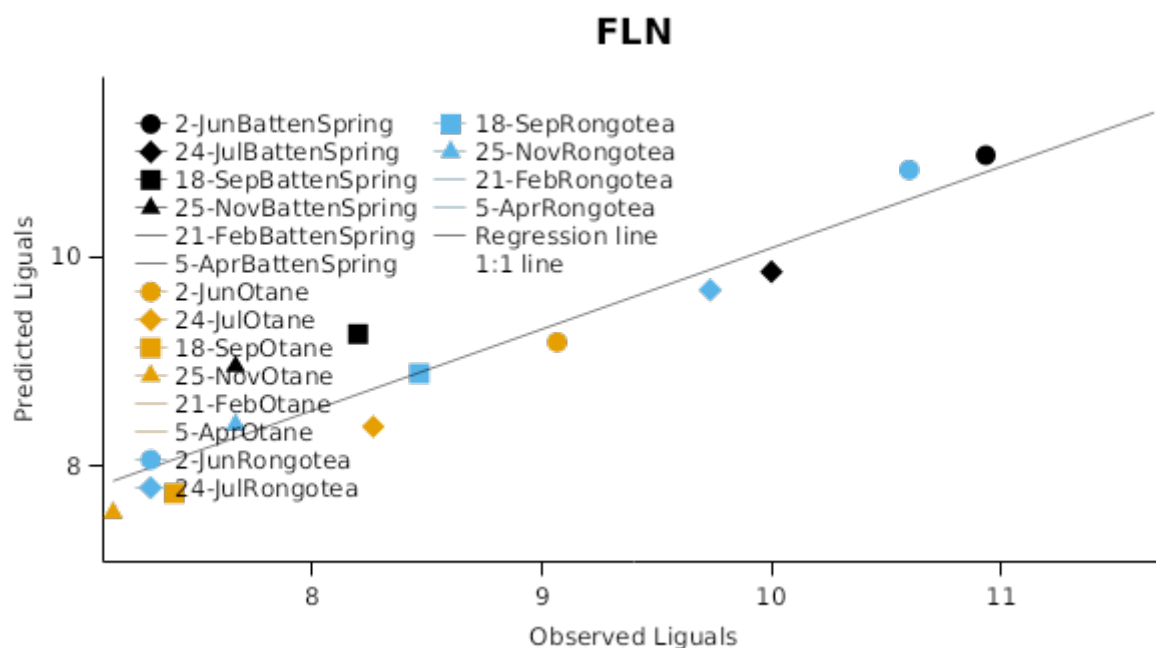
3.5.1 PalmerstonNorth1989

The design, management and yield results of this trial have been described in full by [Craigie R.A., 2015](#). In brief, this trial was conducted to assess the impact of earlier sowing on potential yields of 'Wakanui' wheat grown at Wakanui (the cultivar was named after the area) in Mid Canterbury, New Zealand. it was a 4 x 4 factorial with 4 replicates of the following treatments:

1. Sowing date (20 February, 10 March, 28 March, 23 April)
2. Sowing density (50,100,150 and 200 plants/m²)

In addition to yield, measurements of leaf appearance and senescence and canopy cover (measured with NDVI) were measured at 10 - 14 day intervals and biomass measurements were taken at growth stages 32 and 65.

Considerable canopy decay was observed during the winter for the early sown treatments and we have not introduced mechanisms into the model to capture this yet so there is a genral over prediction of canopy size and biomass in these first sowing dates.



3.5.2 Lincoln9192

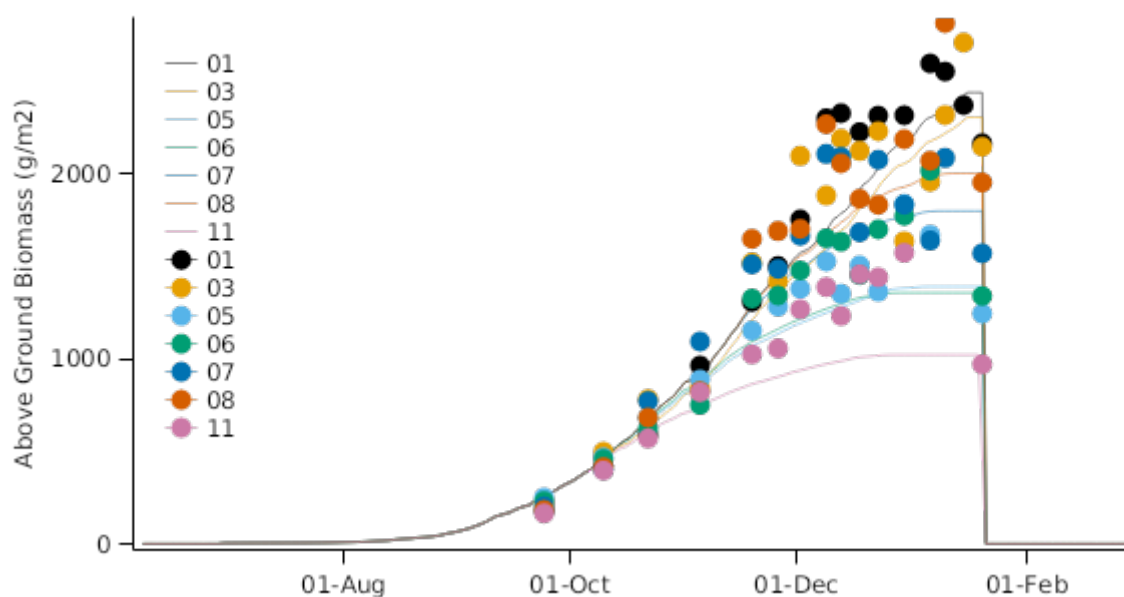
This is a water response trial run in the rain out shelter at Plant and Food Research in Lincoln, New Zealand. It is described in full by [Jamieson et al., 1995](#) but briefly. A winter crop of 'Batten' wheat was sown at 300 plants/m² on the 8th of June 1991 and range of irrigation amount and timing treatments were applied. Six of these treatments have been included in this validation:

1. Full irrigation where measured ET was replaced weekly
2. Short Early Drought where irrigation was withheld from sowing until late October then full irrigation was applied
3. Long Early Drought where irrigation was withheld from sowing until mid December then full irrigation was applied
4. Long Late Drought where full irrigation was applied from sowing until mid September then withheld for the rest of the season
5. Moderate Late Drought where full irrigation was applied from sowing until mid October then withheld for the rest of the season
6. Short Late Drought where full irrigation was applied from sowing until Early November then withheld for the rest of the season
7. Nil where no water was applied and the crop grew on soil stored water only.

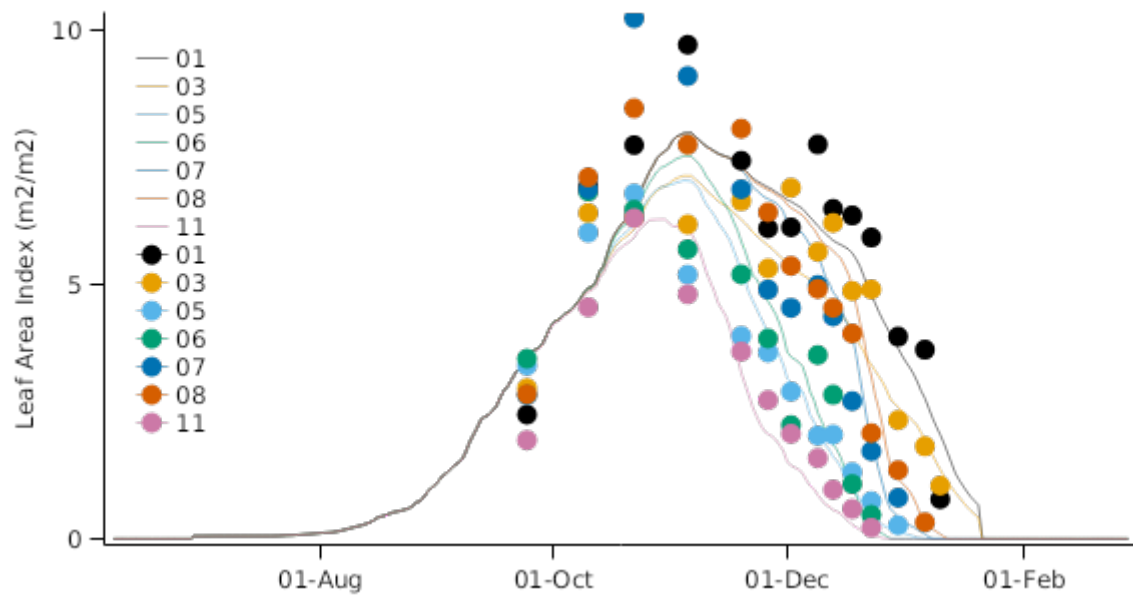
Irrigation was applied at weekly intervals through and assembly of low rate drip emitters on each plot. Soil water content was measured weekly with a neutron probe and biomass was measured at 10 - 14 day intervals. Samples throughout the crop were from two 0.1m² quadrants and the final harvest sample was from a 1 m² quadrant. Each treatment was replicated twice and there was considerable soil variation from plot to plot so each treatment was initialised with unique soil parameters which best described the soil they were growing on.

SoilWaterProfile

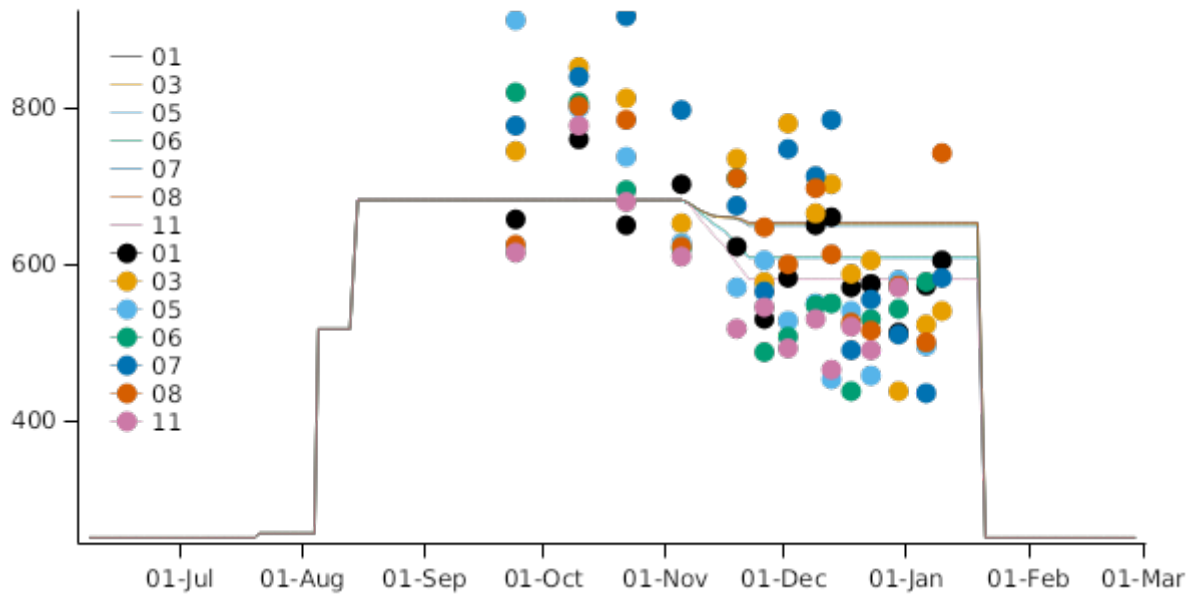
AboveGroundWt



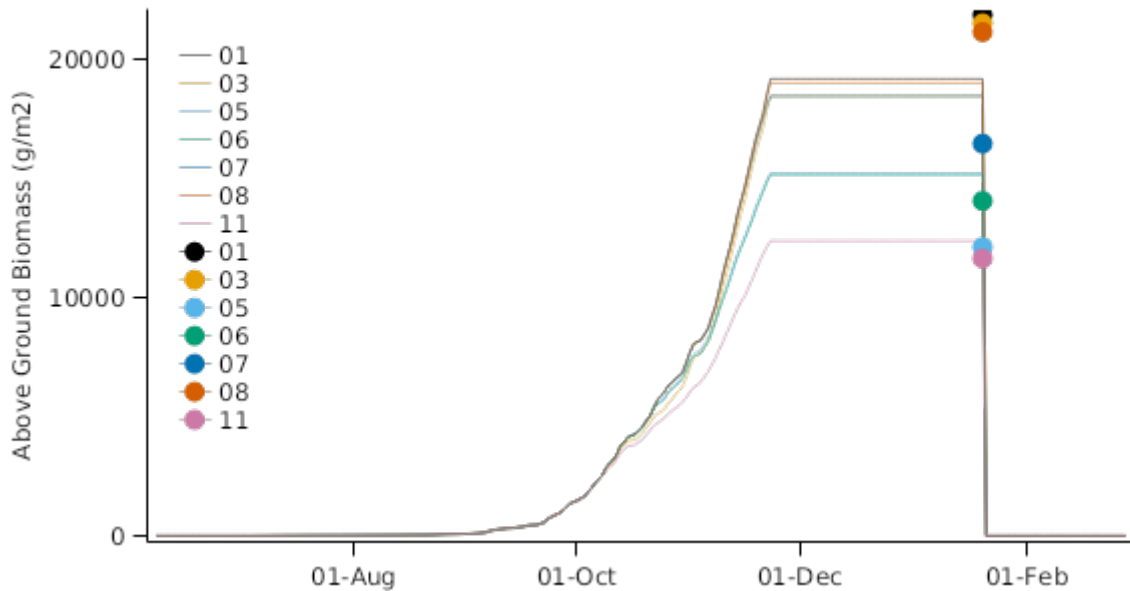
LAI



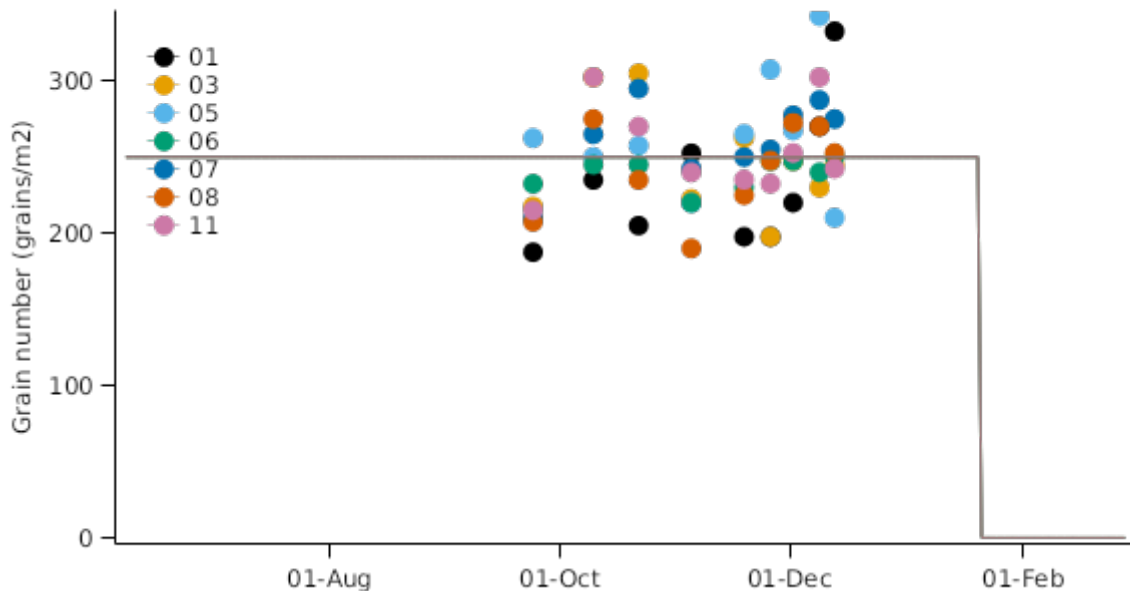
Stems



GrainNumbers



Population



3.5.3 Lincoln1992

This trial has never been formally written up. It was conducted at Plant and Foods A Block, Lincoln, New Zealand with 'Batten' Wheat grown on a Templeton silt loam (160mm AWC/m). It was a 2 x 2 x 4 factorial with the following treatments:

1. Sowing Date (5 May 1992 and 5 Aug 1992)
2. Irrigation (Nil and 120 mm)
3. Nitrogen (0, Low, Medium and High)

The N applied to the Low, Medium and High N treatments was 100, 150 and 250 kg/ha, respectively, for the May sowing and 50, 100 and 150, respectively, for the August sowing.

Could not find information confirming sowing rate so assumed typical values of 300 plants per m² for the spring sowing 100 plants per m² for May sowing. Emergence was recorded as the 28th of May for the first planting. The model was predicting this early so delayed sowing date to get emergence date correct..

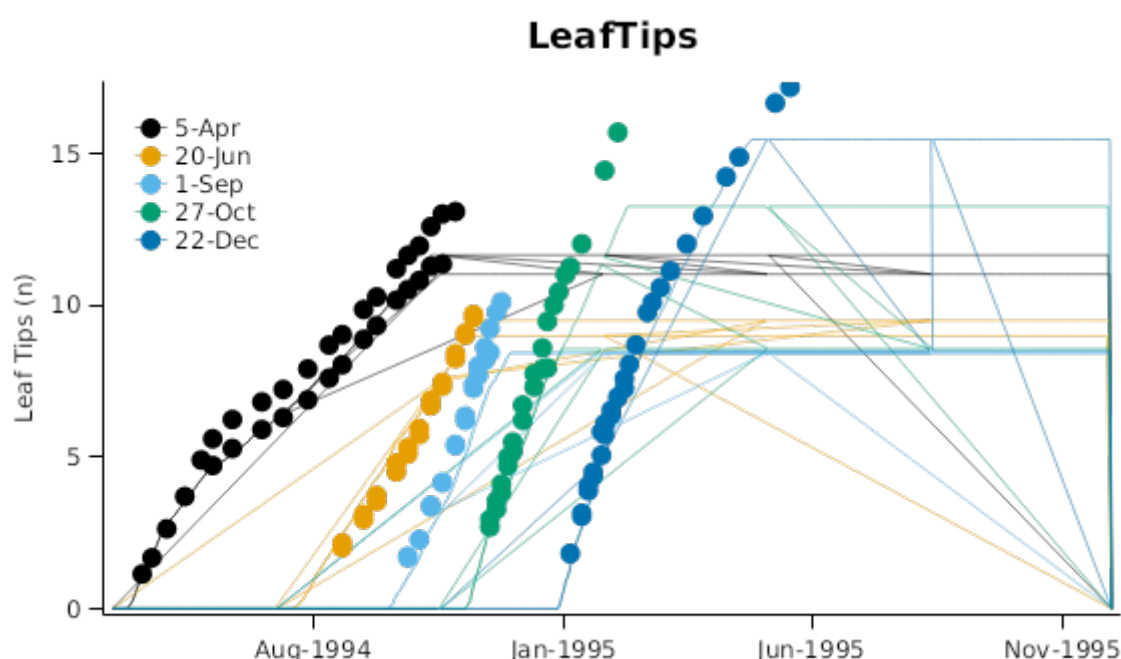
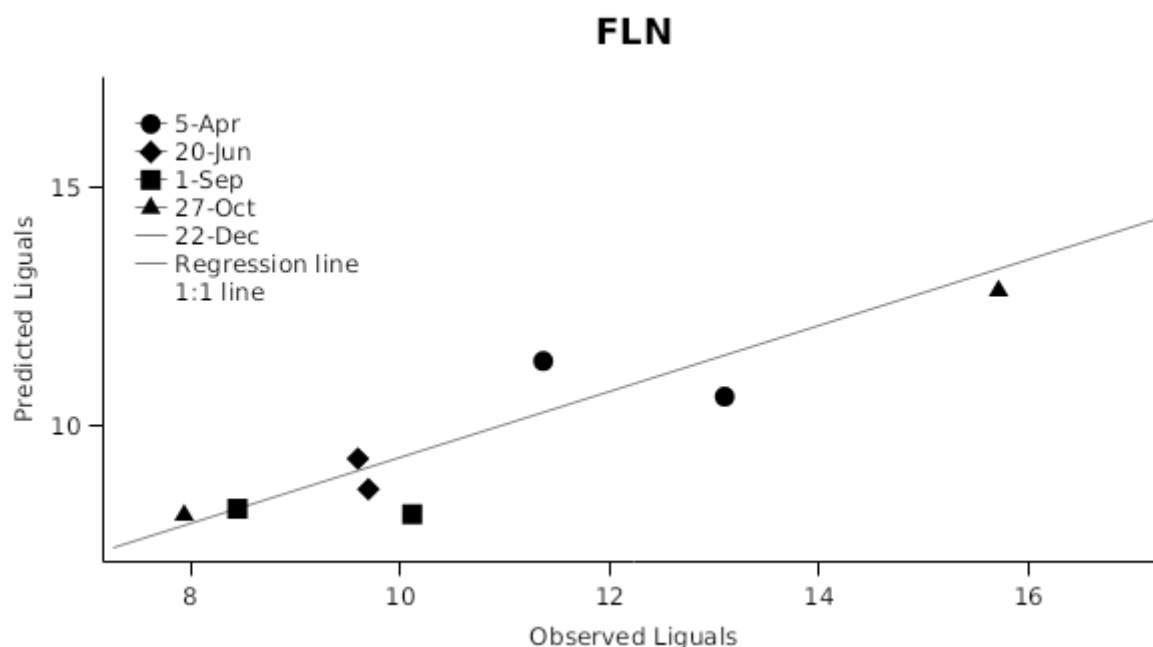
3.5.4 Lincoln1994

The design, management and yield results of this trial have been described in full by [Craigie R.A., 2015](#). In brief, this trial was conducted to assess the impact of earlier sowing on potential yields of 'Wakanui' wheat grown at Wakanui (the cultivar was named after the area) in Mid Canterbury, New Zealand. it was a 4 x 4 factorial with 4 replicates of the following treatments:

1. Sowing date (20 February, 10 March, 28 March, 23 April)
2. Sowing density (50,100,150 and 200 plants/m²)

In addition to yield, measurements of leaf appearance and senescence and canopy cover (measured with NDVI) were measured at 10 - 14 day intervals and biomass measurements were taken at growth stages 32 and 65.

Considerable canopy decay was observed during the winter for the early sown treatments and we have not introduced mechanisms into the model to capture this yet so there is a general over prediction of canopy size and biomass in these first sowing dates.



3.5.5 Lincoln2010

- Could not find information confirming sowing rate. Protocol said aim for 300 plants per m² which is usual for a spring sowing but very high for an Autumn sowing. Assumed 100 plants per m² for May sowing and 300 for August.
- Emergence was recorded as the 28th of May for the first planting. The model was predicting this early so delayed sowing date to get emergence date correct..

This is a water response trial run in the rain out shelter at Plant and Food Research in Lincoln, New Zealand. It is described in full by [E. Chakwizira et al., 2014](#) but briefly. An Autumn crop of 'Wakanui' wheat was sown at 165 plants/m² on the 28th of March 2013 and 6 irrigation timing treatments were applied:

1. Full irrigation where measured ET was replaced weekly .
2. Nil irrigation.
3. Very Early Drought where irrigation was withheld from sowing until the beginning of stem extension.
4. Early Drought where irrigation was withheld between Flag leaf and the beginning of grain fill.
5. Middle Drought where irrigation was withheld between Flag leaf and 1 week into grain fill.
6. Late Drought where irrigation was withheld from heading until harvest.

Irrigation was applied at weekly intervals through and assembly of low rate drip emitters on each plot. Soil water content was measured weekly with a neutron probe and biomass was measured on 5 occasions throughout the crop. Samples throughout the crop were from a 0.43m² quadrat and the final harvest sample was from a 1 m² quadrat. Each treatment was replicated four times and there was considerable soil variation from plot to plot so each treatment was initialised with unique soil parameters which best described the soil they were growing on.

3.5.6 Lincoln2014

This is a water response trial run in the rain out shelter at Plant and Food Research in Lincoln, New Zealand. It is described in full by [E. Chakwizira et al., 2014](#) but briefly. An Autumn crop of 'Wakanui' wheat was sown at 165 plants/m² on the 28th of March 2013 and 6 irrigation timing treatments were applied:

1. Full irrigation where measured ET was replaced weekly .
2. Nil irrigation.
3. Very Early Drought where irrigation was withheld from sowing until the beginning of stem extension.
4. Early Drought where irrigation was withheld between Flag leaf and the beginning of grain fill.
5. Middle Drought where irrigation was withheld between Flag leaf and 1 week into grain fill.
6. Late Drought where irrigation was withheld from heading until harvest.

Irrigation was applied at weekly intervals through and assembly of low rate drip emitters on each plot. Soil water content was measured weekly with a neutron probe and biomass was measured on 5 occasions throughout the crop. Samples throughout the crop were from a 0.43m² quadrat and the final harvest sample was from a 1 m² quadrat. Each treatment was replicated four times and there was considerable soil variation from plot to plot so each treatment was initialised with unique soil parameters which best described the soil they were growing on.

3.5.7 Lincoln2015

3.5.7.1 Lincoln2012 (Rain-Shelter Trail)

Testing of APSIM Maize under New Zealand conditions was undertaken using the data of [Teixeira et al., 2014](#). This dataset includes the impact of three N (0 to 250 kg/ha N) and two water regimes (dryland and fully irrigated) using a rain-shelter structure. Observations include biomass growth and nitrogen content of individual organs, soil water contents, leaf area index, phenology and yield components. Total biomass ranged from 8000 kg/ha for dryland nil N crops to up to 28000kg/ha for fully irrigated and N fertilised crops. Dryland crops recovered 25 percent less N from applied fertilizer than irrigated crops.

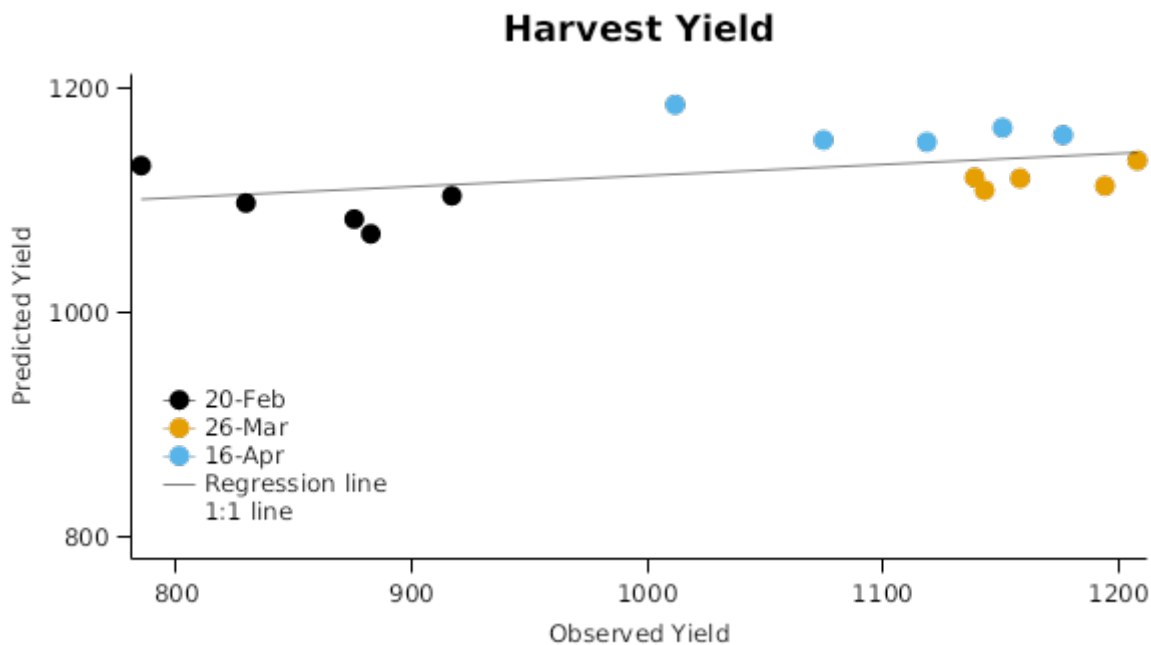
3.5.8 Leeston2013

The design, management and yield results of this trial have been described in full by [Craigie R.A., 2015](#). In brief, this trial was conducted to assess the impact of earlier sowing on potential yields of 'Wakanui' wheat grown at Wakanui (the cultivar was named after the area) in Mid Canterbury, New Zealand. it was a 4 x 4 factorial with 4 replicates of the following treatments:

1. Sowing date (20 February, 10 March, 28 March, 23 April)
2. Sowing density (50,100,150 and 200 plants/m²)

In addition to yield, measurements of leaf appearance and senescence and canopy cover (measured with NDVI) were measured at 10 - 14 day intervals and biomass measurements were taken at growth stages 32 and 65.

Considerable canopy decay was observed during the winter for the early sown treatments and we have not introduced mechanisms into the model to capture this yet so there is a general over prediction of canopy size and biomass in these first sowing dates.



3.5.9 Leeston2014

The design, management and yield results of this trial have been described in full by [Craigie R.A., 2015](#). In brief, this trial was conducted to assess the impact of earlier sowing on potential yields of 'Wakanui' wheat grown at Wakanui (the cultivar was named after the area) in Mid Canterbury, New Zealand. it was a 4 x 4 factorial with 4 replicates of the following treatments:

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Considerable canopy decay was observed during the winter for the early sown treatments and we have not introduced mechanisms into the model to capture this yet so there is a genral over prediction of canopy size and biomass in these first sowing dates.

3.5.10 Wakanui2015

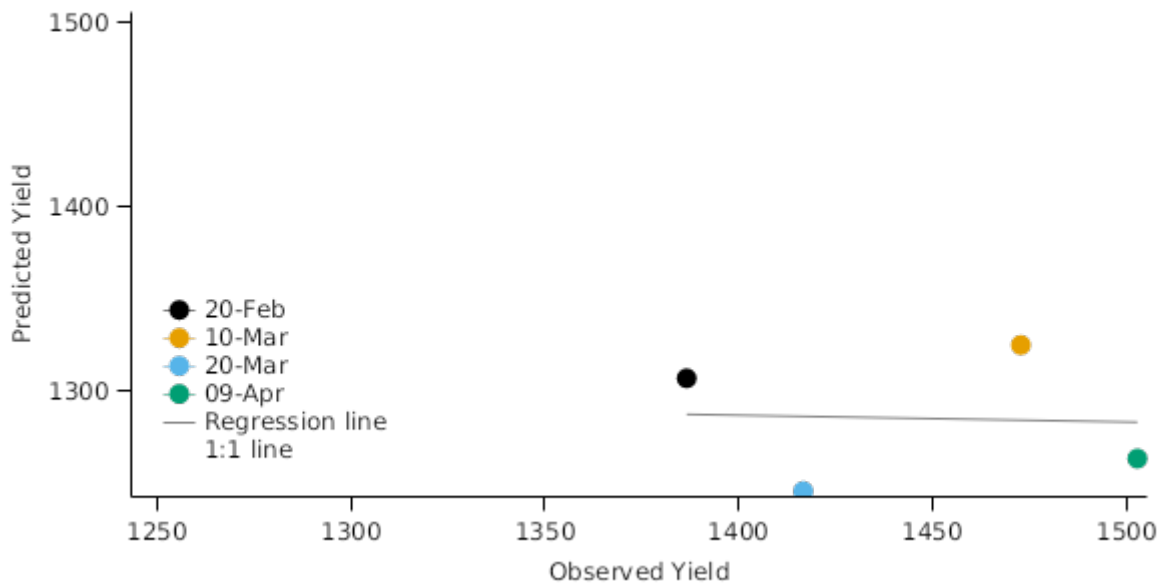
The design, management and yield results of this trial have been described in full by [Craigie R.A., 2015](#). In brief, this trial was conducted to assess the impact of earlier sowing on potential yields of 'Wakanui' wheat grown at Wakanui (the cultivar was named after the area) in Mid Canterbury, New Zealand. it was a 4 x 4 factorial with 4 replicates of the following treatments:

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Considerable canopy decay was observed during the winter for the early sown treatments and we have not introduced mechanisms into the model to capture this yet so there is a genral over prediction of canopy size and biomass in these first sowing dates.

Harvest Yield



3.5.11 Wakanui2016

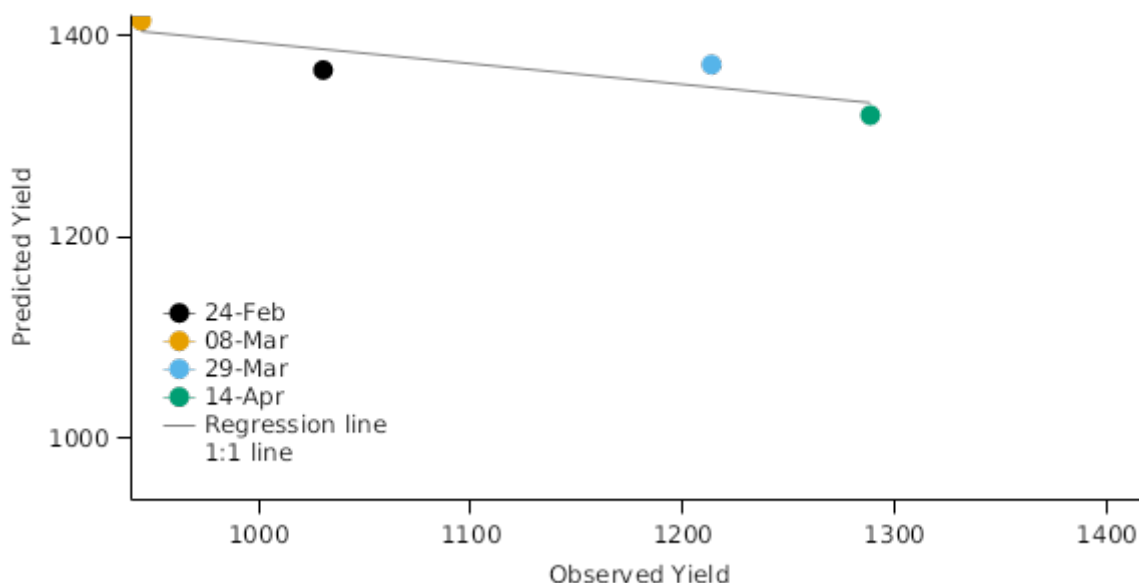
The design, management and yield results of this trial have been described in full by [Craigie R.A., 2015](#). In brief, this trial was conducted to assess the impact of earlier sowing on potential yields of 'Wakanui' wheat grown at Wakanui (the cultivar was named after the area) in Mid Canterbury, New Zealand. it was a 4 x 4 factorial with 4 replicates of the following treatments:

1. Sowing date (20 February, 10 March, 28 March, 23 April)
2. Sowing density (50,100,150 and 200 plants/m²)

In addition to yield, measurements of leaf appearance and senescence and canopy cover (measured with NDVI) were measured at 10 - 14 day intervals and biomass measurements were taken at growth stages 32 and 65.

Considerable canopy decay was observed during the winter for the early sown treatments and we have not introduced mechanisms into the model to capture this yet so there is a genral over prediction of canopy size and biomass in these first sowing dates.

Harvest Yield



3.5.12 Wakanui2017

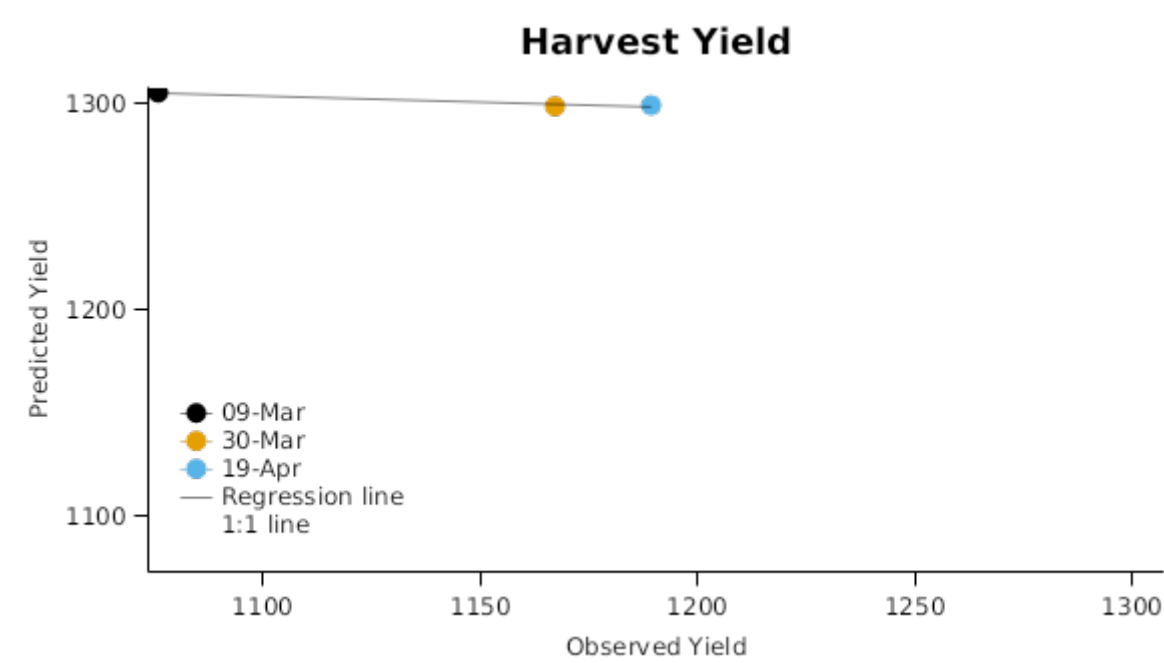
The design, management and yield results of this trial have been described in full by [Craigie R.A., 2015](#). In brief, this trial was conducted to assess the impact of earlier sowing on potential yields of 'Wakanui' wheat grown at Wakanui (the

cultivar was named after the area) in Mid Canterbury, New Zealand. it was a 4 x 4 factorial with 4 replicates of the following treatments:

- 1. Sowing date (20 February, 10 March, 28 March, 23 April)
- 2. Sowing density (50,100,150 and 200 plants/m²)

In addition to yield, measurements of leaf appearance and senescence and canopy cover (measured with NDVI) were measured at 10 - 14 day intervals and biomass measurements were taken at growth stages 32 and 65.

Considerable canopy decay was observed during the winter for the early sown treatments and we have not introduced mechanisms into the model to capture this yet so there is a genral over prediction of canopy size and biomass in these first sowing dates.



3.5.13 CPTPhenology

A range of soon to be released cultivars have their phenology assesed each year at Plant and Food Research in Lincoln, New Zealand. Each cultivar is planted on 4 sowing dates representing Autumn, Winter, Early Spring and Late Spring sowings. (approx April, June, Aug, Nov). Each cultivar is observed for 3 years but a number of standards are included each year or for more than 3 years because of the value of the data they provided.

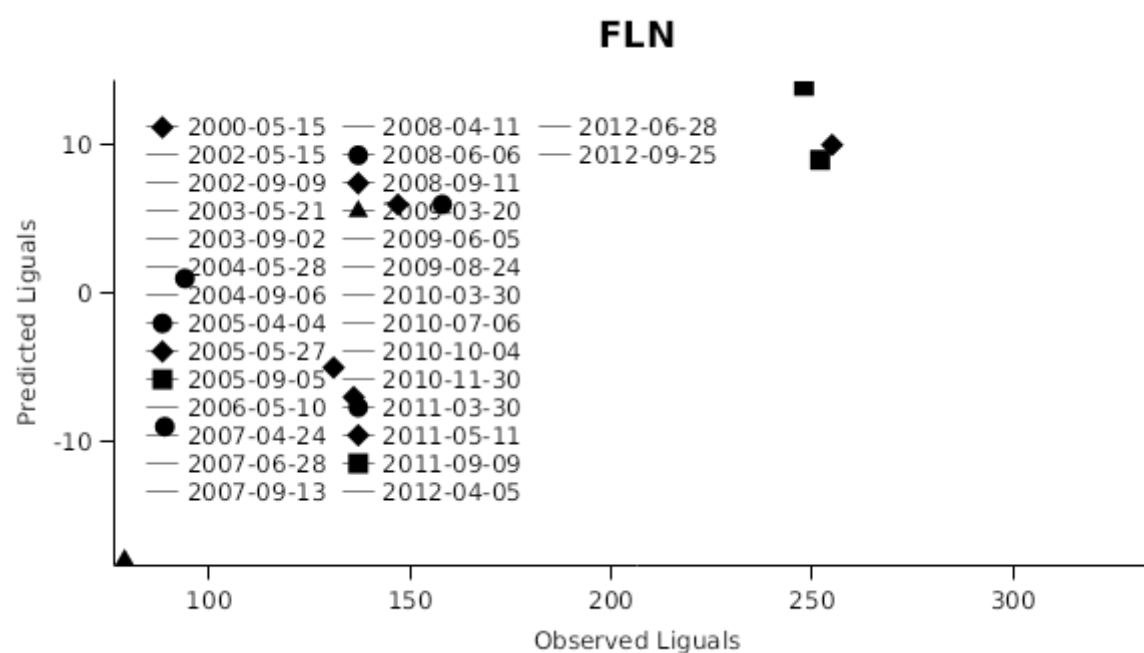
List of experiments.

Experiment Name	Design (Number of Treatments)
CPTCultOtane	Sow (40)
CPTCultAmarok	Sow (26)
CPTCultClaire	Sow (43)
CPTCultWakanui	Sow (6)
CPTCultBattenSpring	Sow (13)
CPTCultBattenWinter	Sow (12)
CPTCultYitpi	Sow x Cv (13)
CPTCultSunco	Sow (13)
CPTCultMcCubbin	Sow (13)
CPTCultMacKellar	Sow (13)
CPTCultJanz	Sow x Cv (13)

Experiment Name	Design (Number of Treatments)
CPTCultLang	Sow (13)
CPTCultH45	Sow (13)

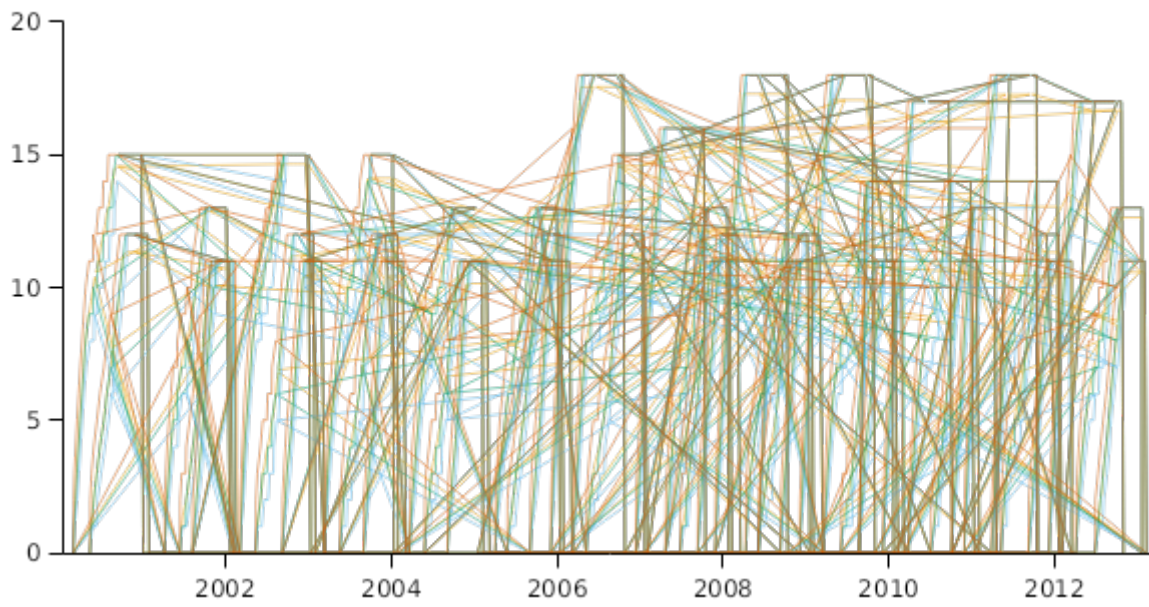
3.5.13.1 CPTCultOtane

Graph1

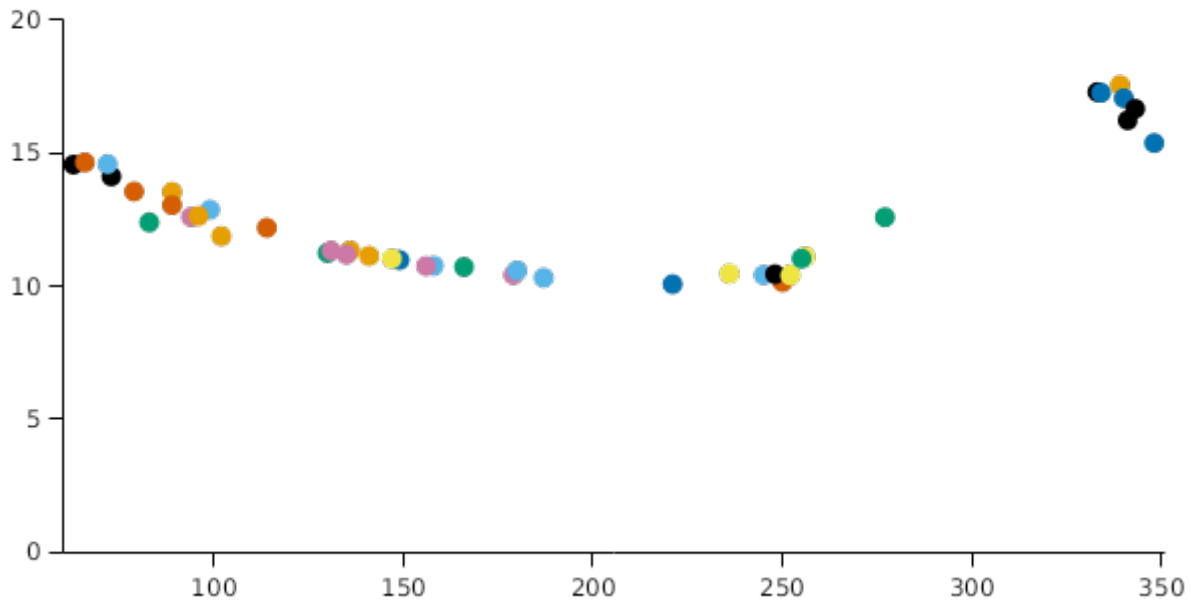


3.5.13.2 CPTCultClaire

FLNdynamics



Graph1



HSTSDynamics

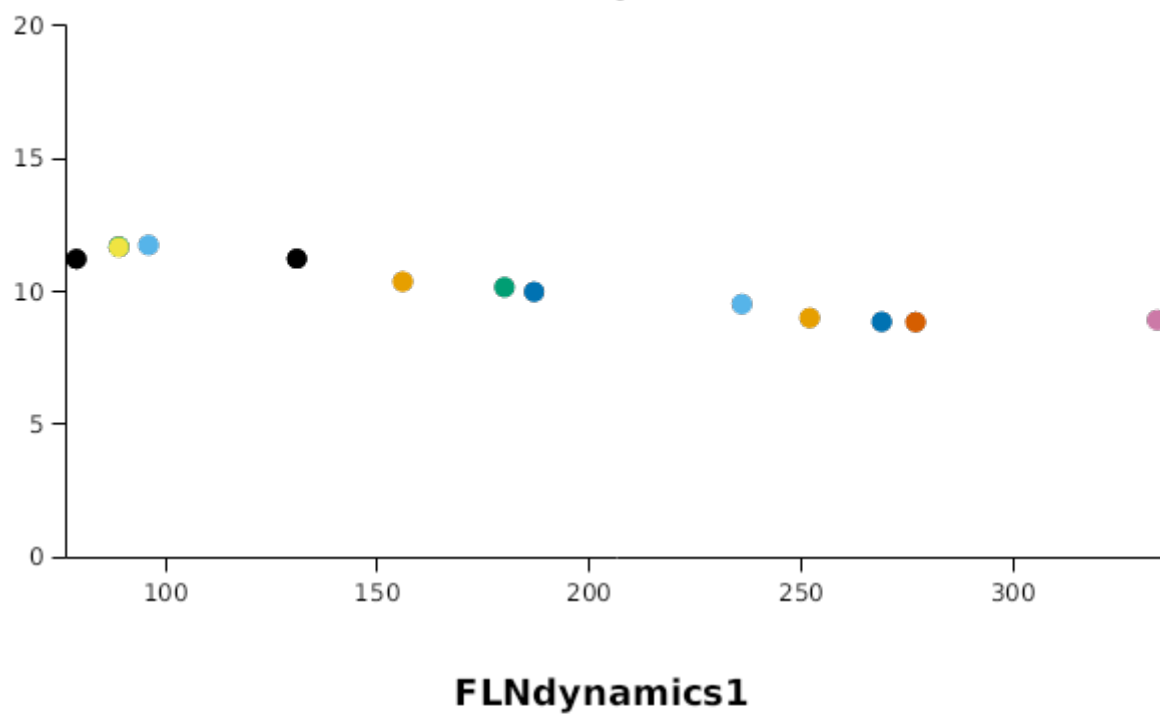
FLNdynamics1

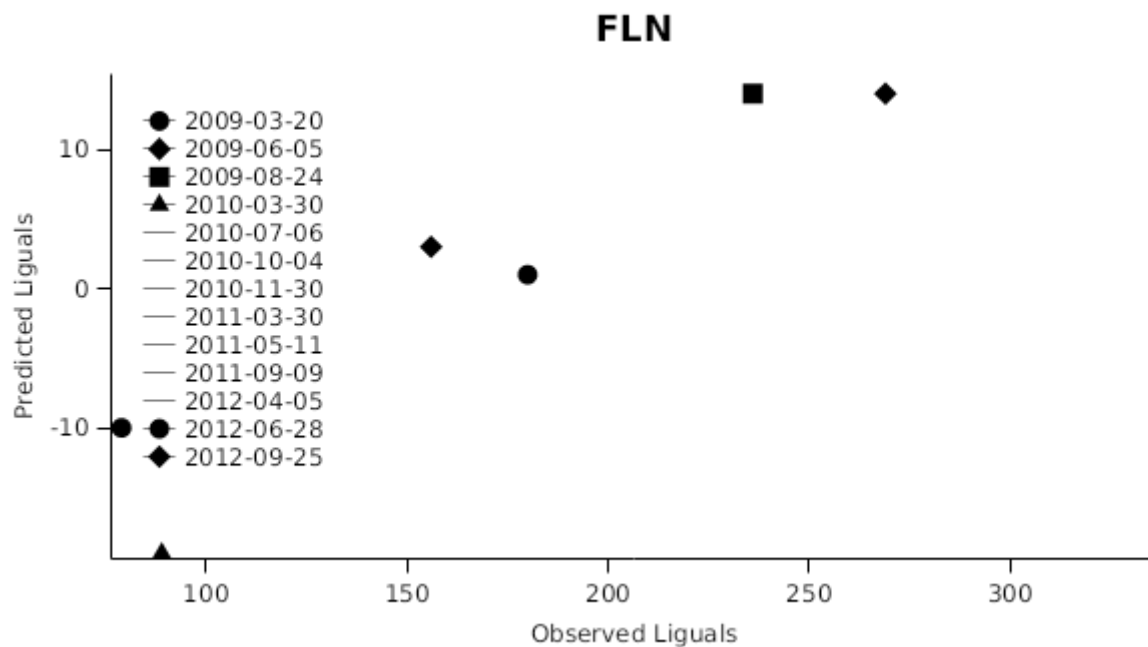
Graph11

Graph111

3.5.13.3 CPTCultBattenSpring

Graph1

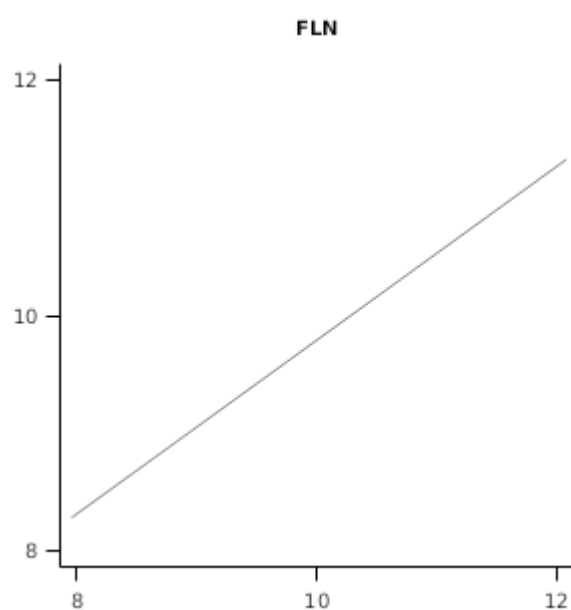
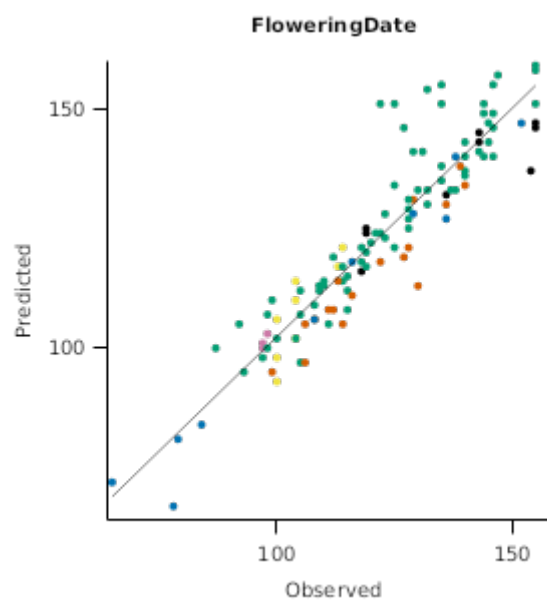
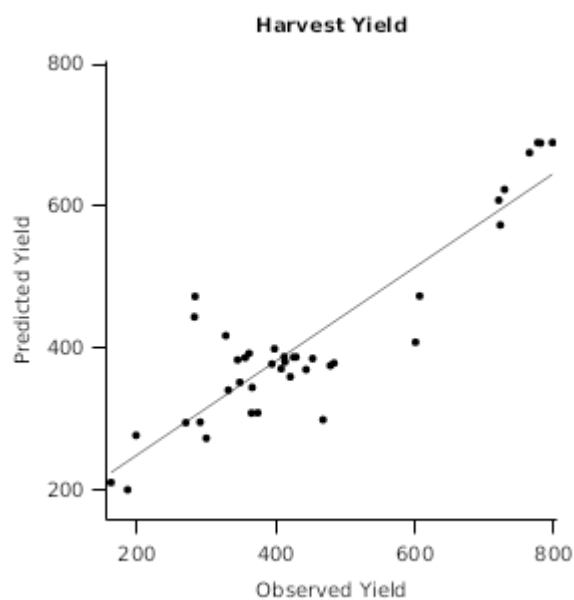




3.6 Southern Australia

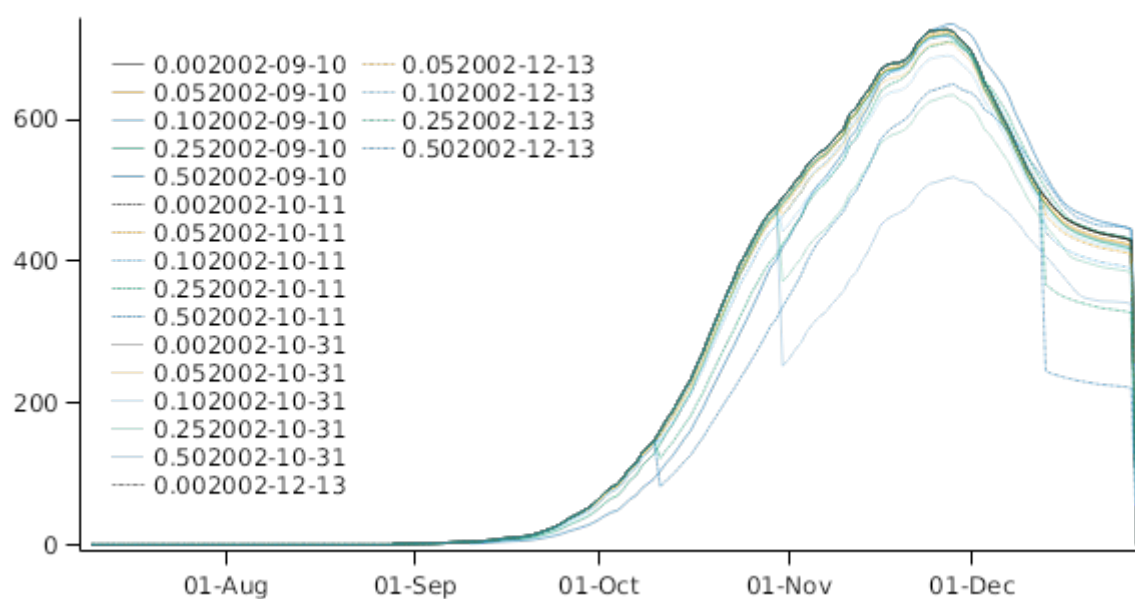
List of experiments.

Experiment Name	Design (Number of Treatments)
Mouse	Removal x Date (20)
Walpeup2011	Cv x TOS (12)
Walpeup2012	Cv x TOS (8)
Minnipa2012	Cv x TOS (9)
Temora2012	Cv x TOS (9)
Birchip2011	TOS x Cv (16)
Tarlee2011	TOS x Cv (16)
Tamworth1992	Cv x TOS (75)

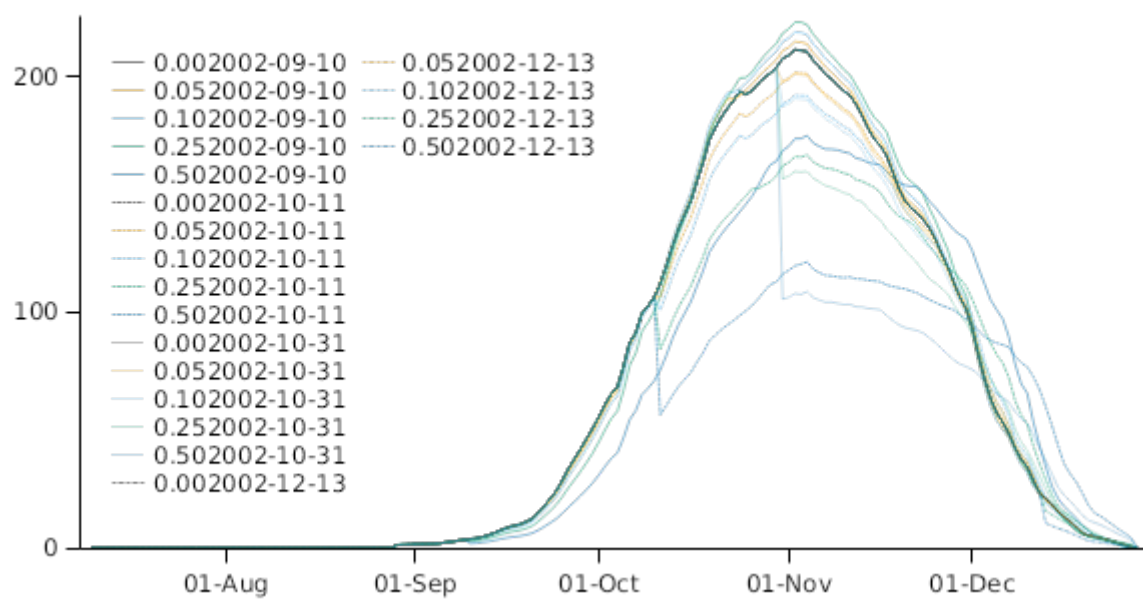


3.6.1 Mouse

Biomass

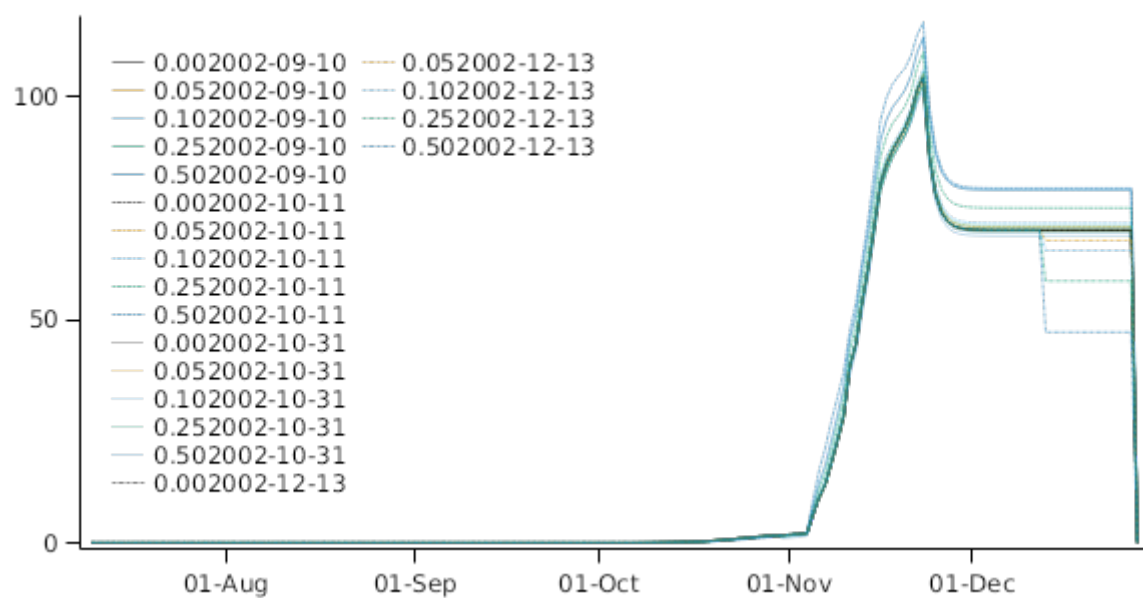


Leaf

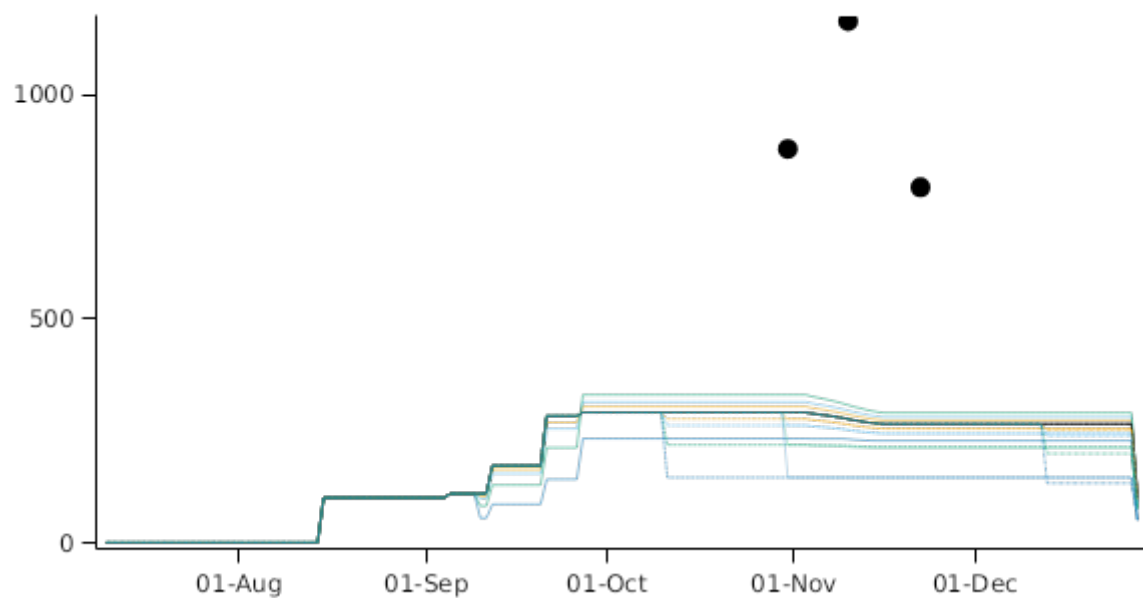


Stem

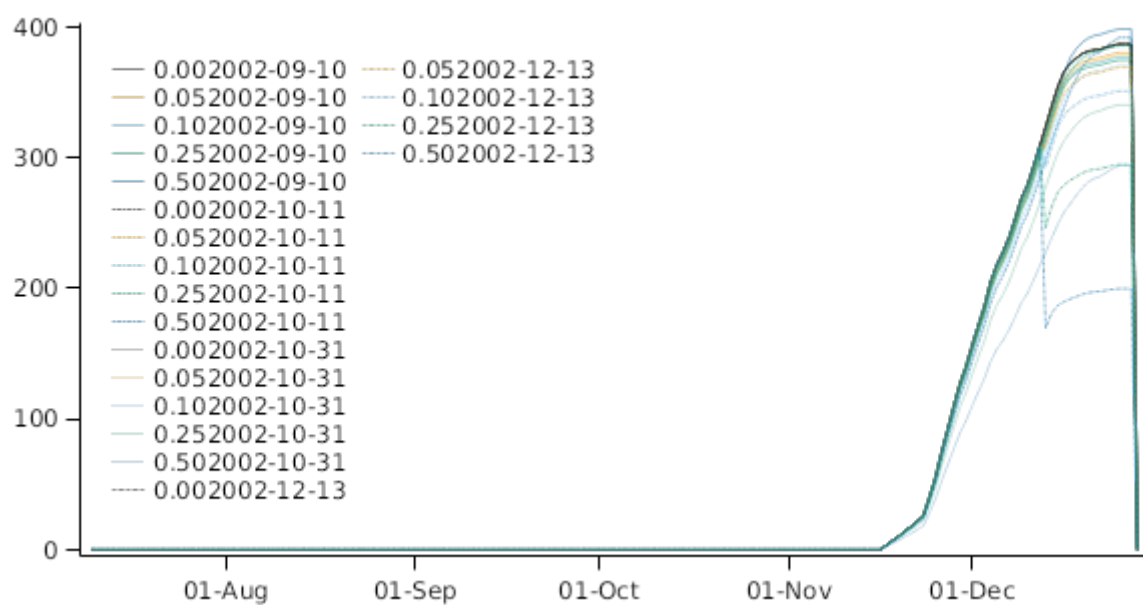
Spike



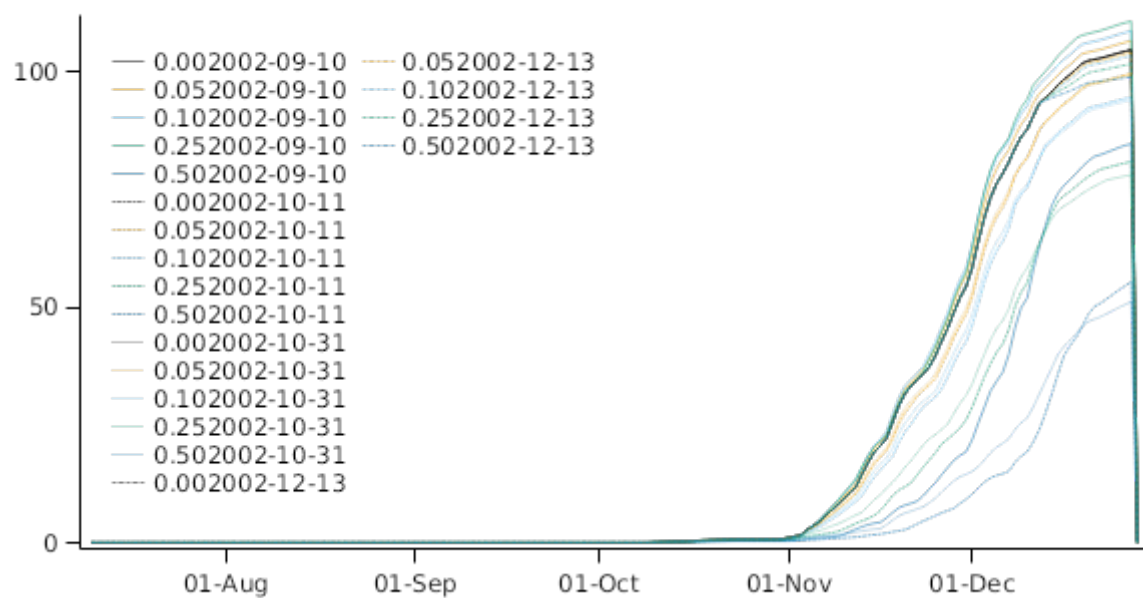
StemPopn



Grain

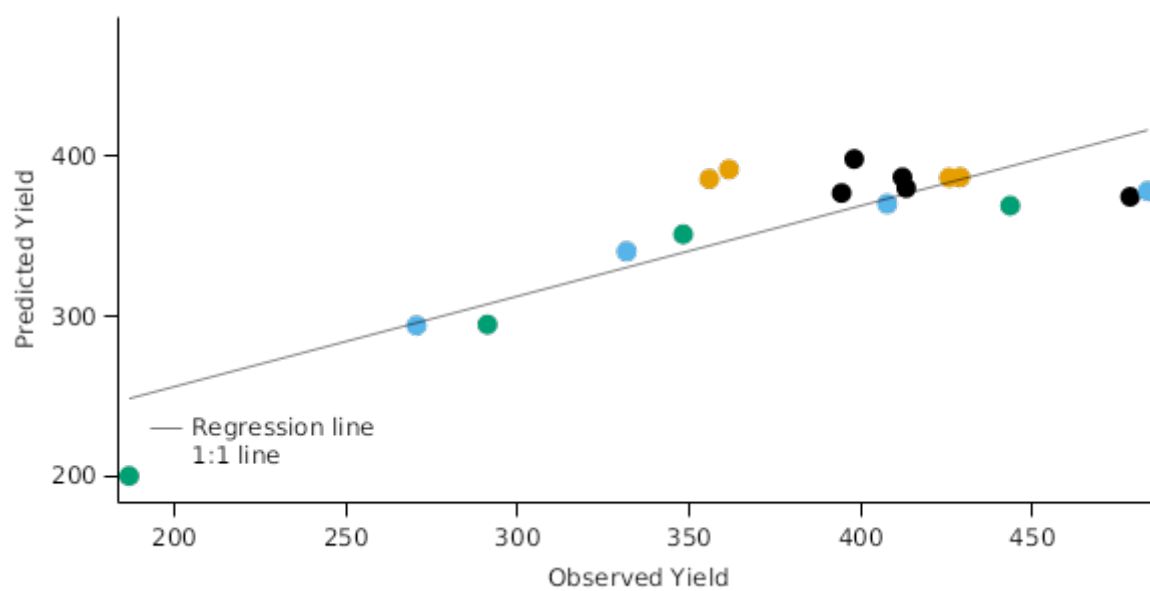


DeadLeaf

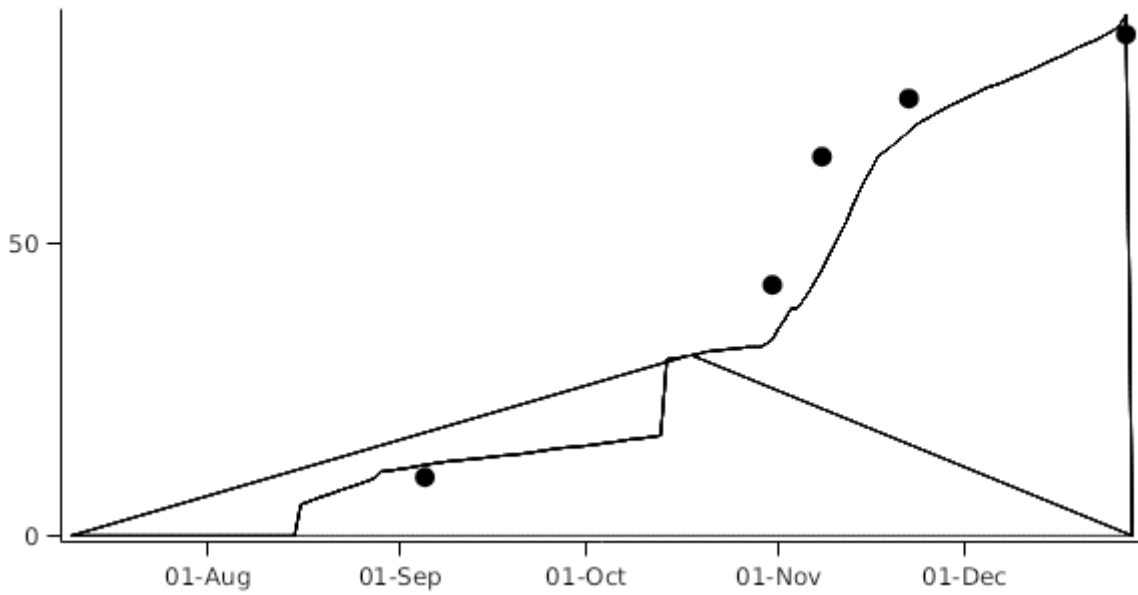


SurfaceOM

Harvest Yield



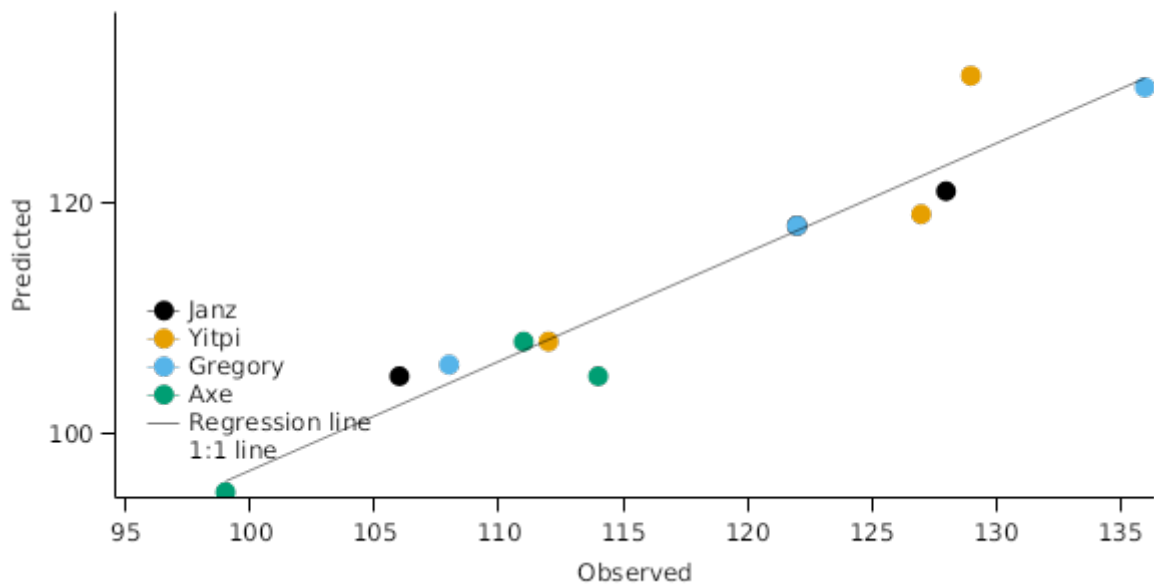
Phenology



3.6.2 Walpeup2011

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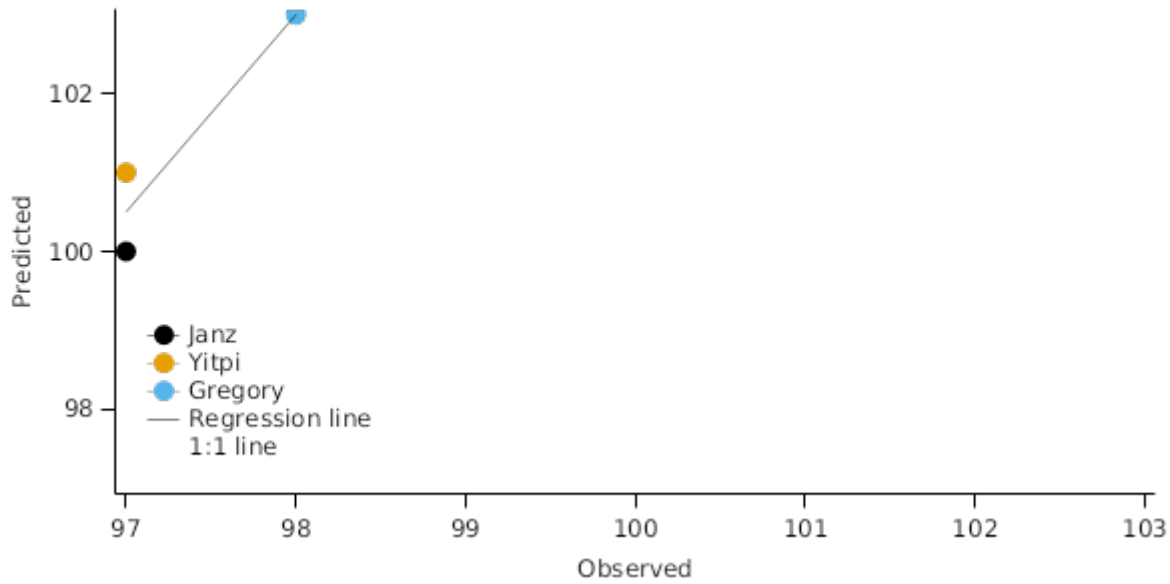
FloweringDate



3.6.3 Walpeup2012

INSERT TEXT HERE

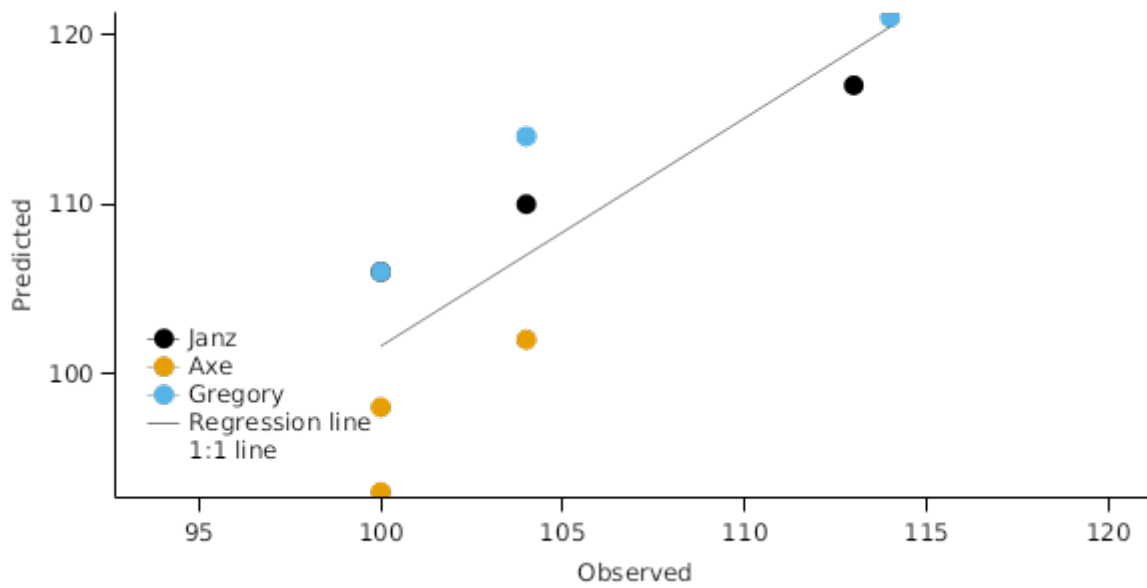
FloweringDate



3.6.4 Minnipa2012

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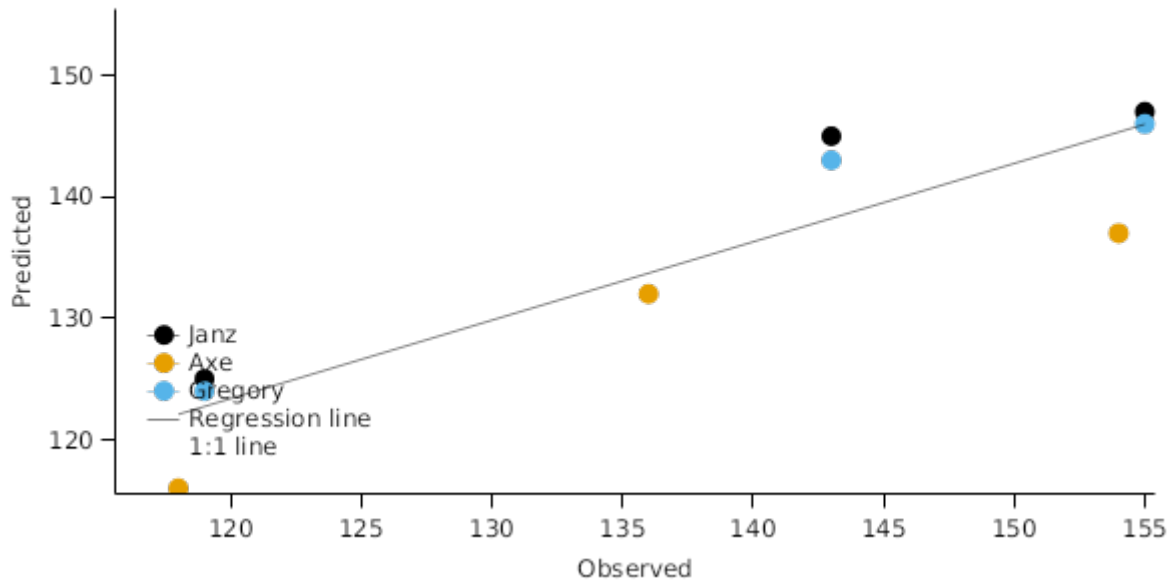
FloweringDate



3.6.5 Temora2012

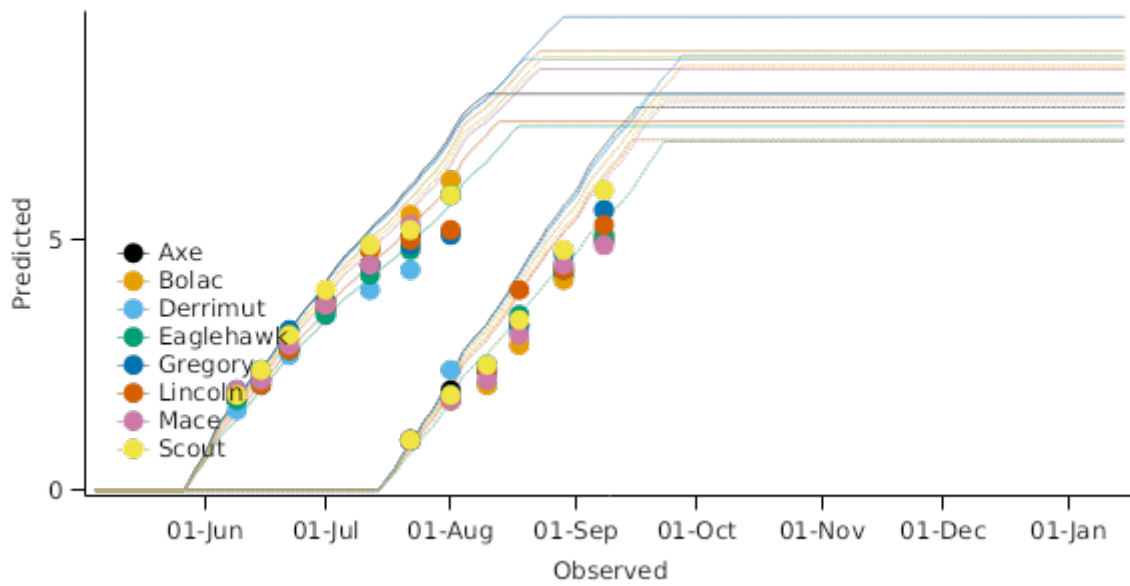
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FloweringDate

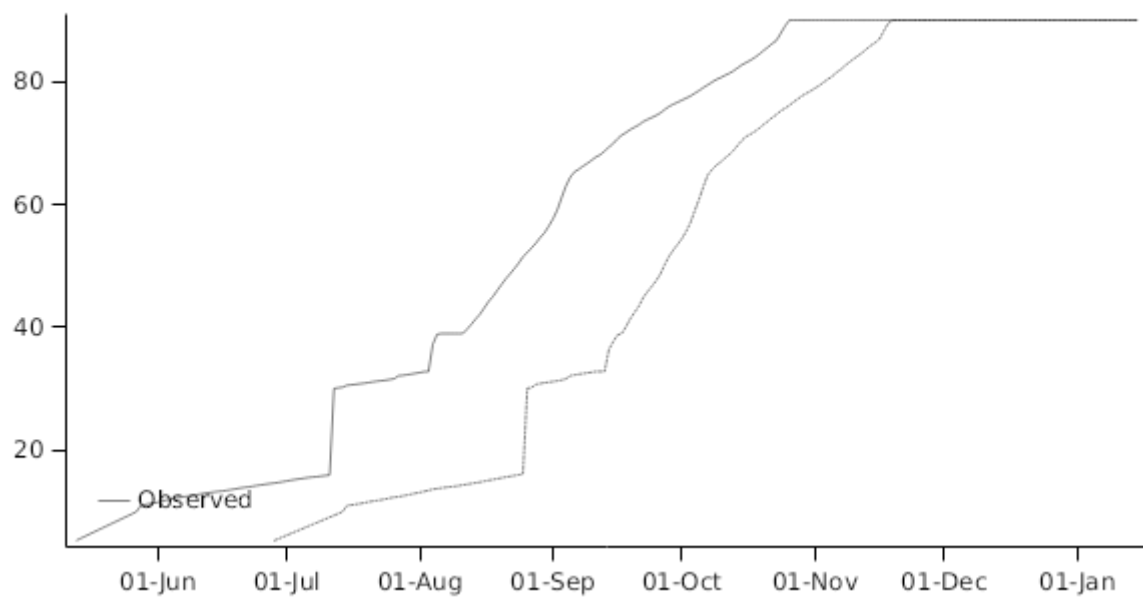


3.6.6 Birchchip2011

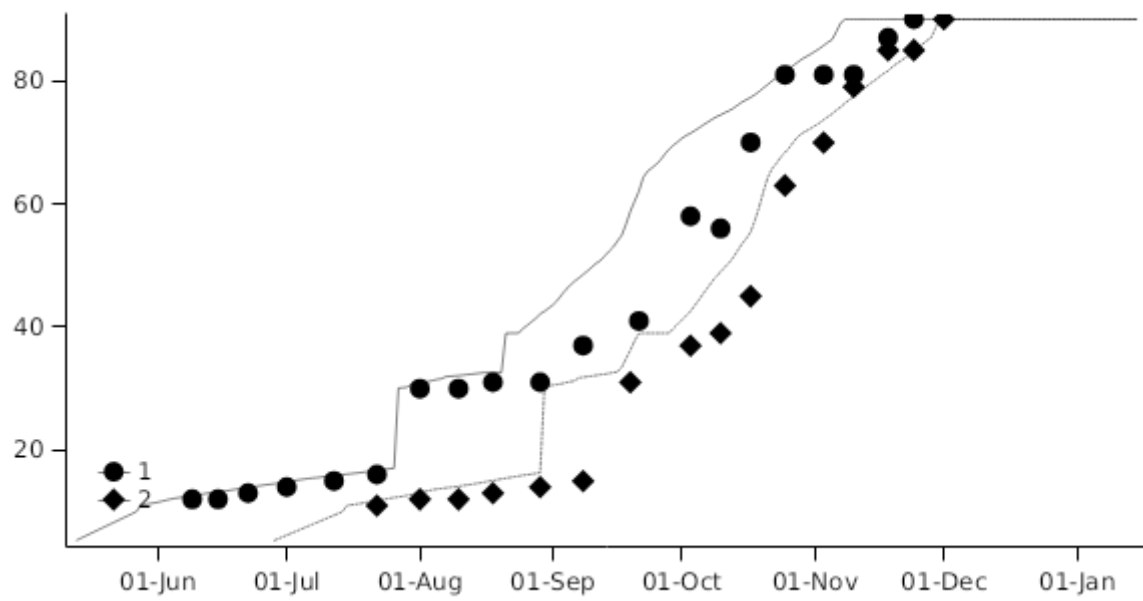
LeafNumberTimeSeries



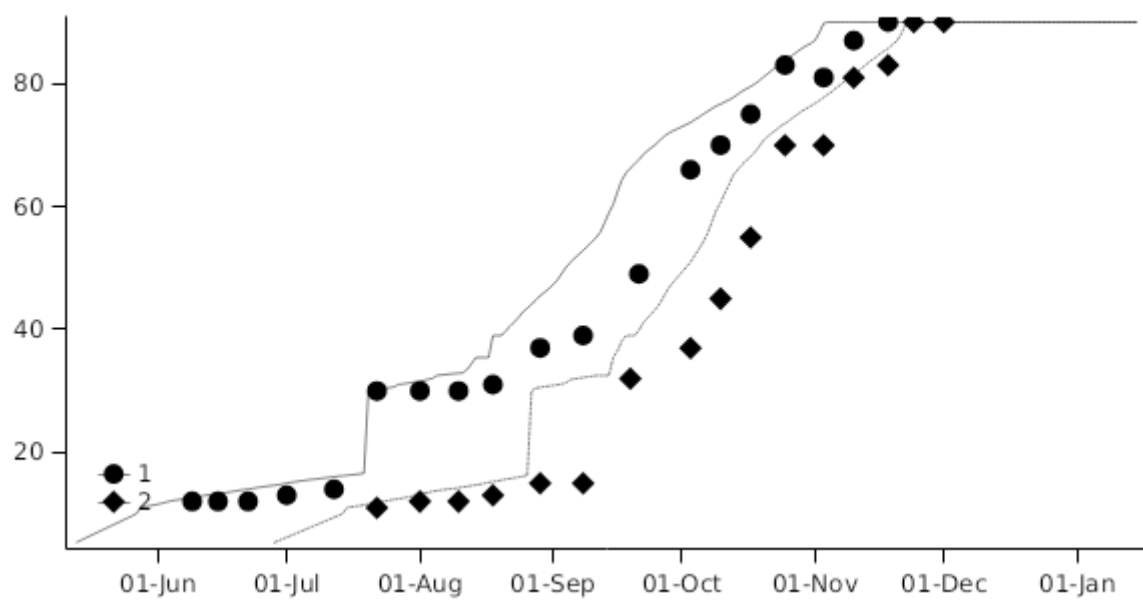
Axe



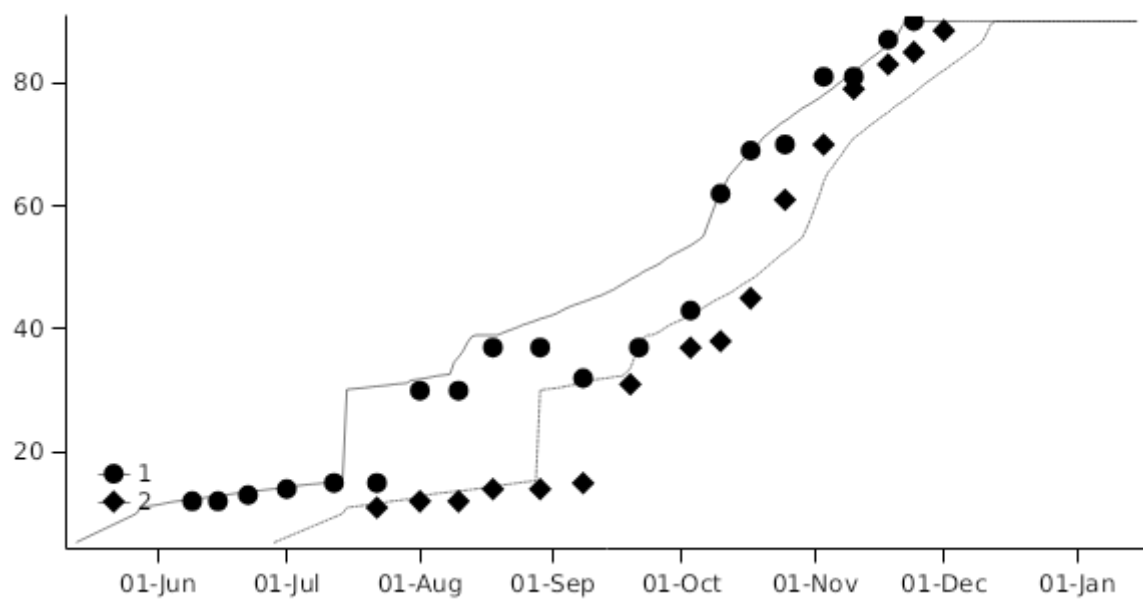
Bolac



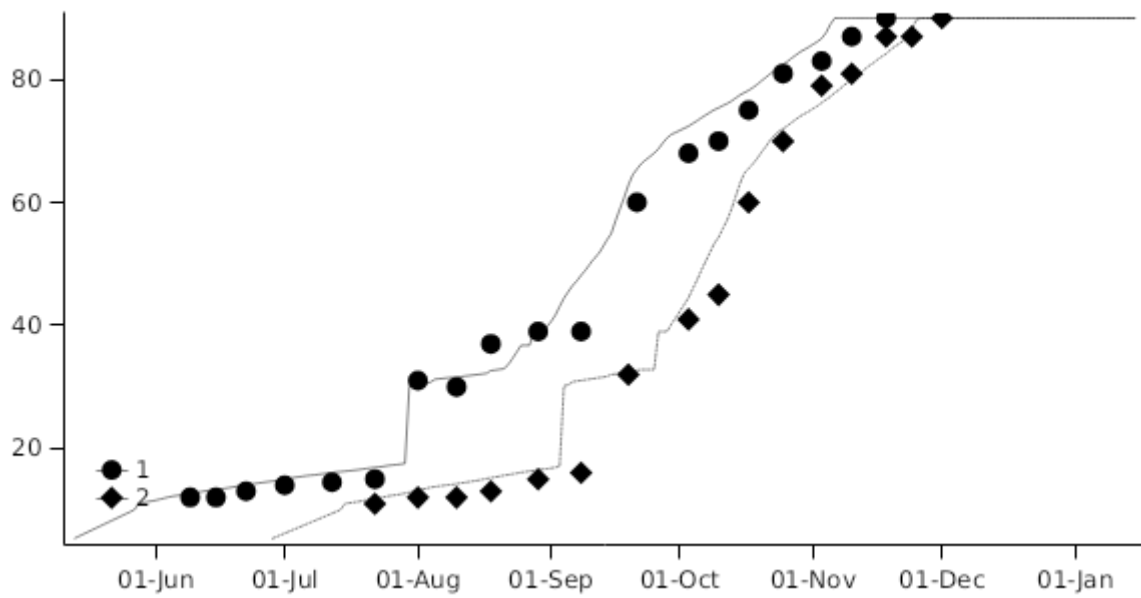
Derrimut



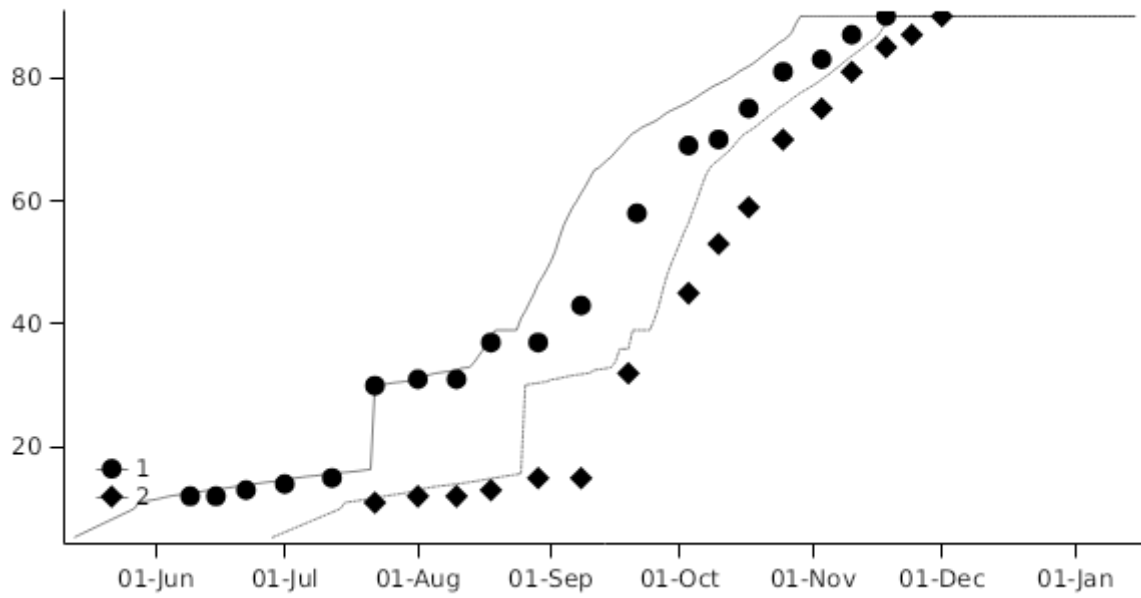
EagleHawk



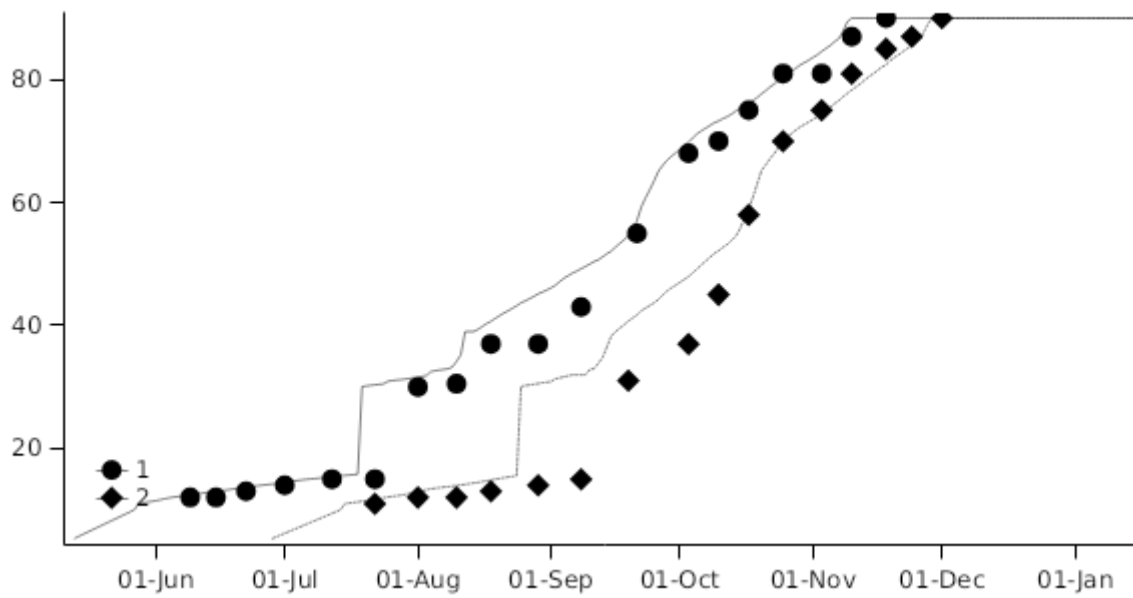
Gregory



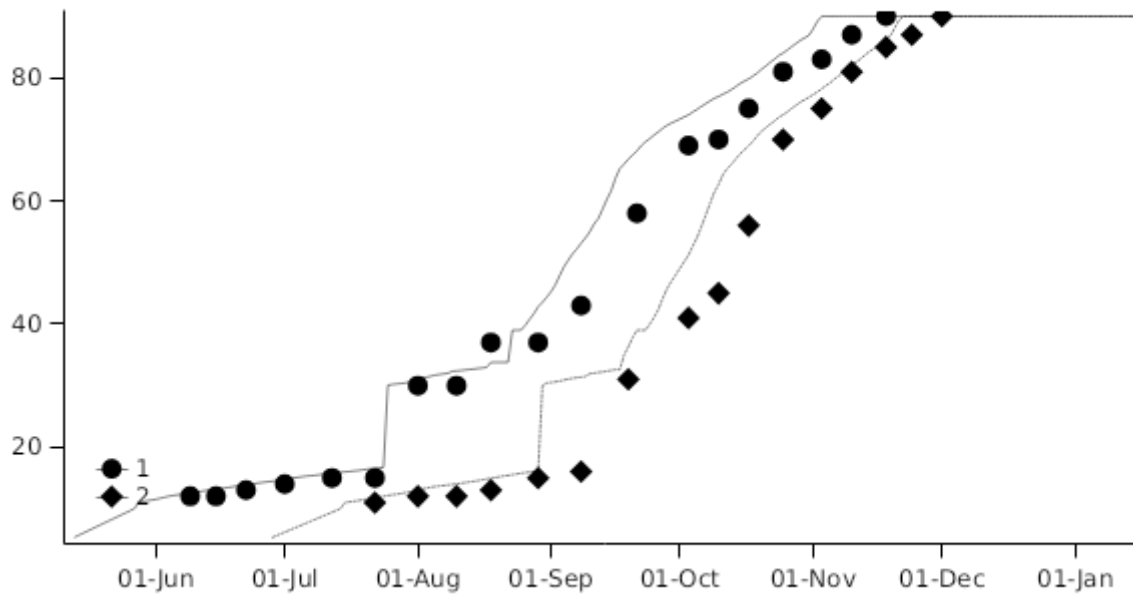
Mace



Lincoln

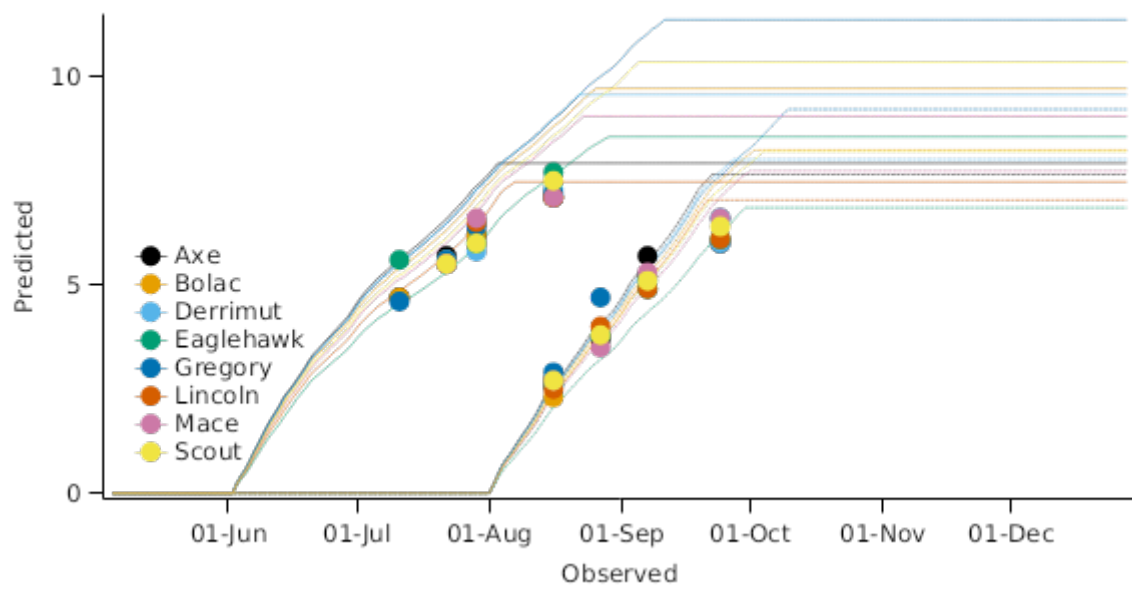


Scout

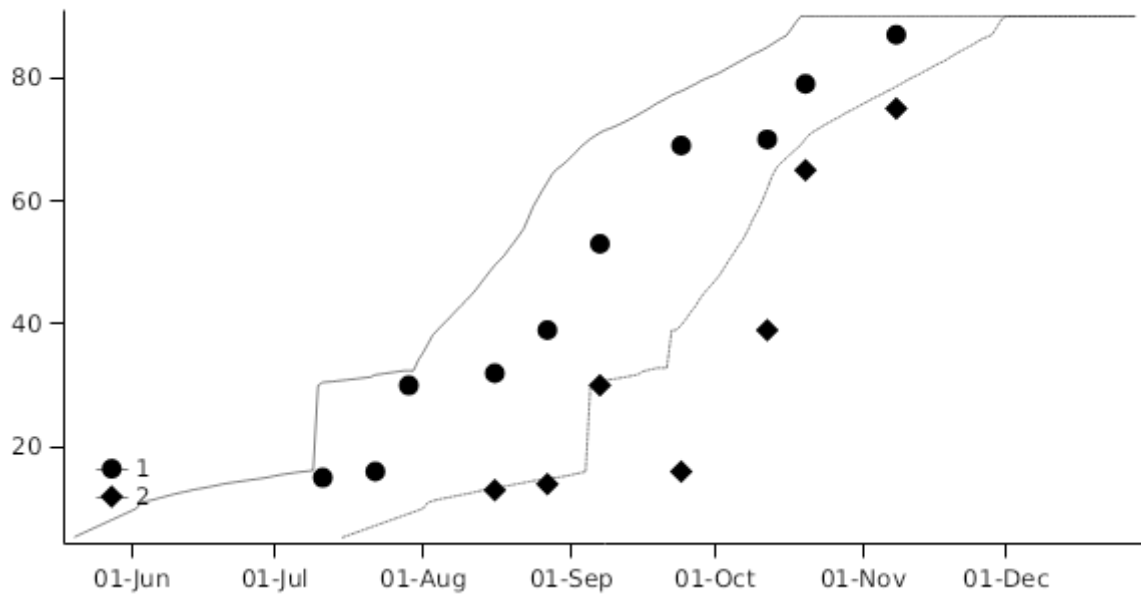


3.6.7 Tarlee2011

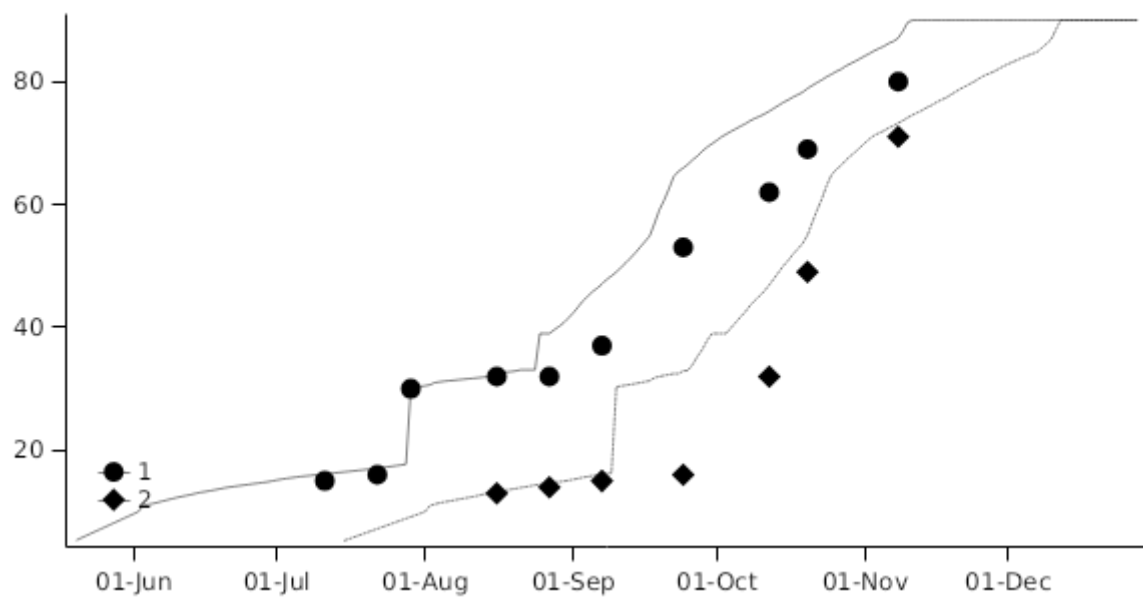
LeafNumberTimeSeries



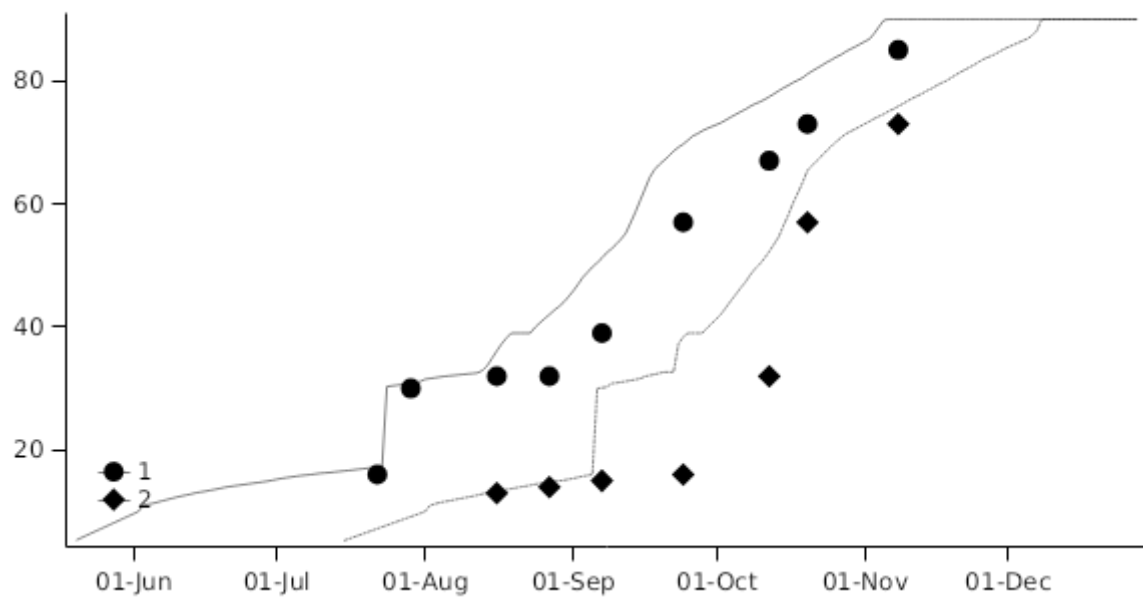
Axe



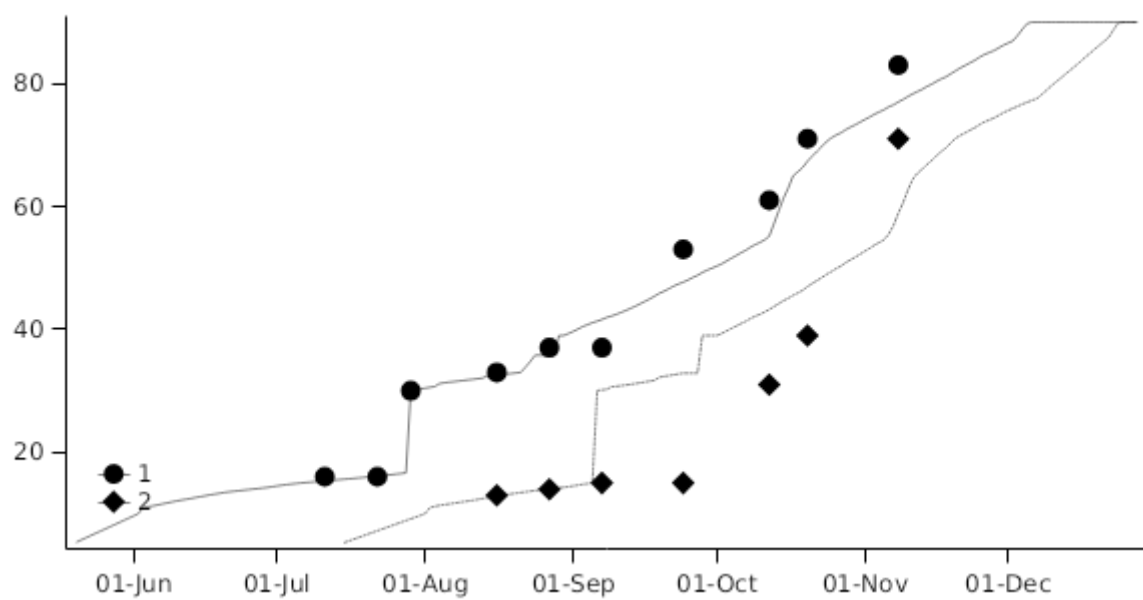
Bolac



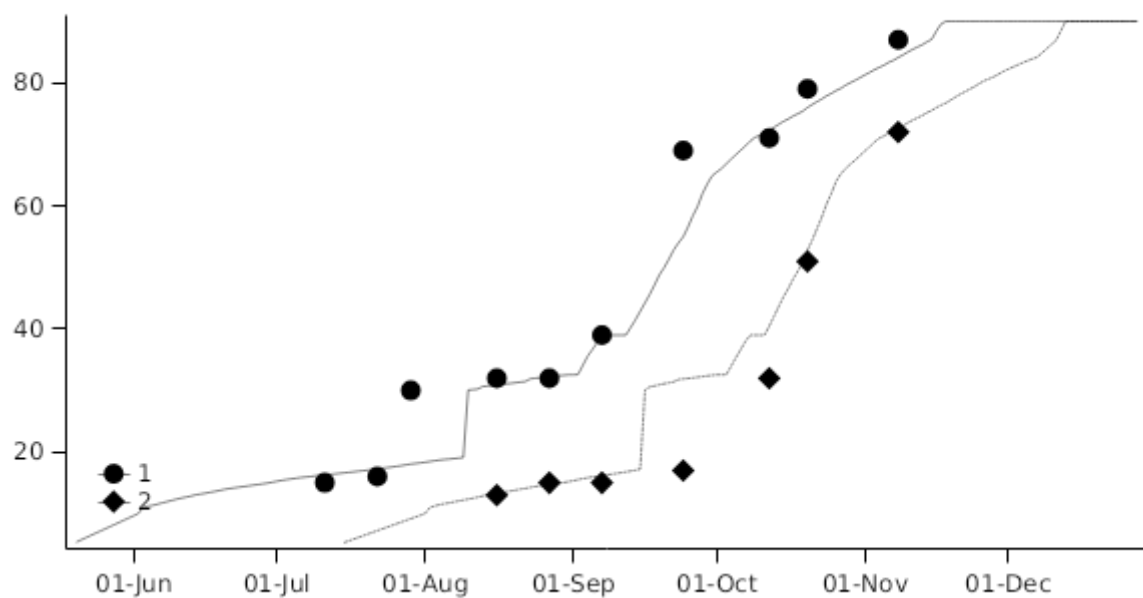
Derrimut



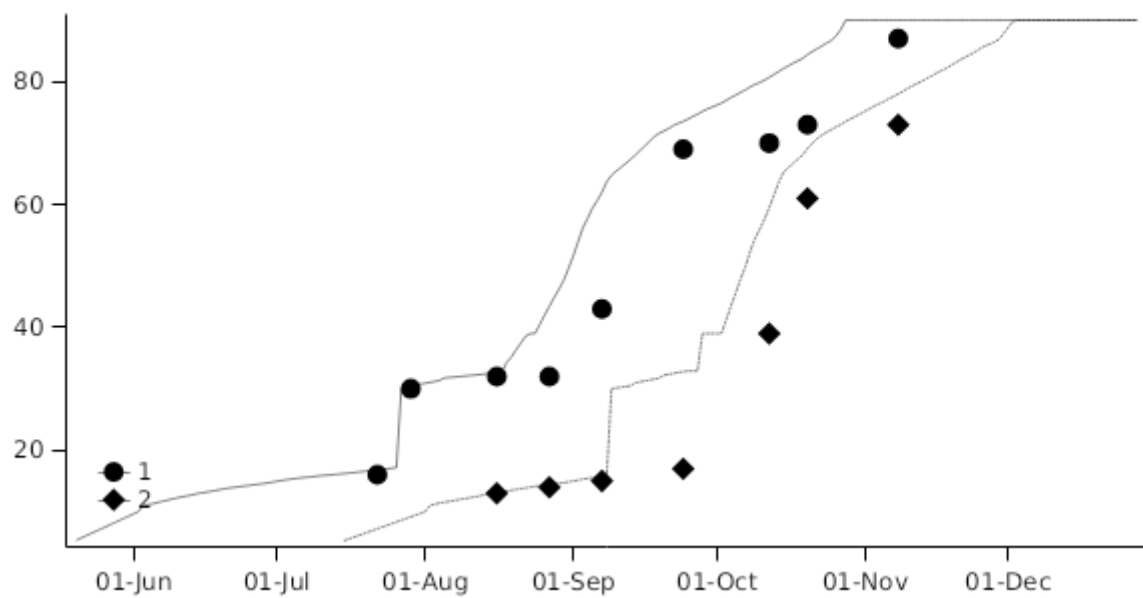
EagleHawk



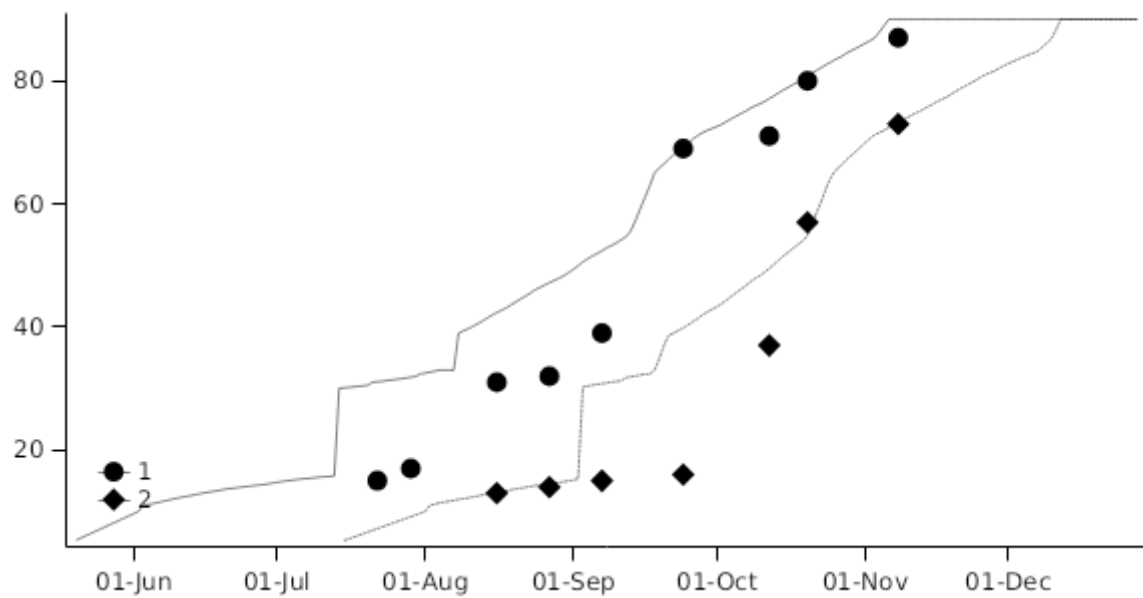
Gregory



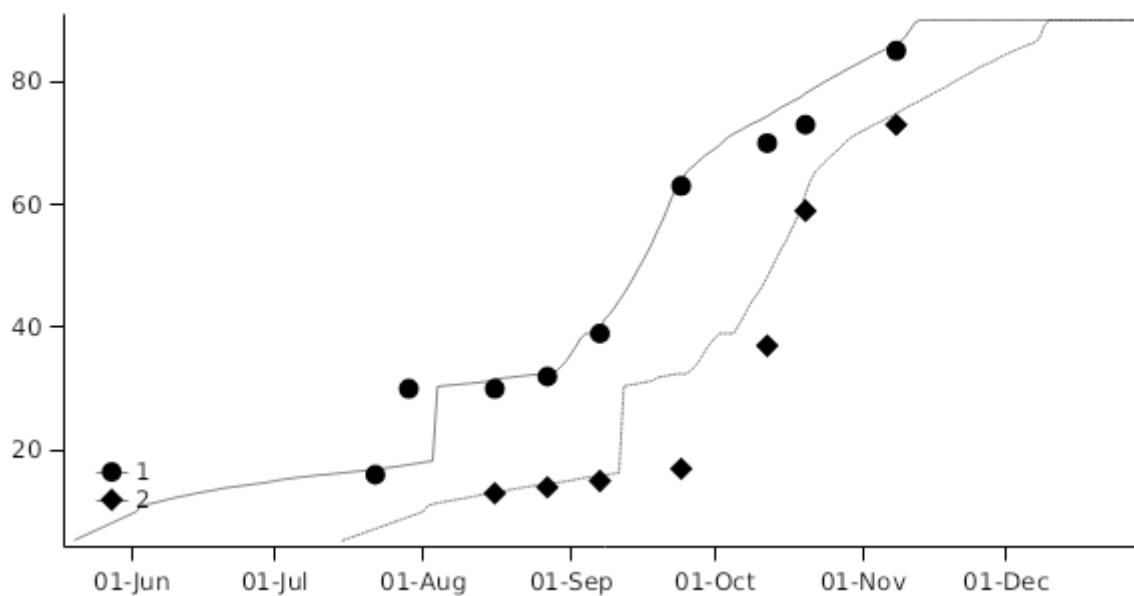
Mace



Lincoln



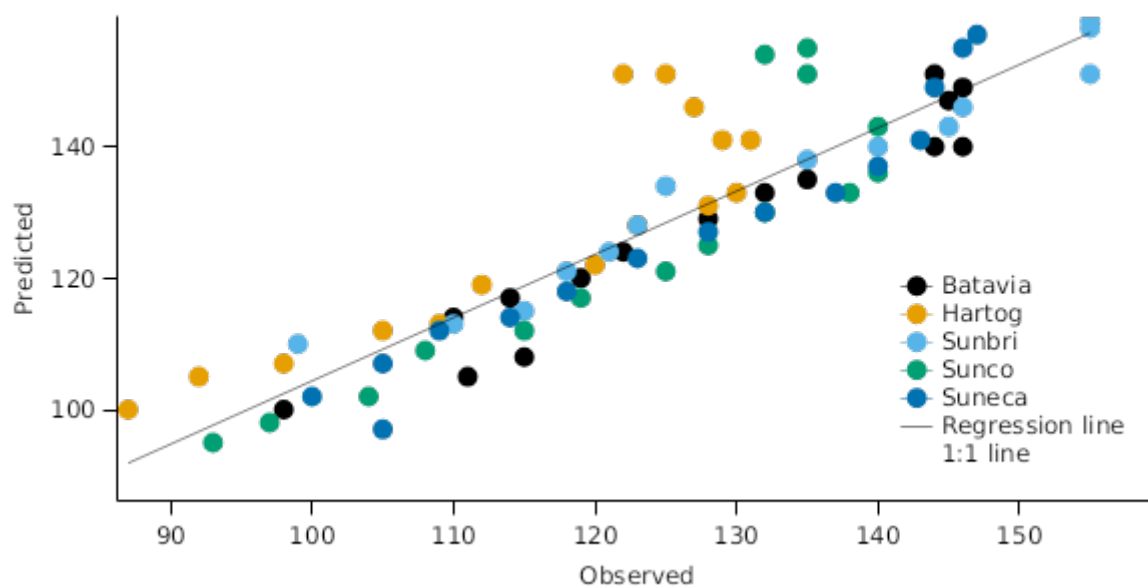
Scout



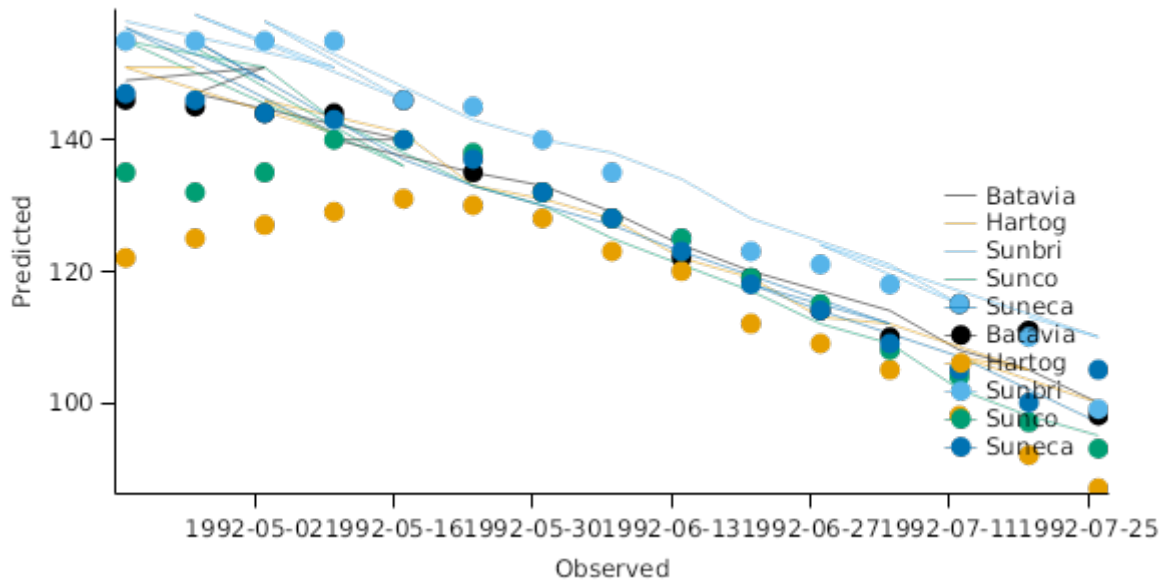
3.6.8 Tamworth1992

This dataset includes observed flowering date for five cultivars (Batavia, Hartog, Sunbri, Sunco, Suneca) for a range planting dates at Tamworth.

Flowering DAS



Flowering DAS vs TOS



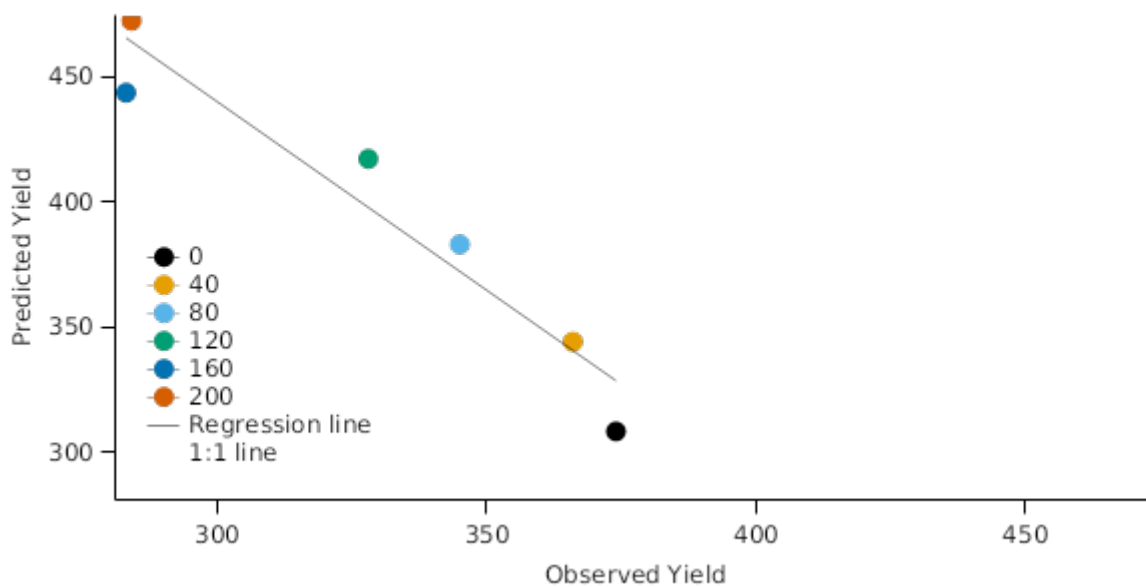
3.6.9 van Herwaarden et al 1998

List of experiments.

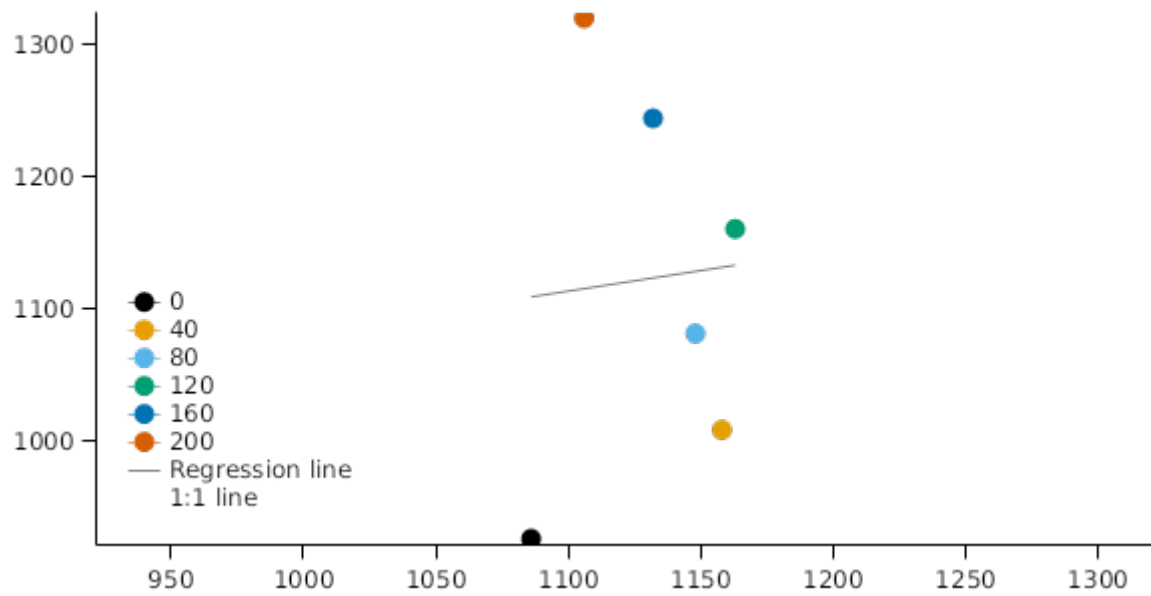
Experiment Name	Design (Number of Treatments)
Wagga1991	N (6)
Ginninderra1991	N x Cv (7)

3.6.9.1 Wagga1991

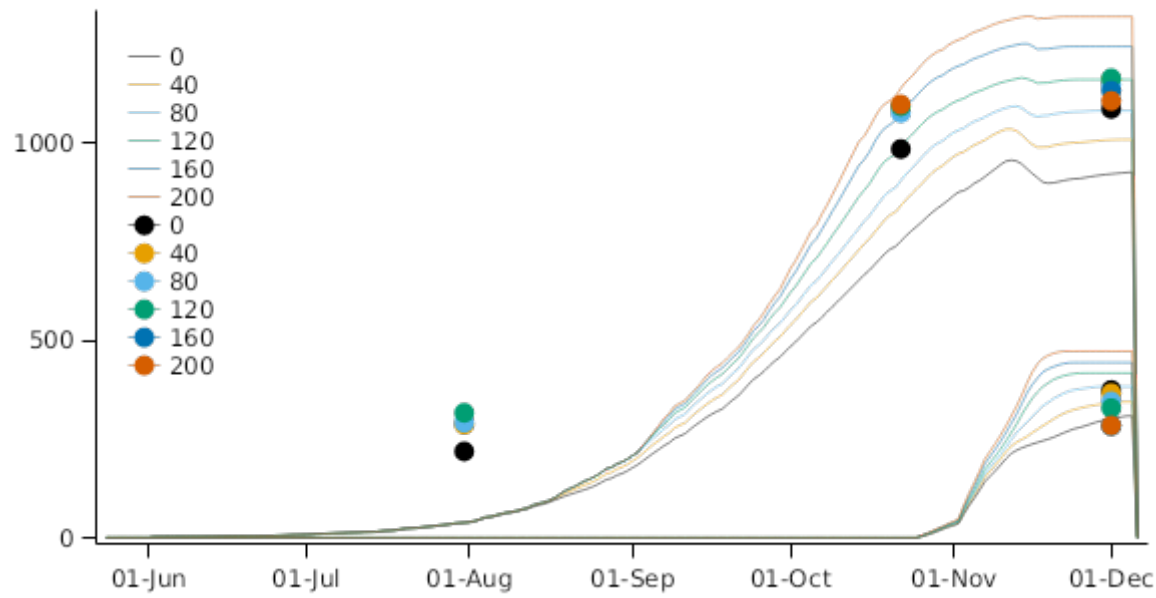
Yield



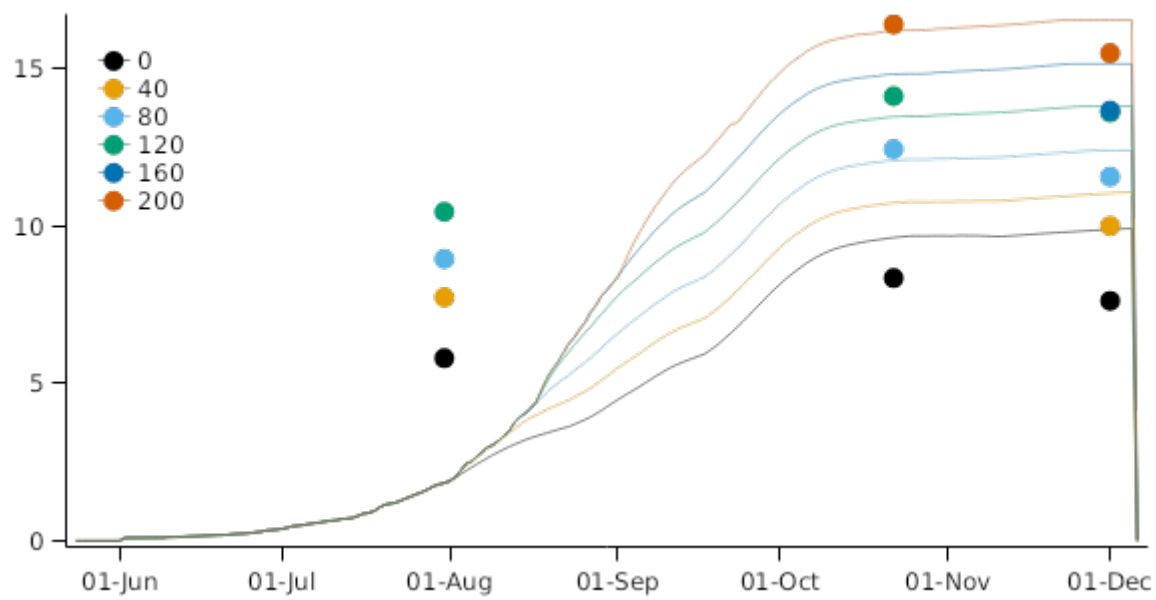
Biomass



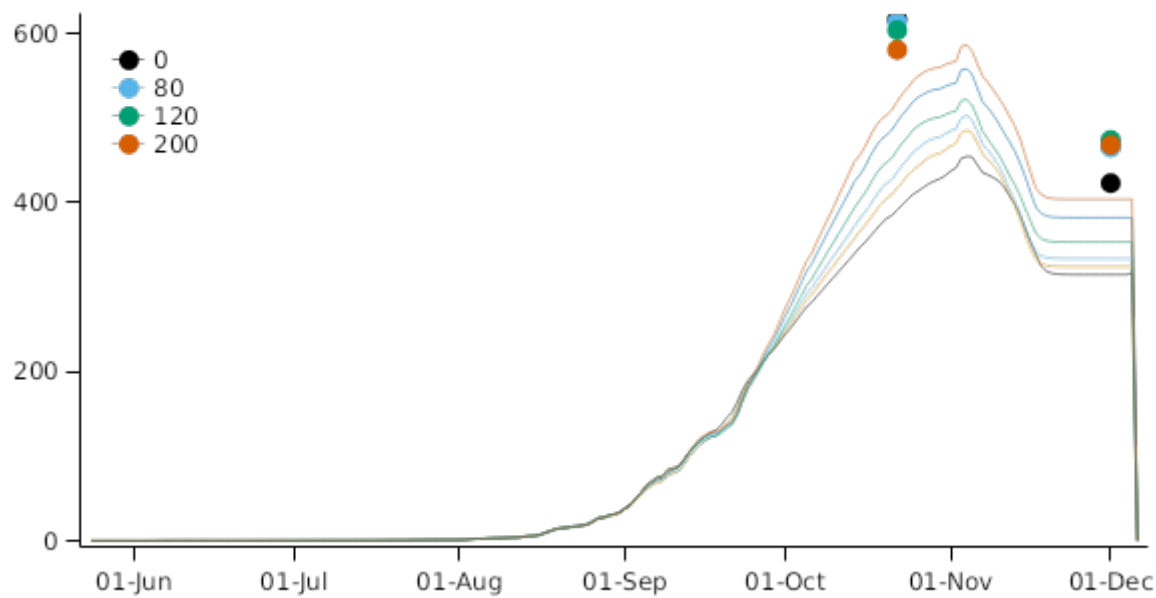
Biomass Timeseries



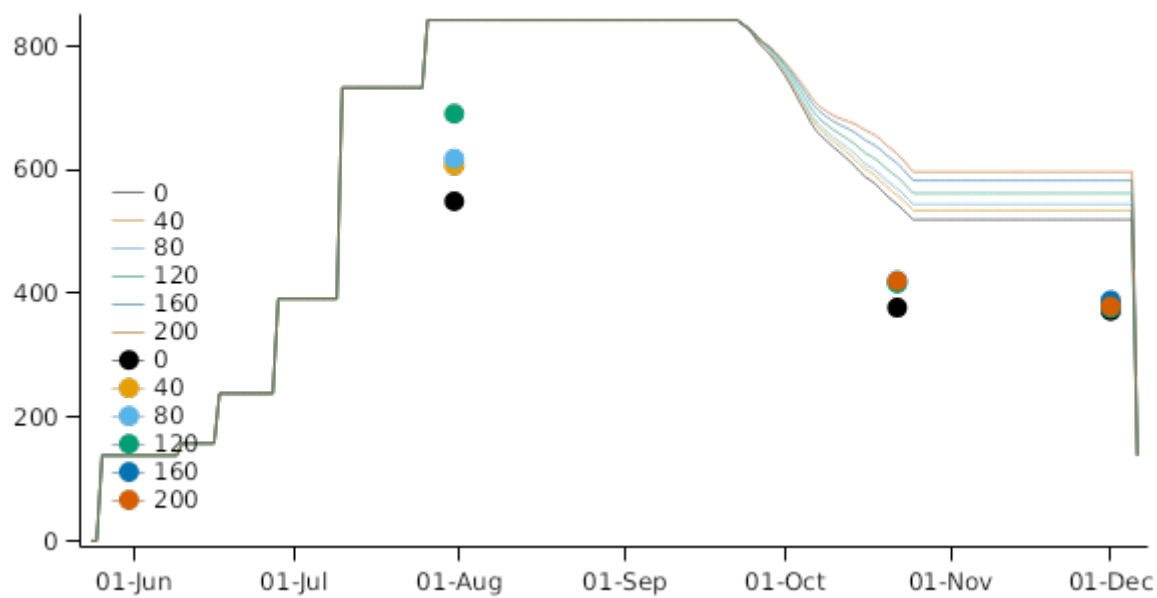
N Uptake Timeseries



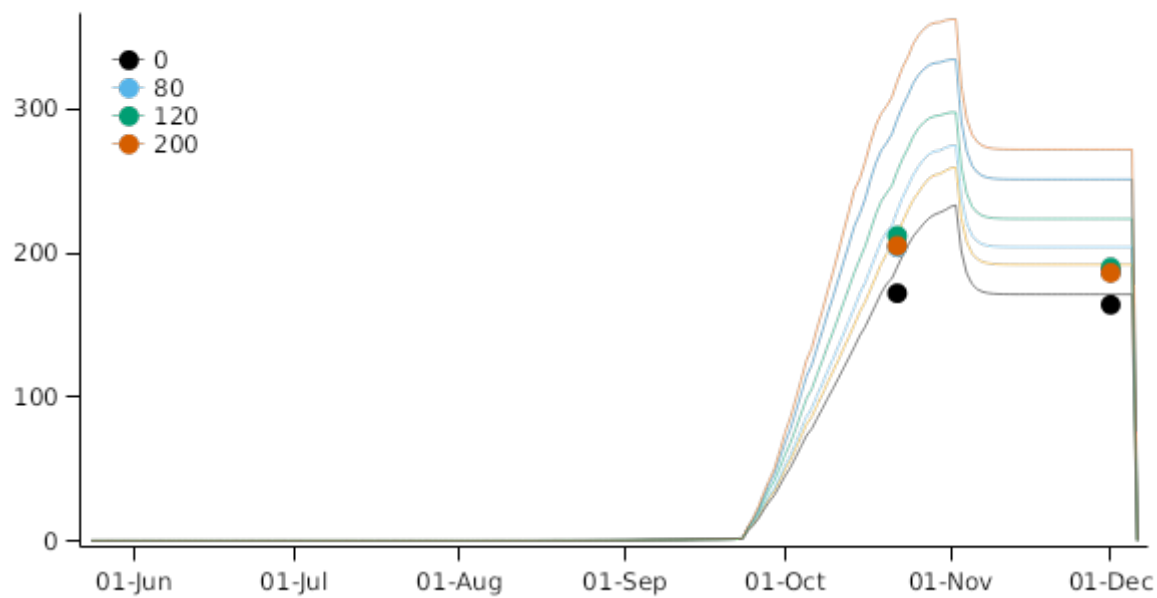
StemWt Timeseries



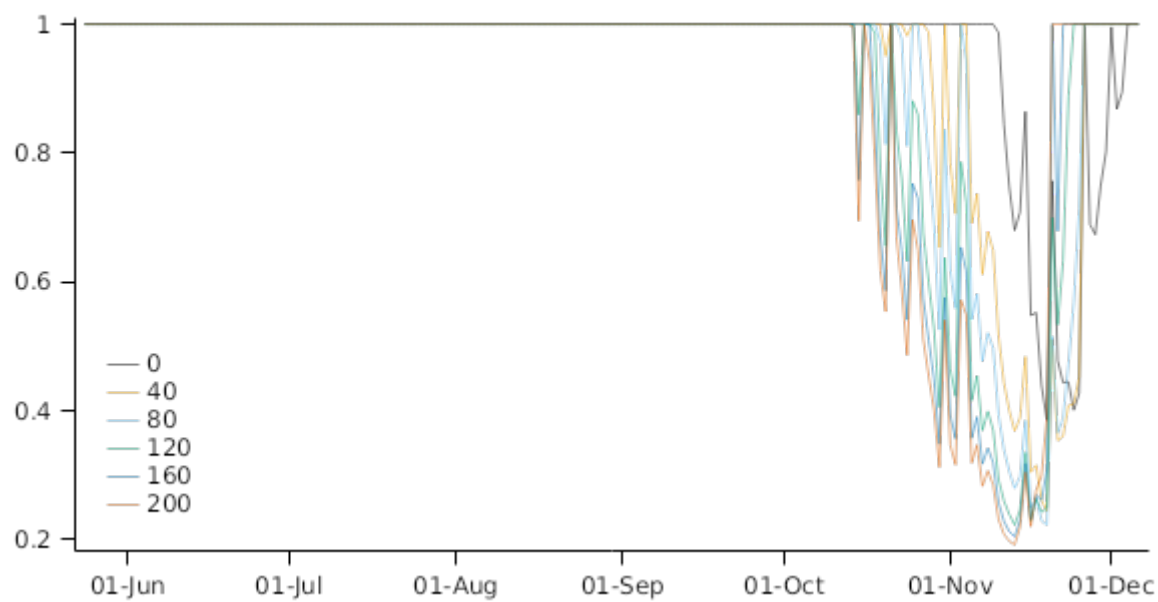
Stem Number Timeseries



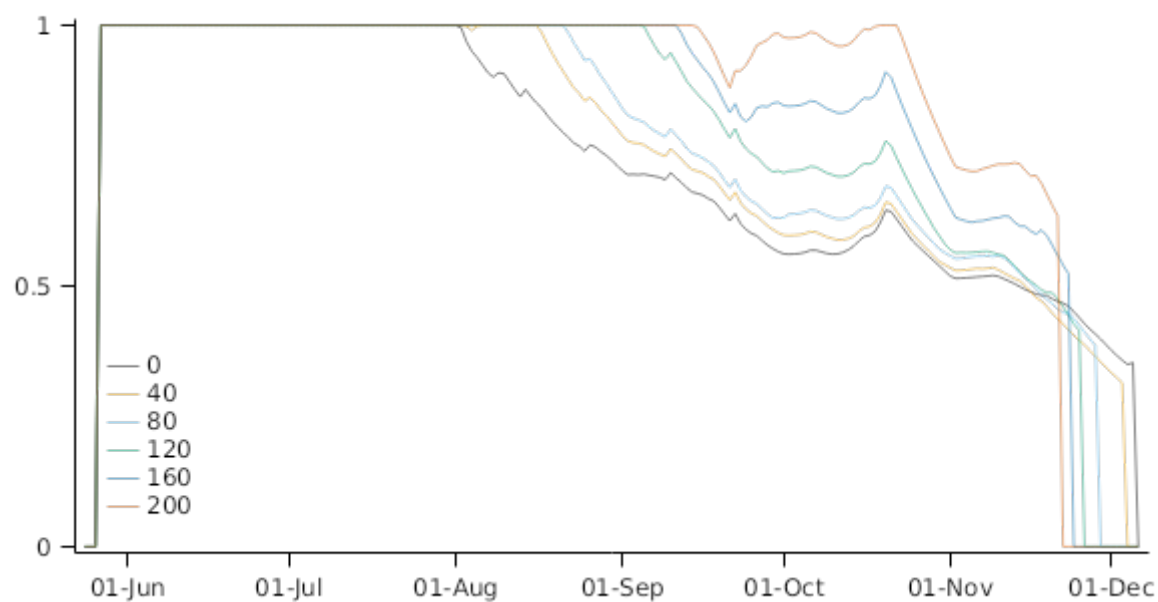
SpikeWt Timeseries



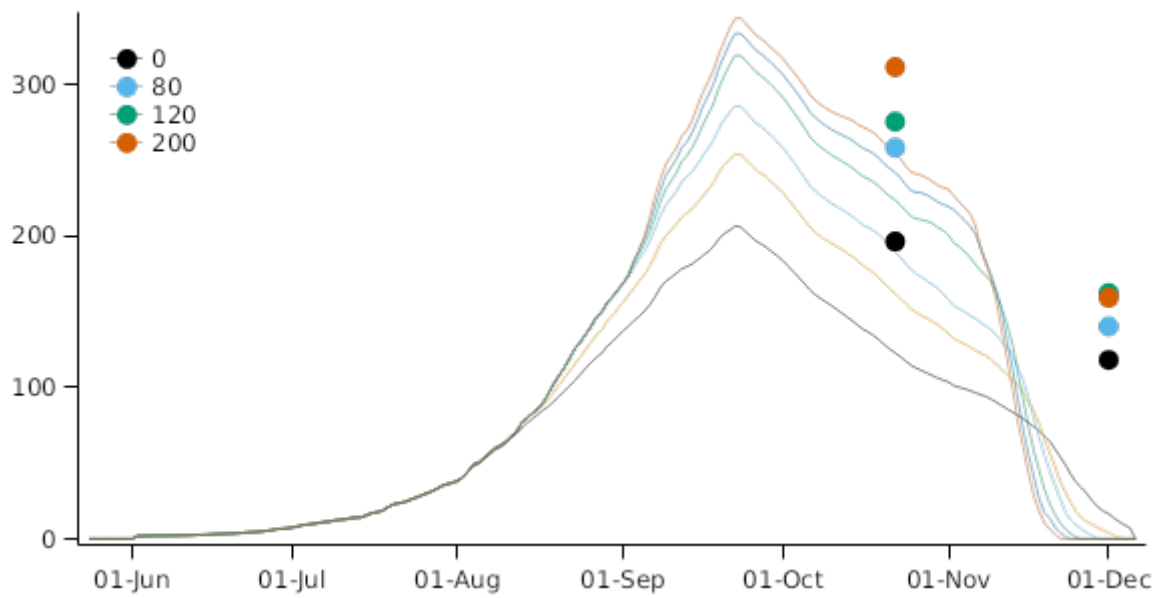
Water Stress



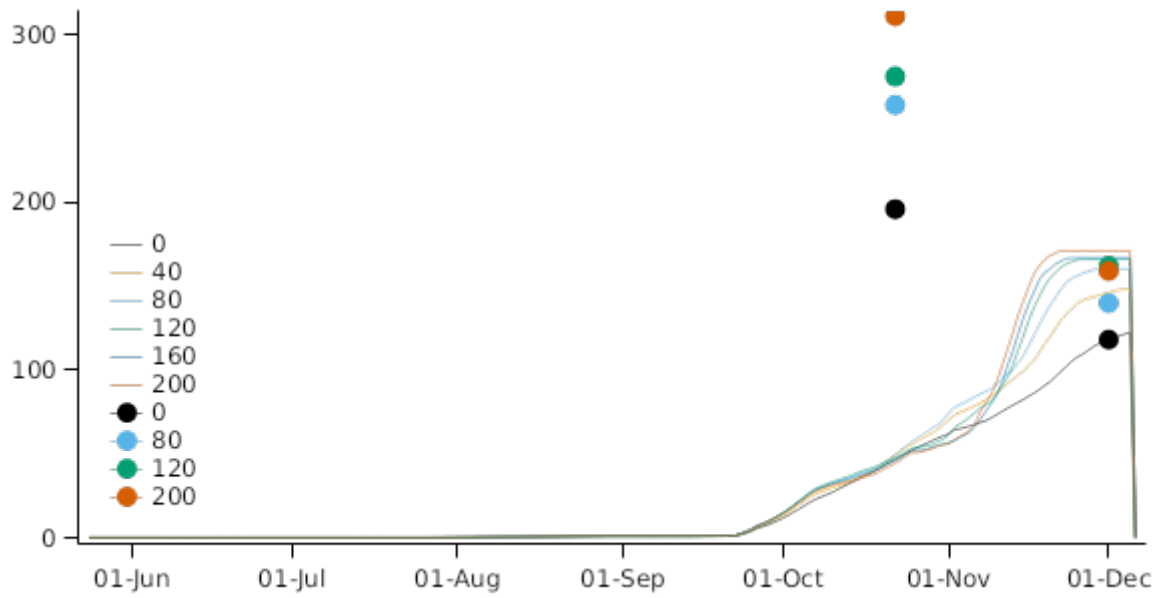
N Stress



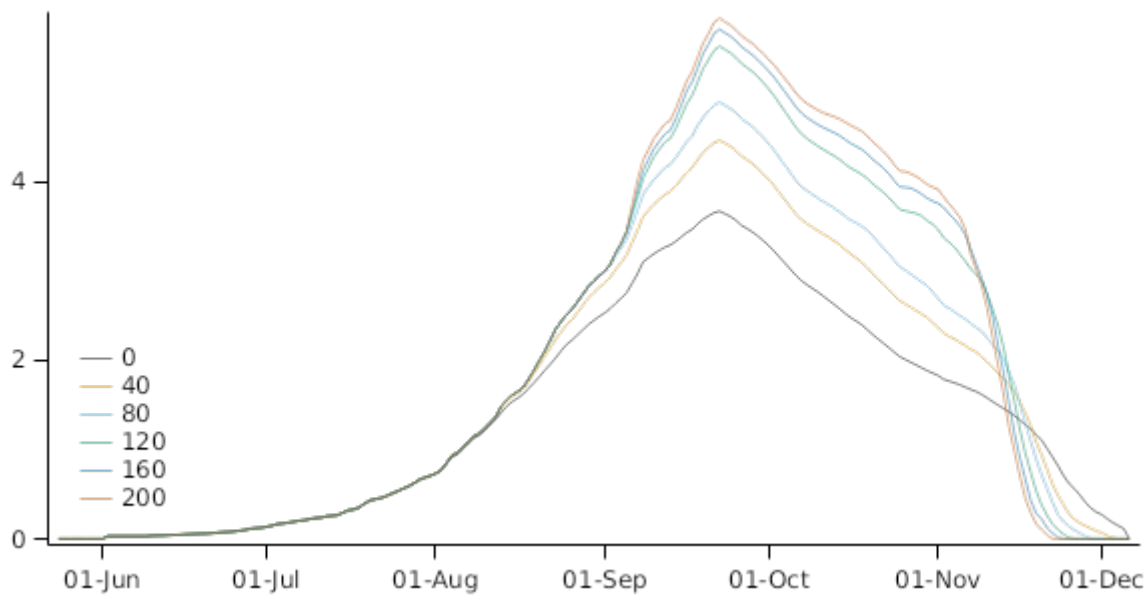
LeafWt Timeseries



LeafDeadWt Timeseries

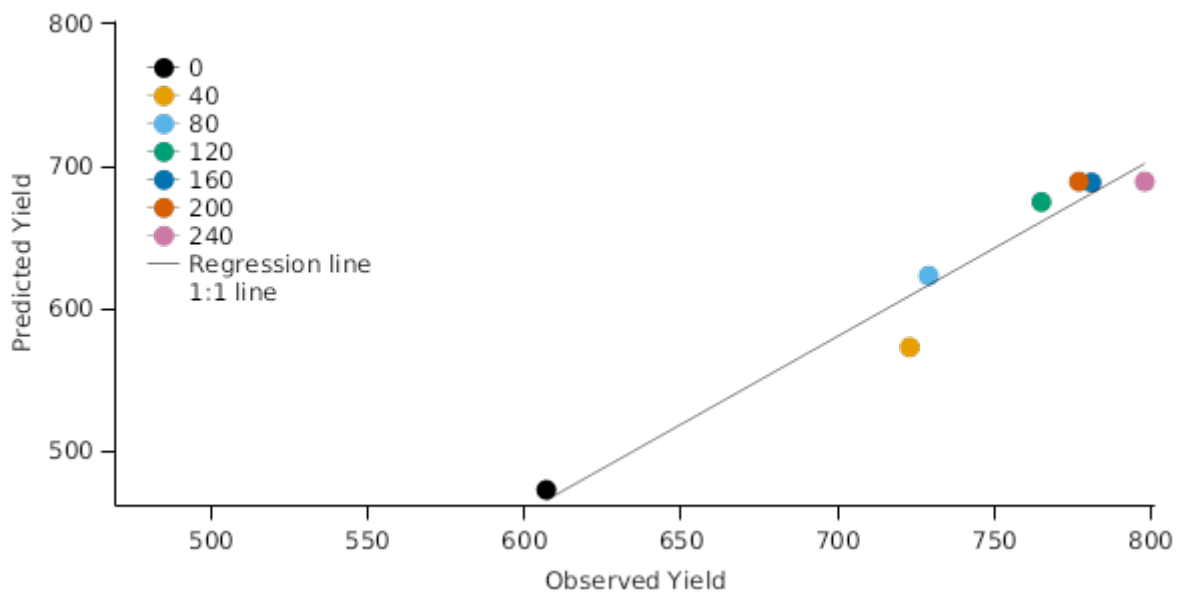


LAI

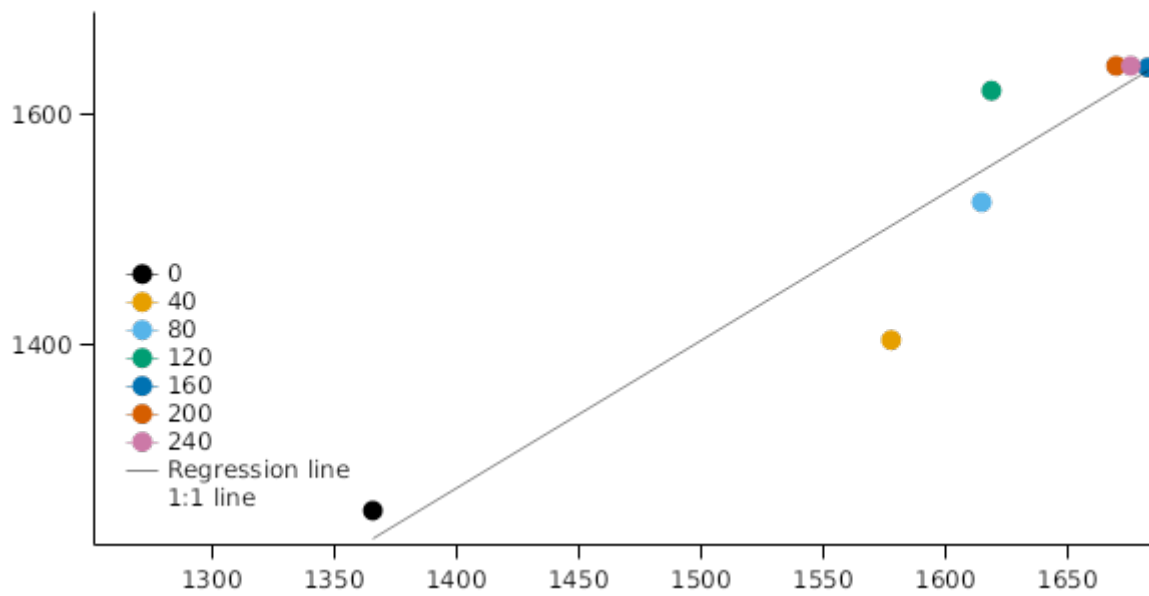


3.6.9.2 Ginninderra1991

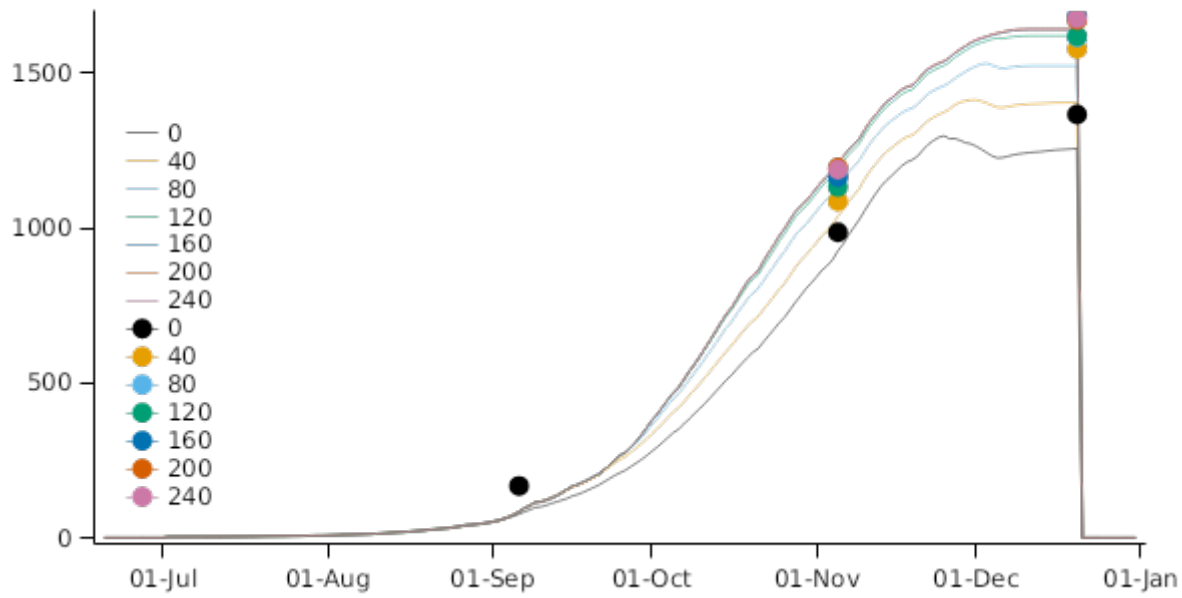
Yield



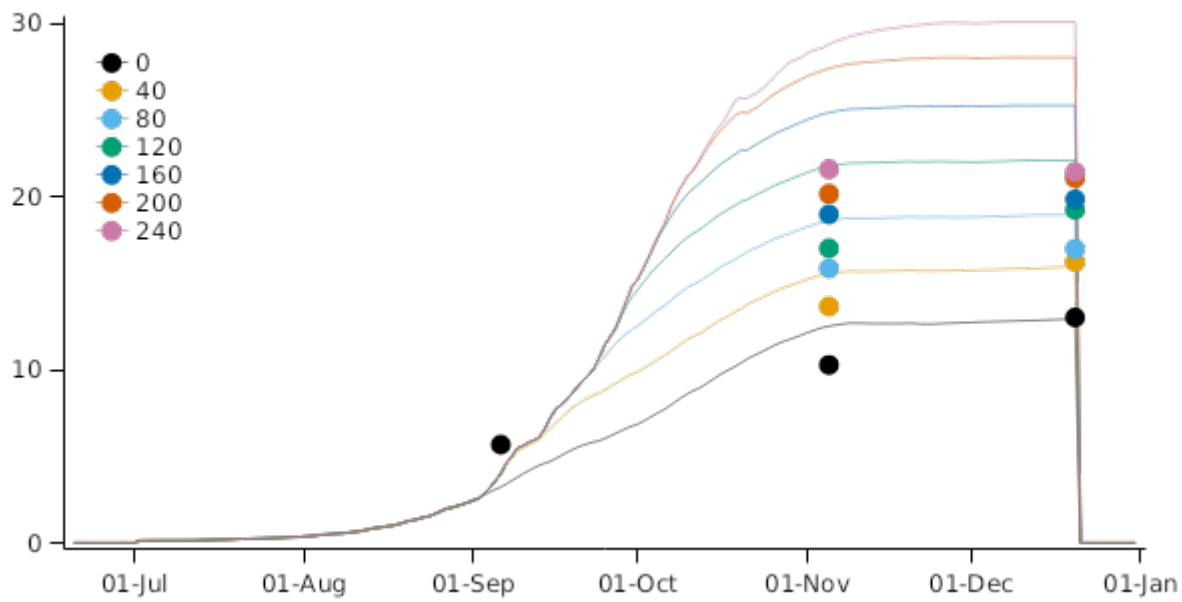
Biomass



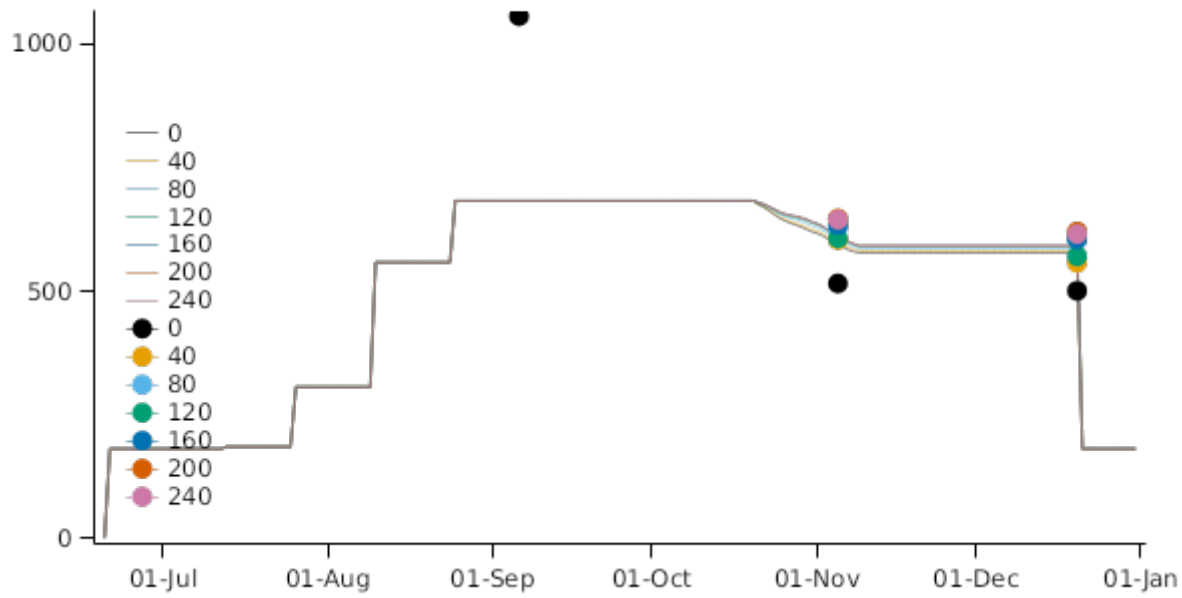
Biomass Timeseries



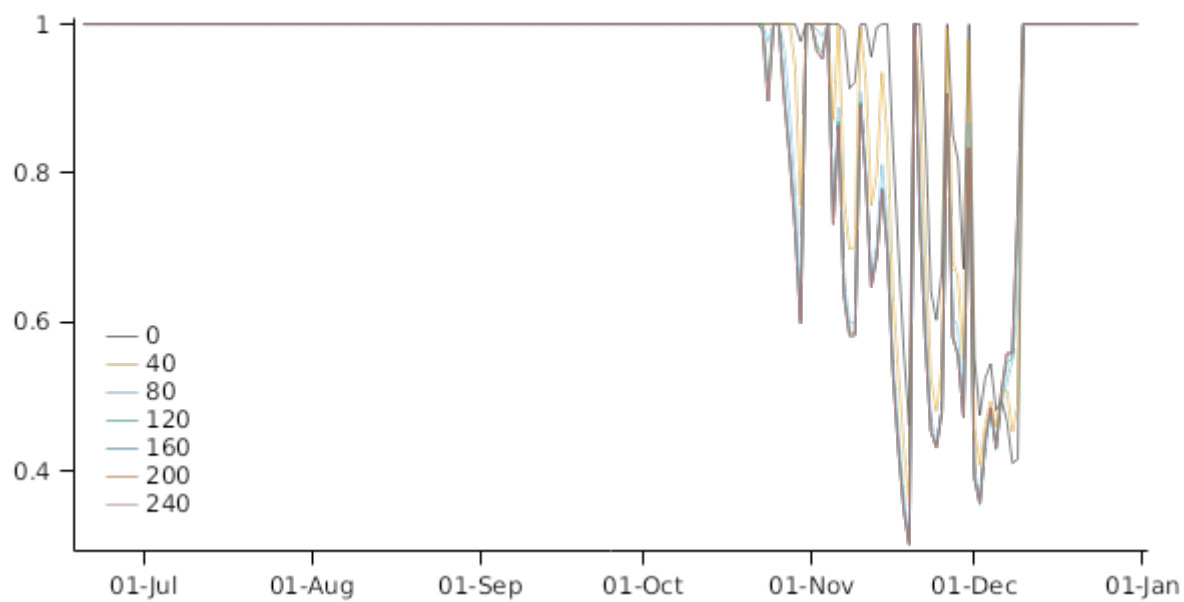
N Uptake Timeseries



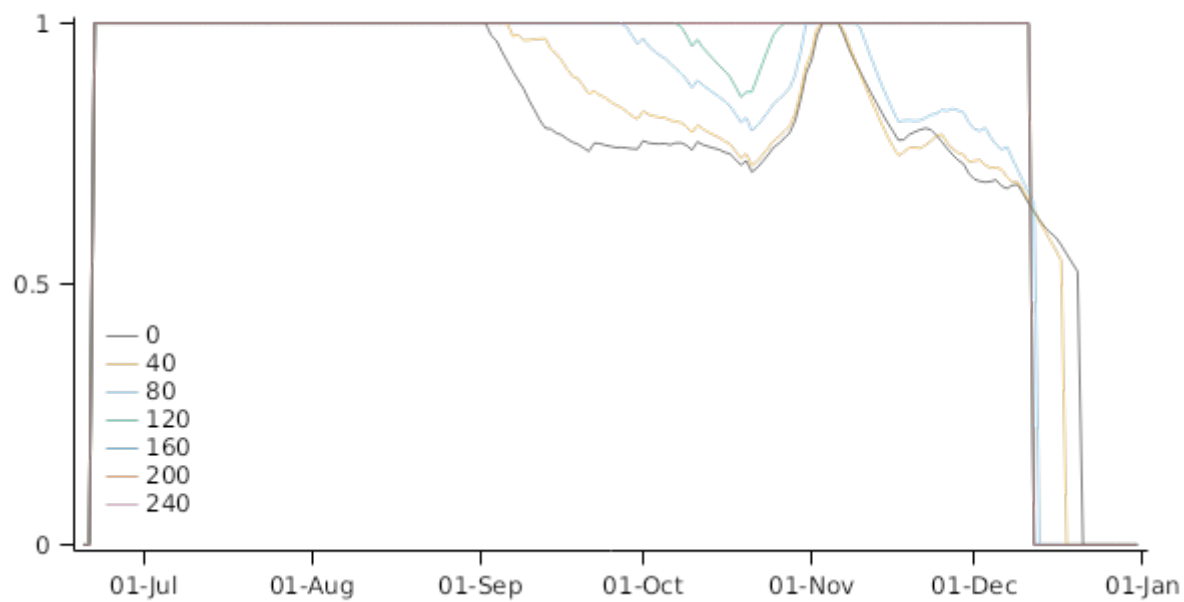
Stem Number Timeseries



Water Stress



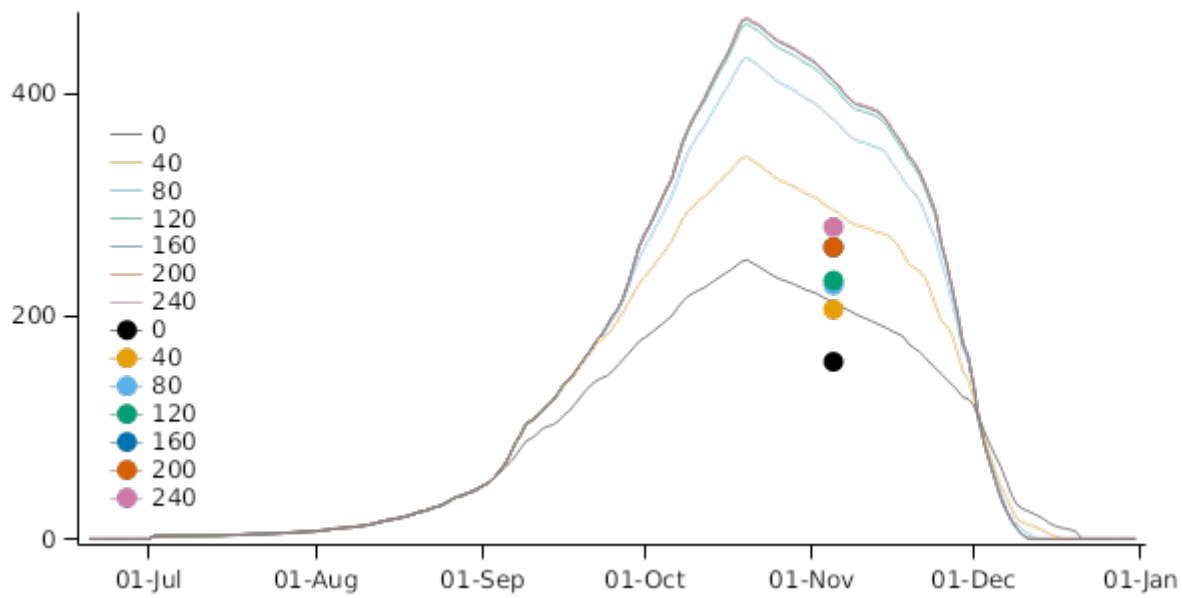
N Stress



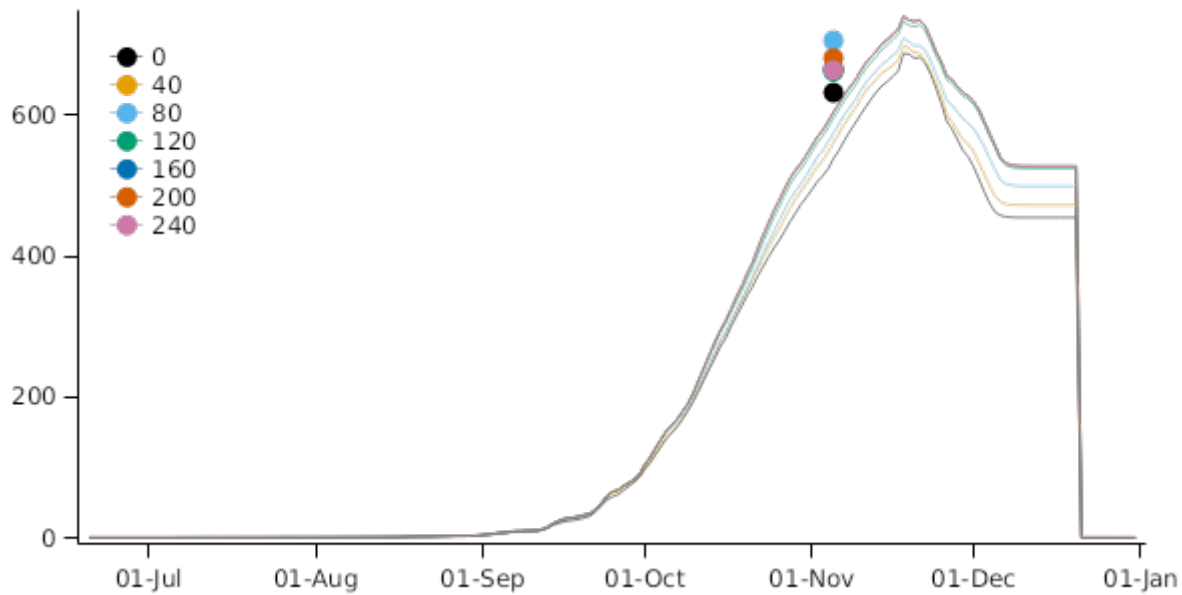
ET

Profile Water

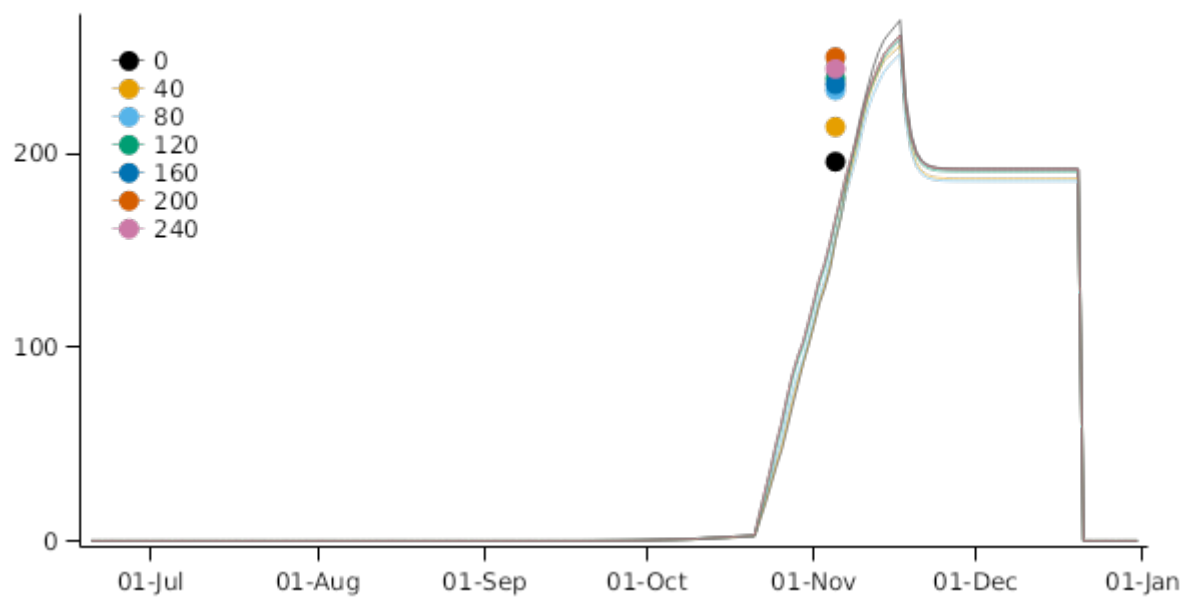
LeafWt Timeseries



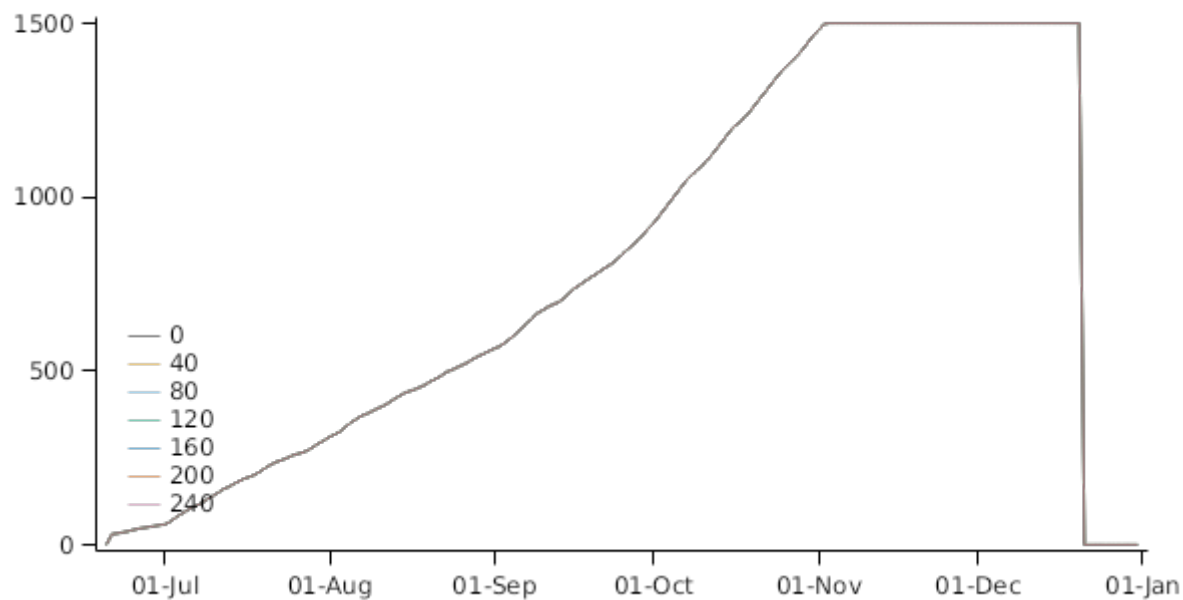
StemWt Timeseries



SpikeWt Timeseries



RootDepth



SoilNO3

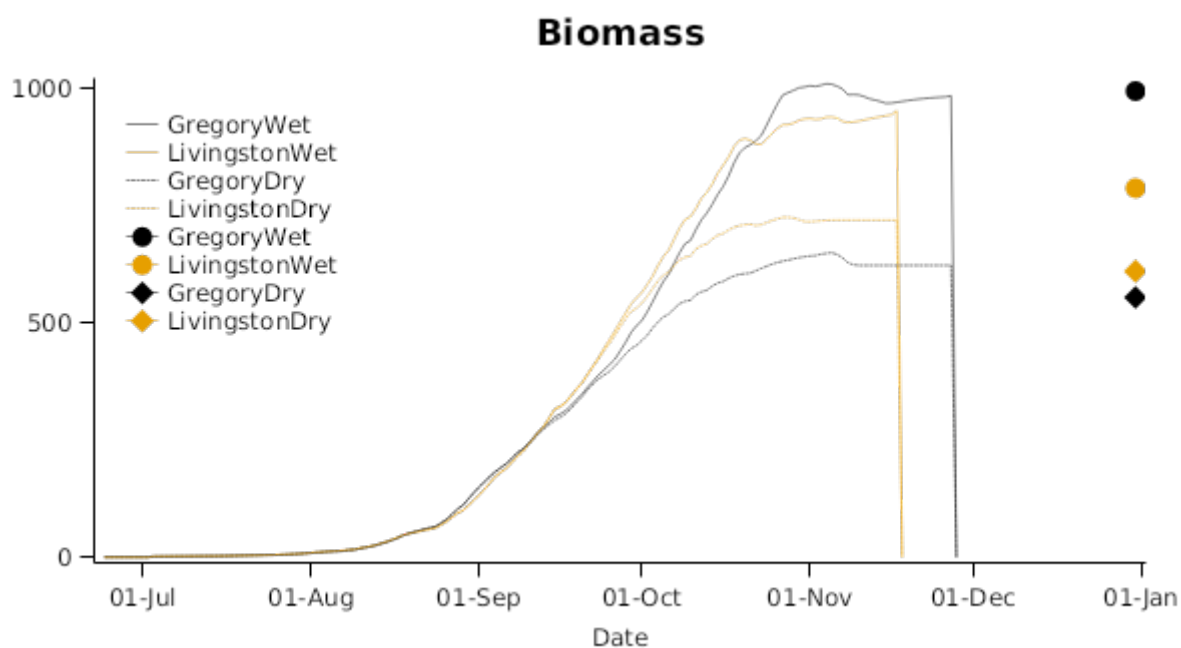
3.6.10 Wagga1314

The dataset of [K.T. Zeleke et al., 2016](#) includes plantings of two wheat varieties (Gregory, Livingston) under two water regimes (dry and irrigated) for 2013 and 2014 at the Wagga Wagga Agricultural Research Institute. Yields ranged from 1.63 t/ha to 6.01 t/ha.

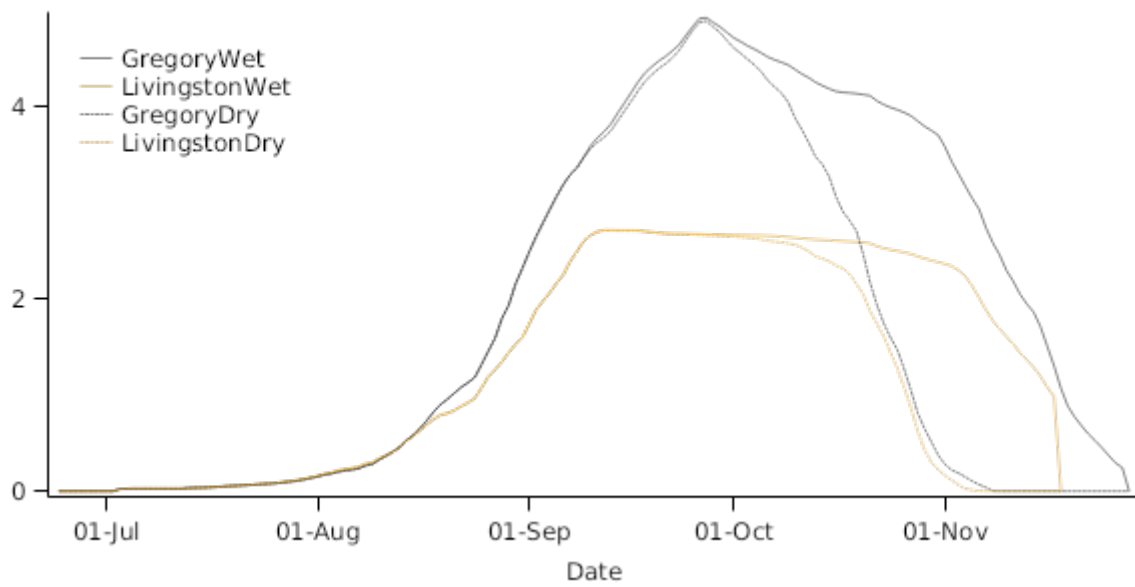
List of experiments.

Experiment Name	Design (Number of Treatments)
Wagga2013	Cv x Water (4)
Wagga2014	Cv x Water (4)

3.6.10.1 Wagga2013

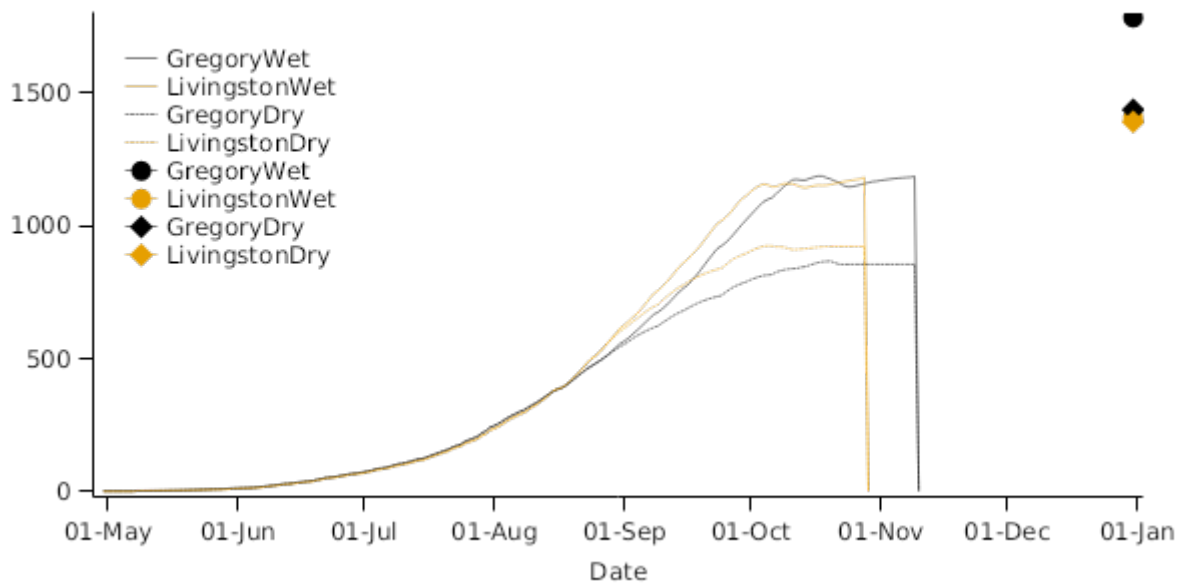


LeafAreaIndex

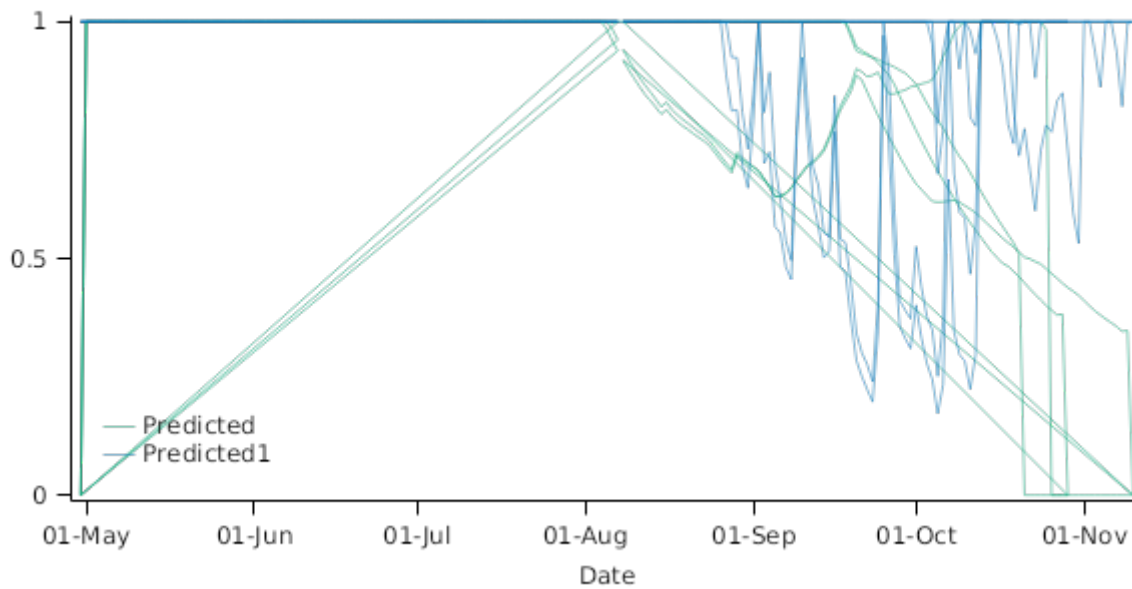


3.6.10.2 Wagga2014

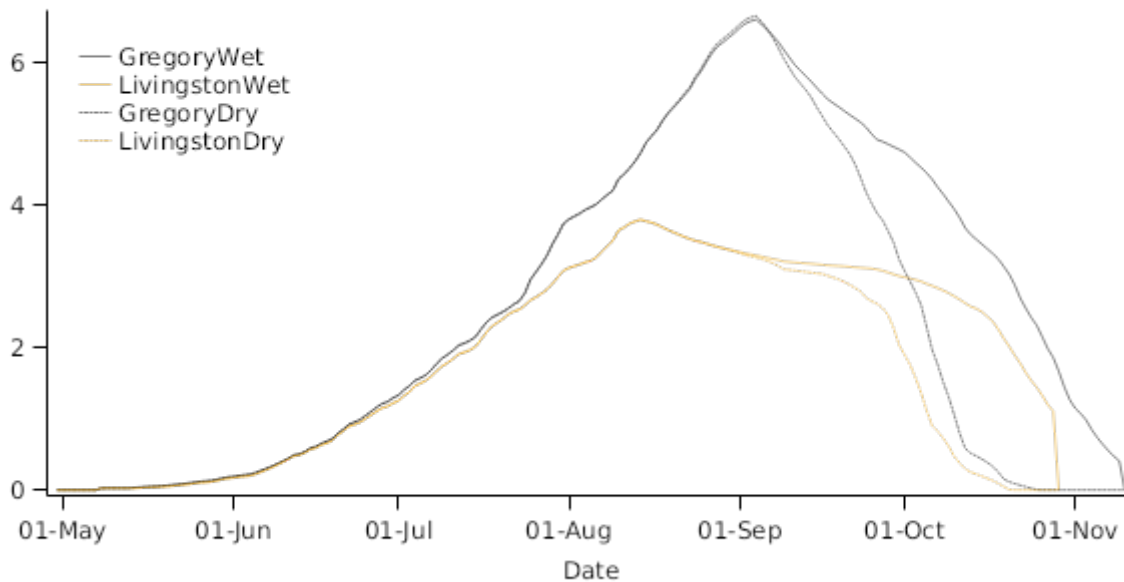
Biomass



Stress



LeafAreaIndex



3.6.11 YarrabahCreek

This trial was conducted on a Vertosol soil on the Liverpool Plains, central-eastern Australia in 2001. Hybrid Mercury was sown on 19th of June and biomass, leaf area, phenology, soil water (Neutron Moisture Meter) and water use (Bowen Ratio method) were monitored. More information can be found in [Young et al., 2008](#).

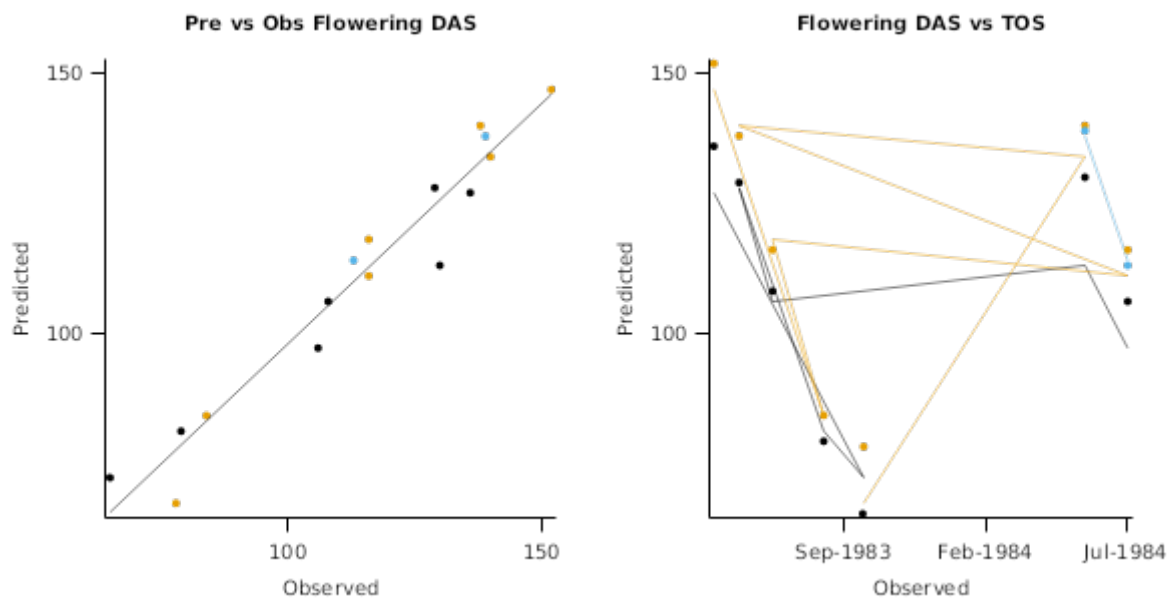
YarrabahCreek

3.6.12 Griffith

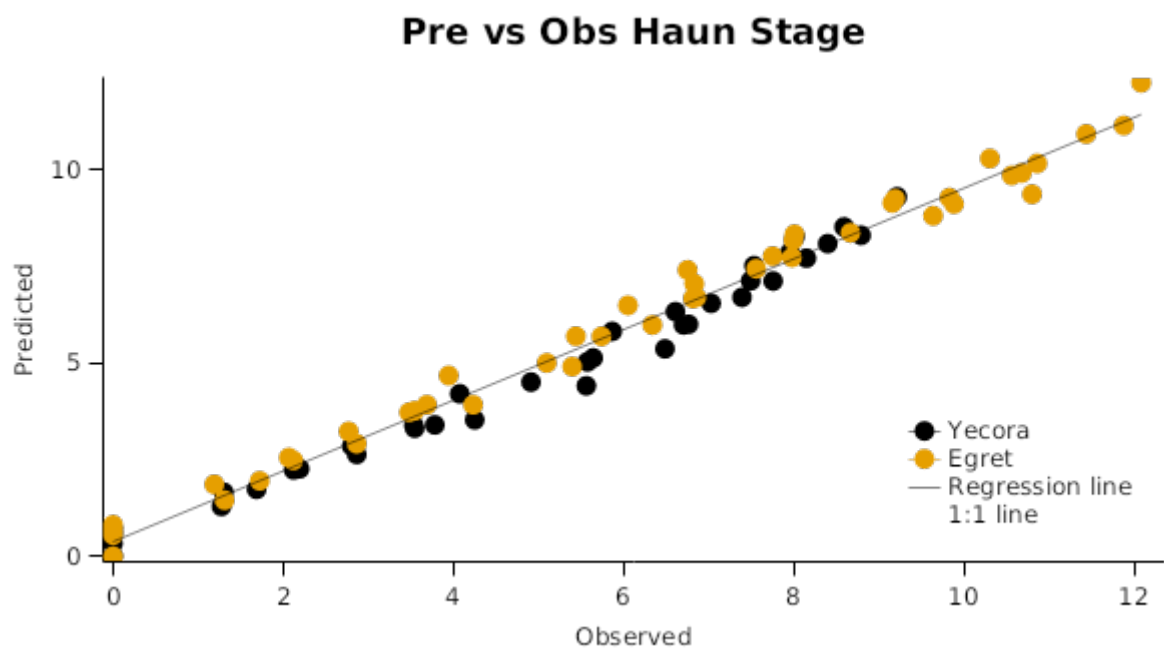
This dataset from [Stapper et al., 0](#) includes observed phenological data for range of cultivars, three of which have been used here (Yecora, Egret, Hartog). Planting dates from 1983 and 1984 provide a range of climatic conditions.

List of experiments.

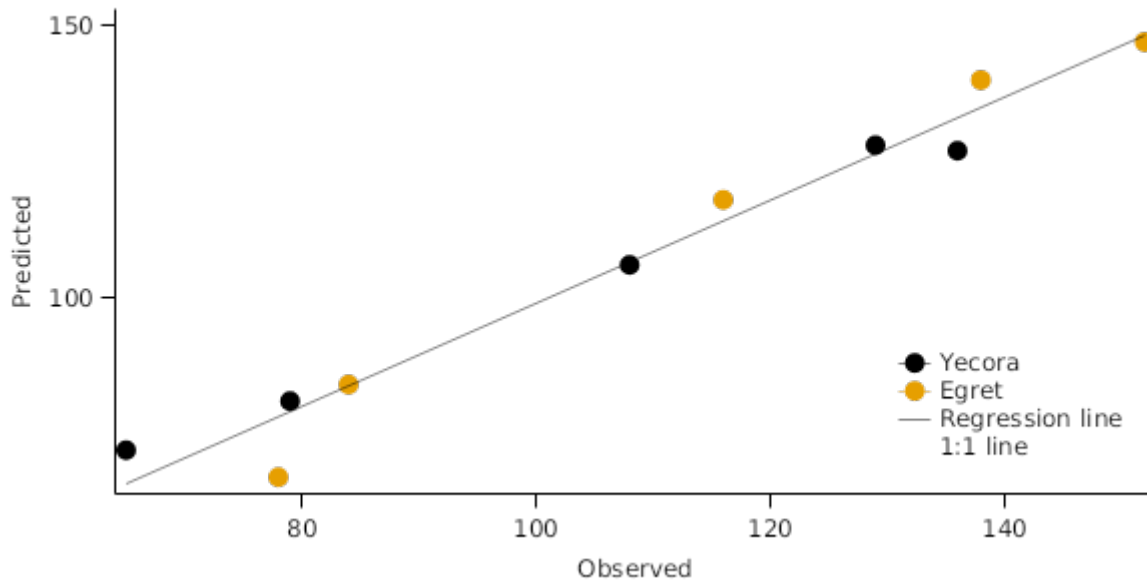
Experiment Name	Design (Number of Treatments)
Griffith1983	Cv x TOS (10)
Griffith1984	Cv x TOS (6)



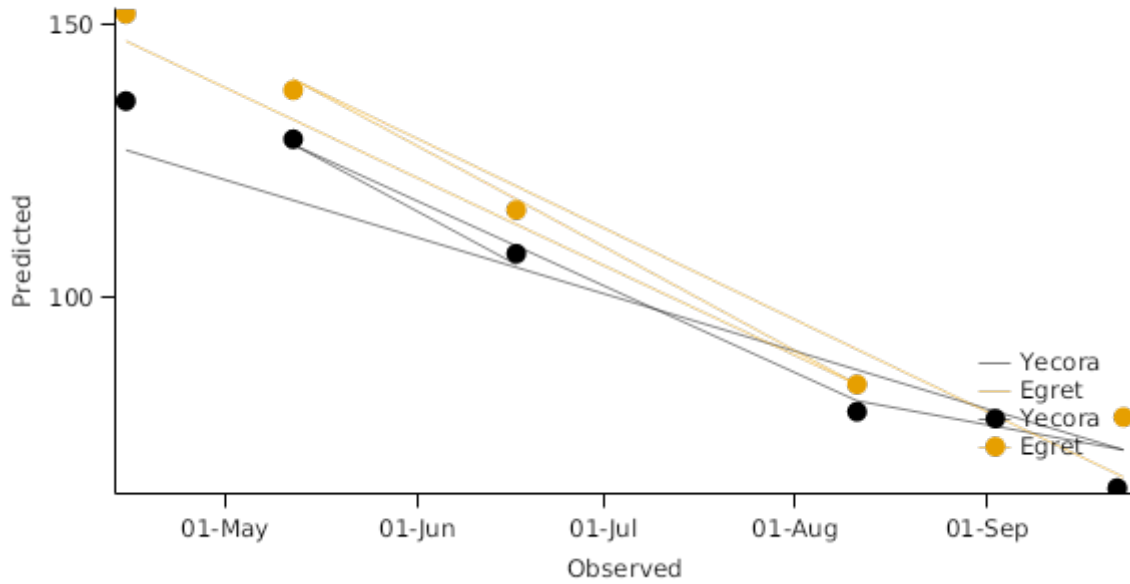
3.6.12.1 Griffith1983



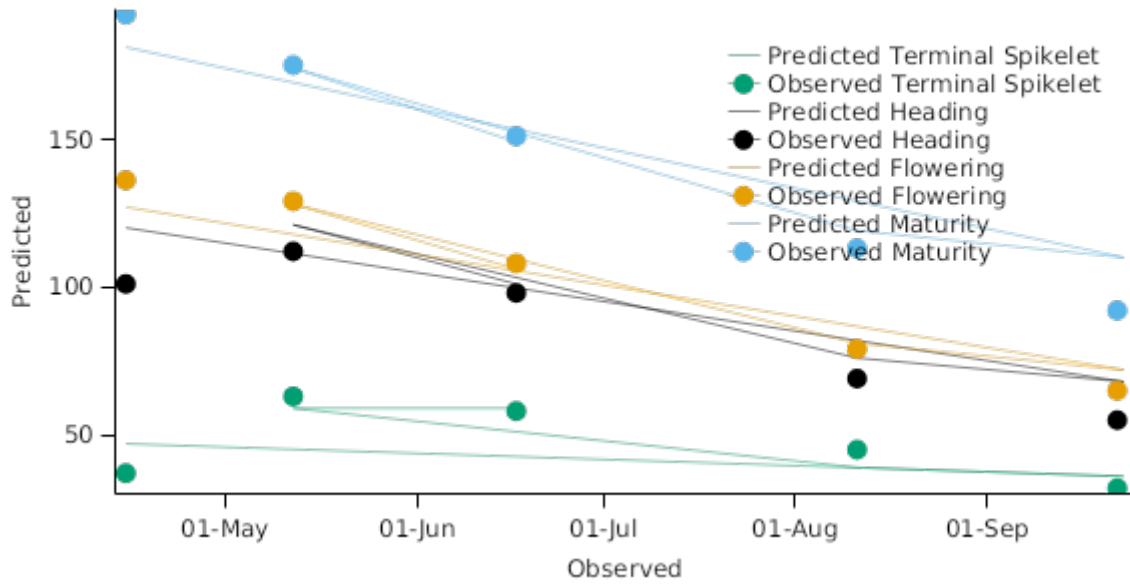
Pre vs Obs Flowering DAS



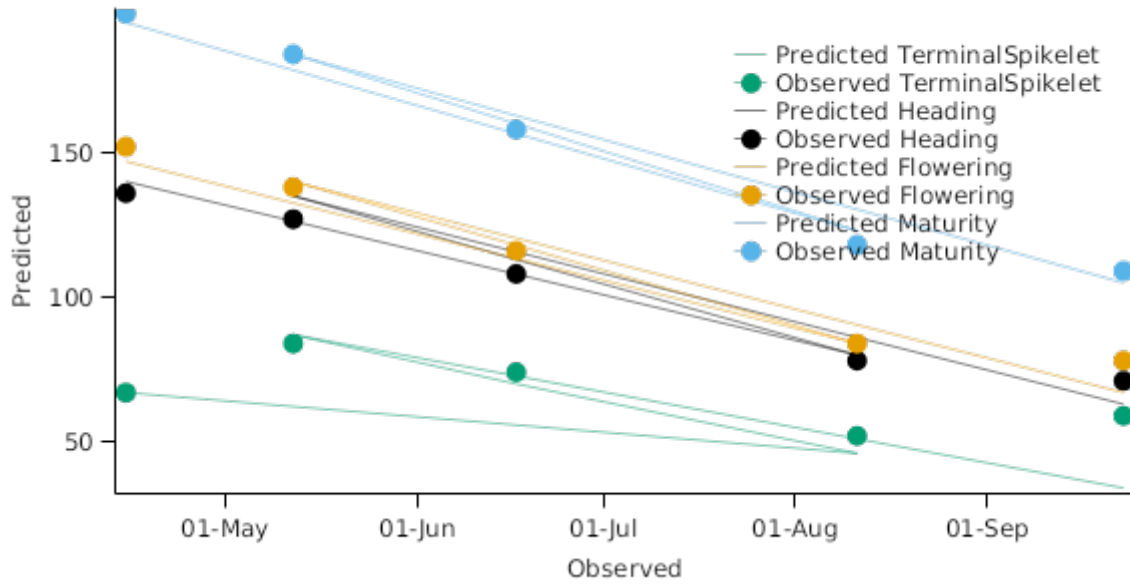
Flowering DAS vs TOS



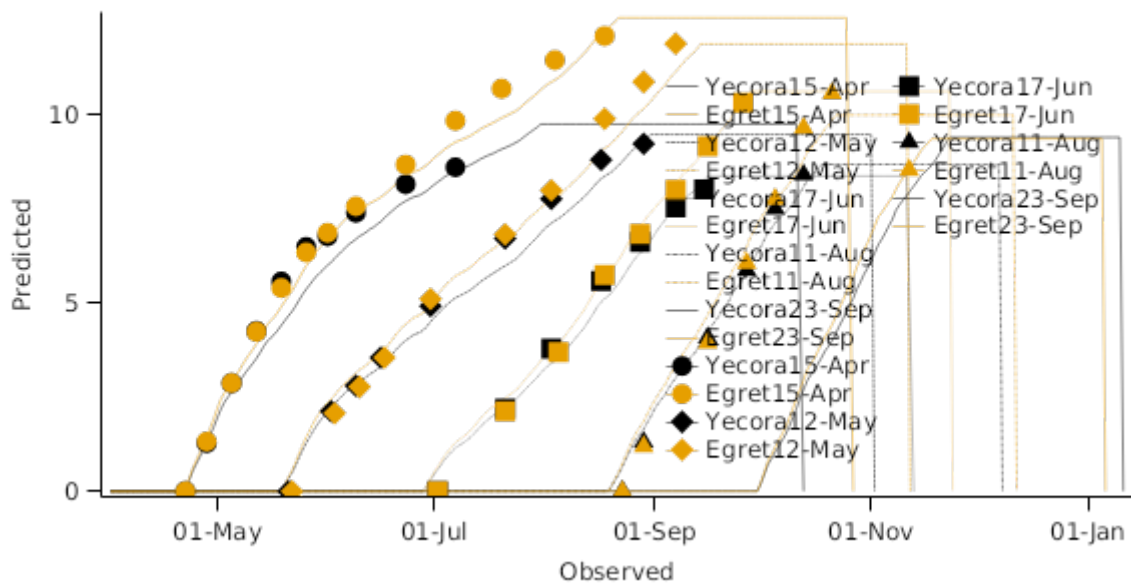
Yecora



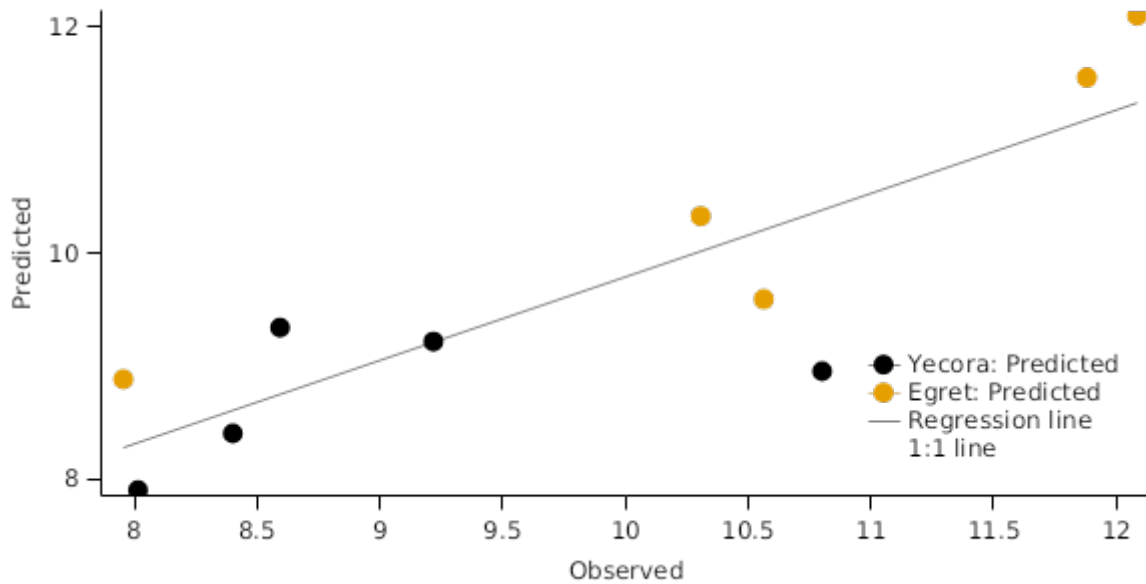
Egret



Leaf Appearance

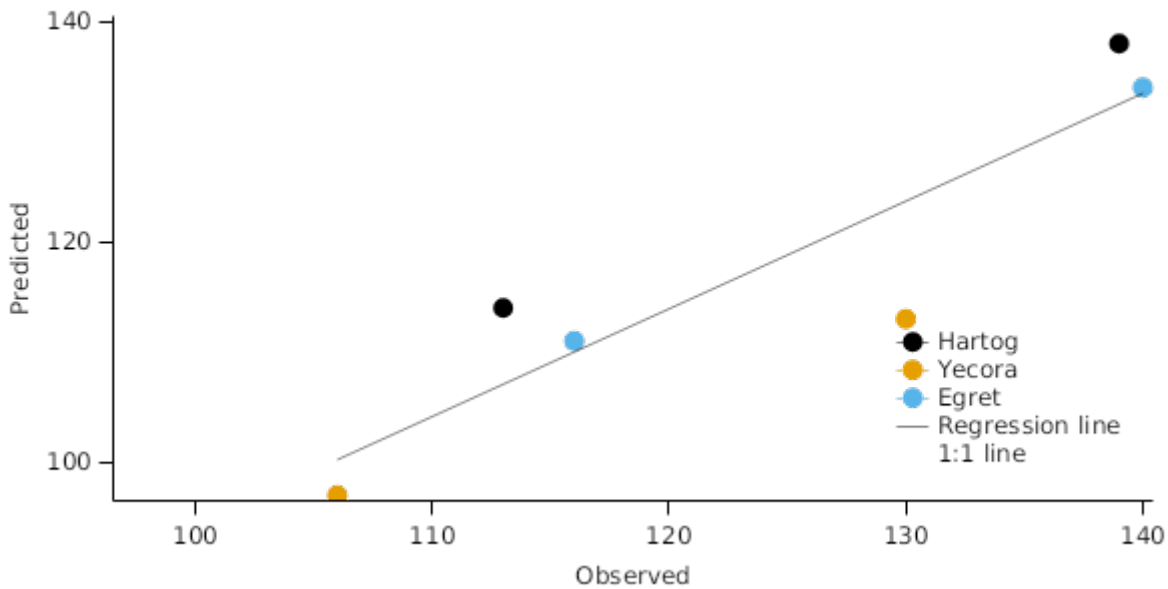


FLN

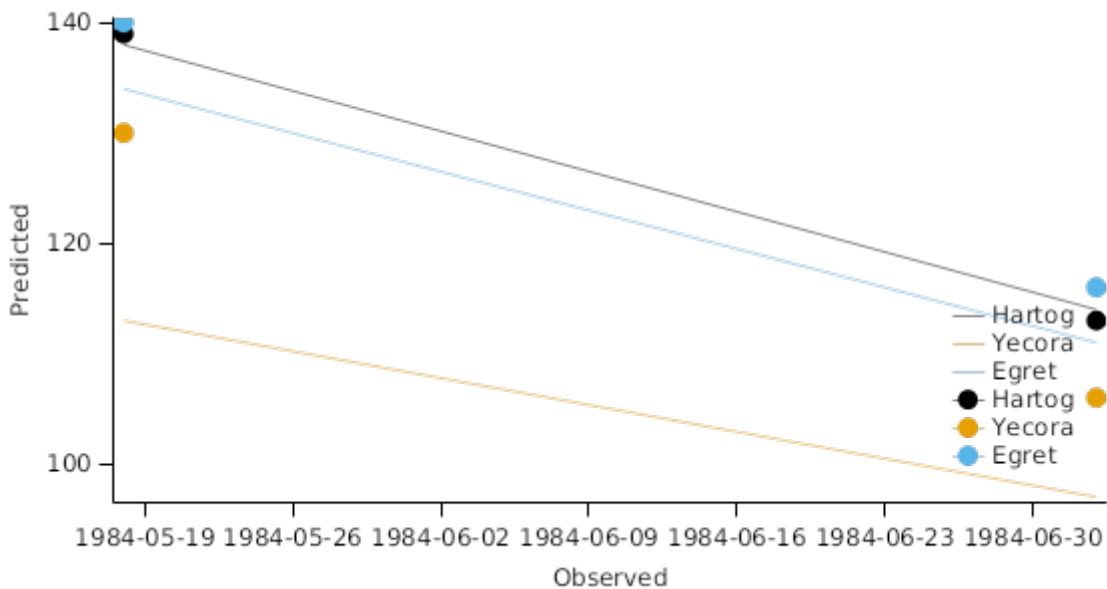


3.6.12.2 Griffith1984

Pre vs Obs Flowering DAS



Flowering DAS vs TOS



3.7 Europe

3.7.1 Belgium

This trial was conducted at Lonze near Gembuloux in Belgium and is described in detail by [Dufranne et al., 2011](#) and [Moureaux et al., 2008](#). The trial was run to measure carbon flux from wheat crops using eddy covariance but sufficient crop information was collected to make it suitable as a model validation dataset also. Crops of wheat (cultivars 'Dekan', 'Rosario', 'Ararat' for the three respective sowing dates) were sown on 14/10/2004, 13/10/2004 and 13/11/2004. Standard management practices for winter wheat in this area were followed. Dates for the timing of key phenological events were used to determine the developmental coefficients for each of the cultivars.

Lonze04

Lonze06

Lonze08

3.8 NorthAmerica

3.8.1 Arizona

These FACE trials were conducted to investigate the effects of atmospheric CO2 concentrations and water stress on wheat growth and development [Hanksar_1996_FACE]. It was conducted at Maricopa, Arazona using Free Air Carbon Enrichment to create elevated CO2 treatments:

- 1. Normal CO2 (370 ppm) (that is no longer normal)
- 2. High CO2 (550 ppm)

Irrigation treatmetnts were also applied with:

- 1. High Irrigation (~600 mm)
- 2. Low irrigation (~265 mm)

Crop development, Biomass production and soil moisture were monitored throughout the crops duration.

List of experiments.

Experiment Name	Design (Number of Treatments)
ArizonaFACE92	CO2 x Irr (4)
ArizonaFACE93	CO2 x Irr (4)

3.8.1.1 ArizonaFACE92

This trial was conducted to investigate the effects of atmospheric CO2 concentrations and water stress on wheat growth and development [Hanksar_1996_FACE]. It was conducted at Maricopa, Arazona using Free Air Carbon Enrichment to create elevated CO2 treatments:

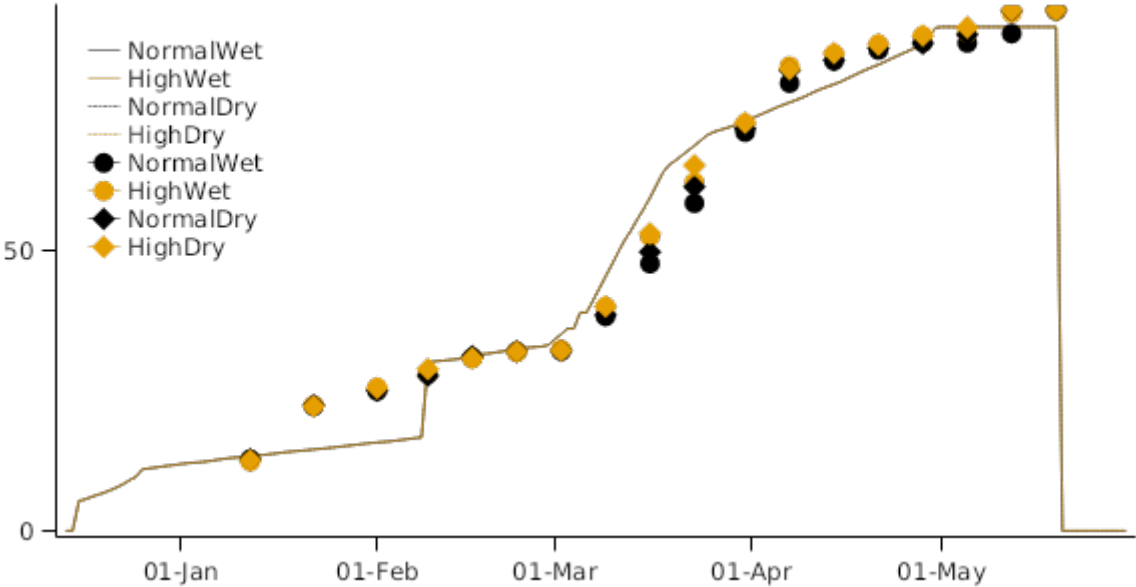
- 1. Normal CO2 (370 ppm) (that is no longer normal)
- 2. High CO2 (550 ppm)

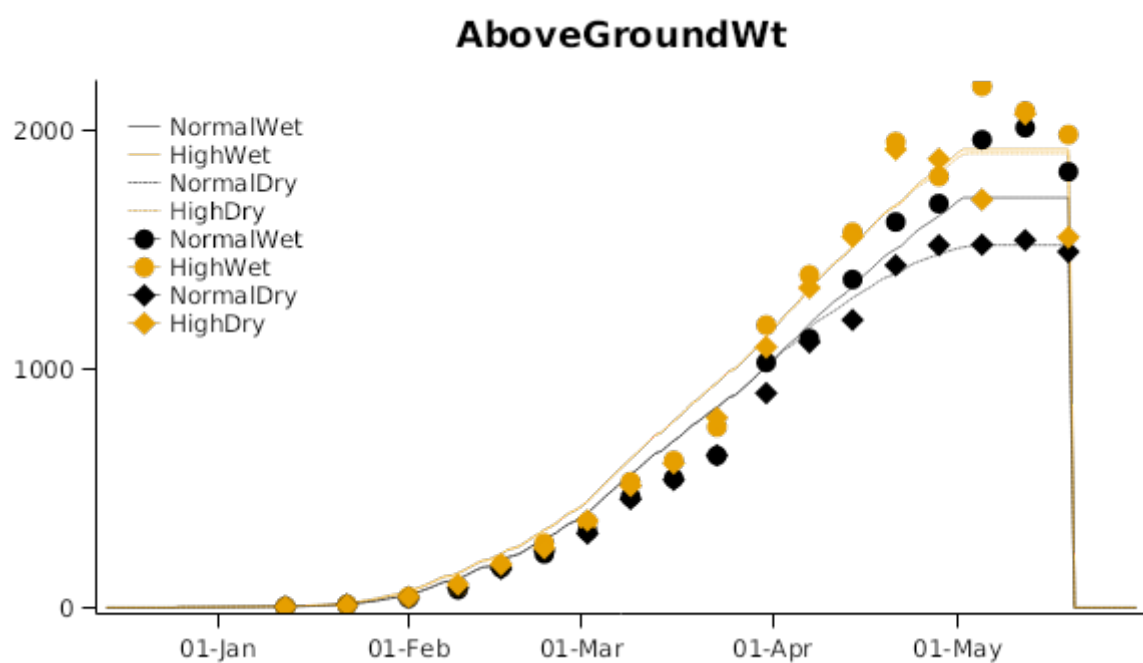
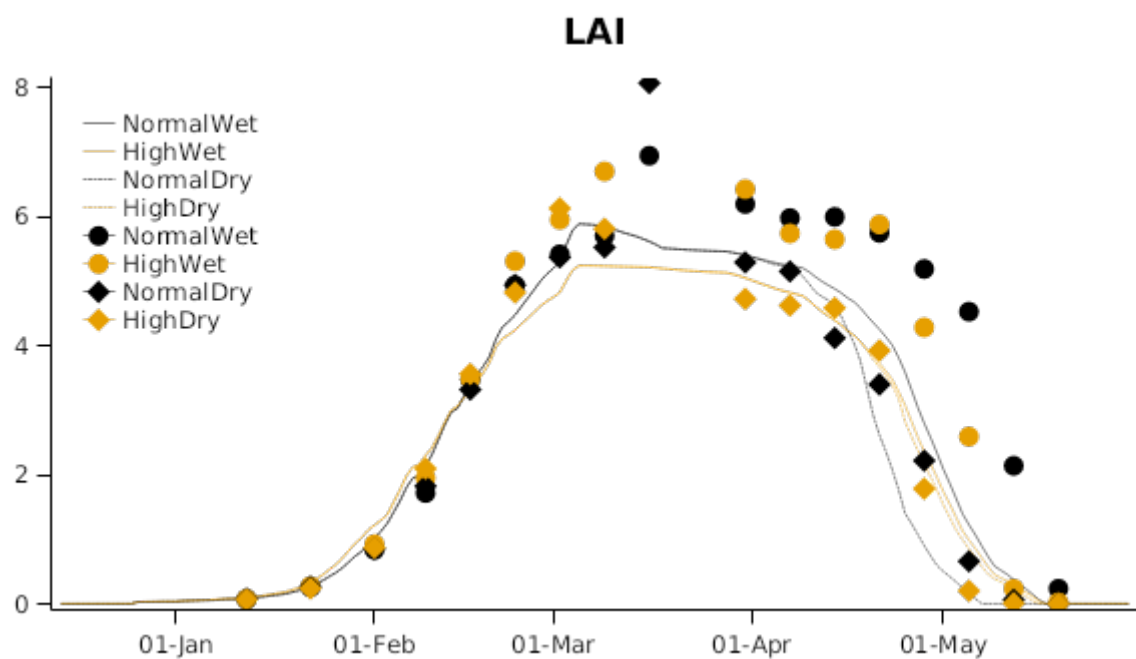
Irrigation treatmetnts were also applied with:

- 1. High Irrigation (~600 mm)
- 2. Low irrigation (~265 mm)

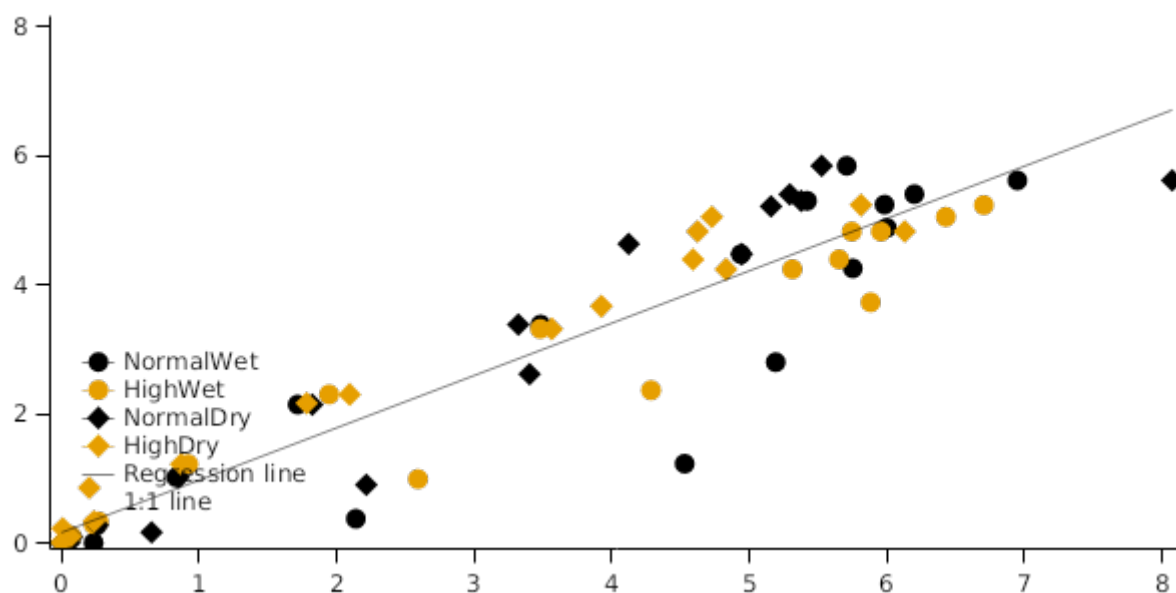
Crop development, Biomass production and soil moisture were monitored throughout the crops duration.

Phenology

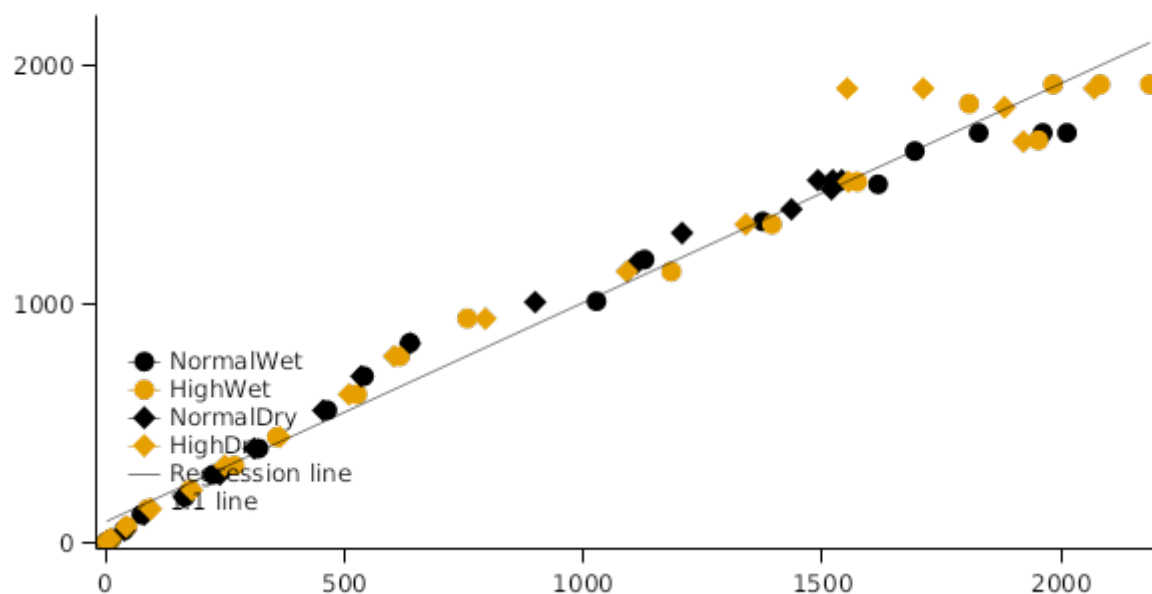




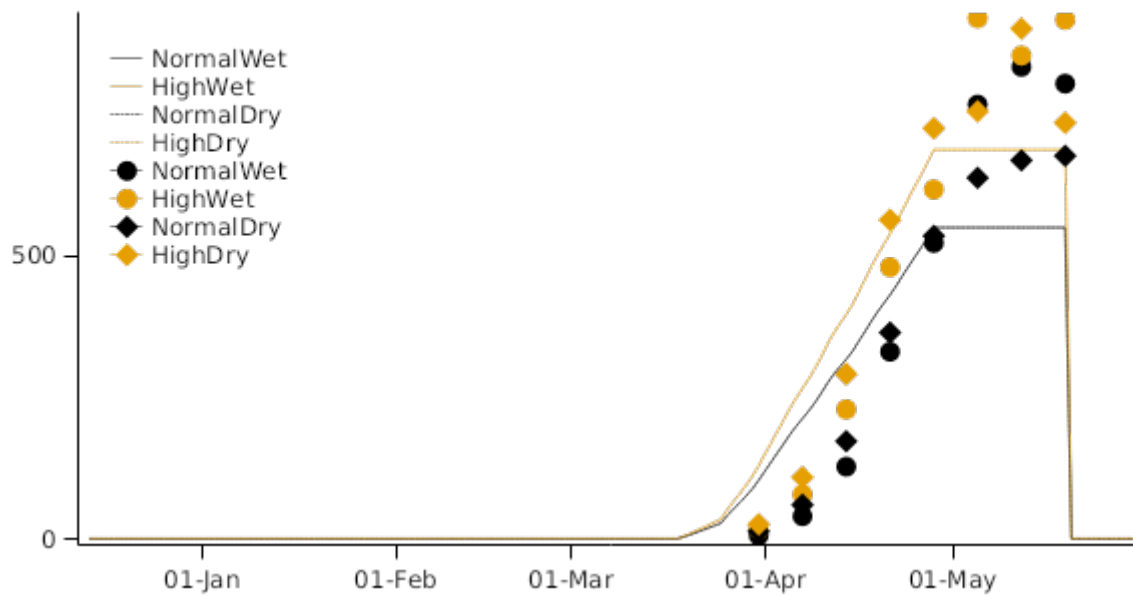
Pre vs Obs LAI



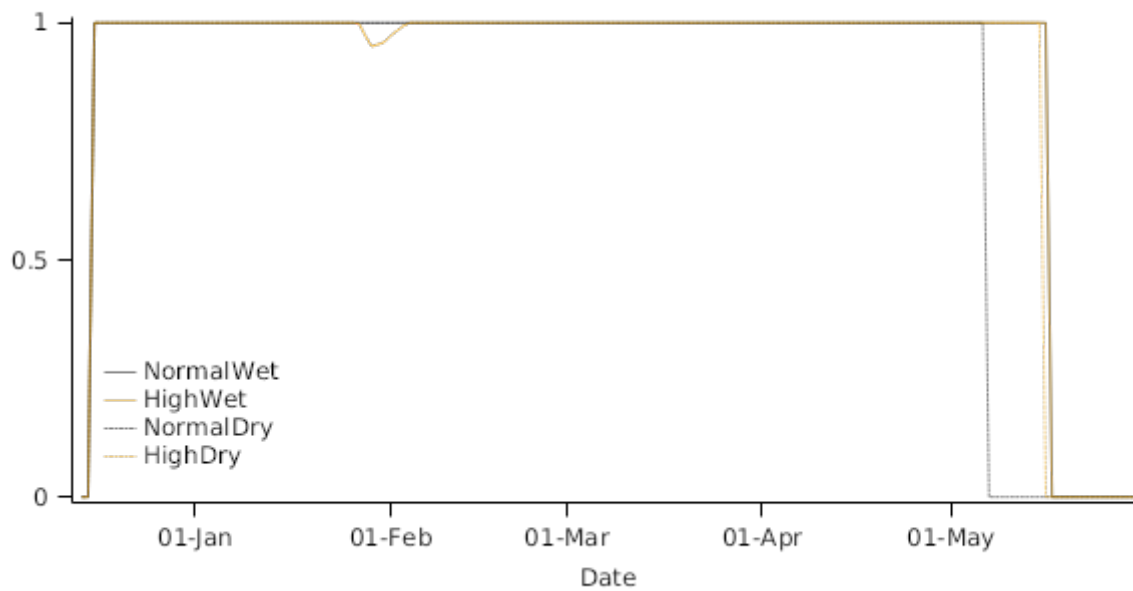
Pre vs Obs AboveGroundWt



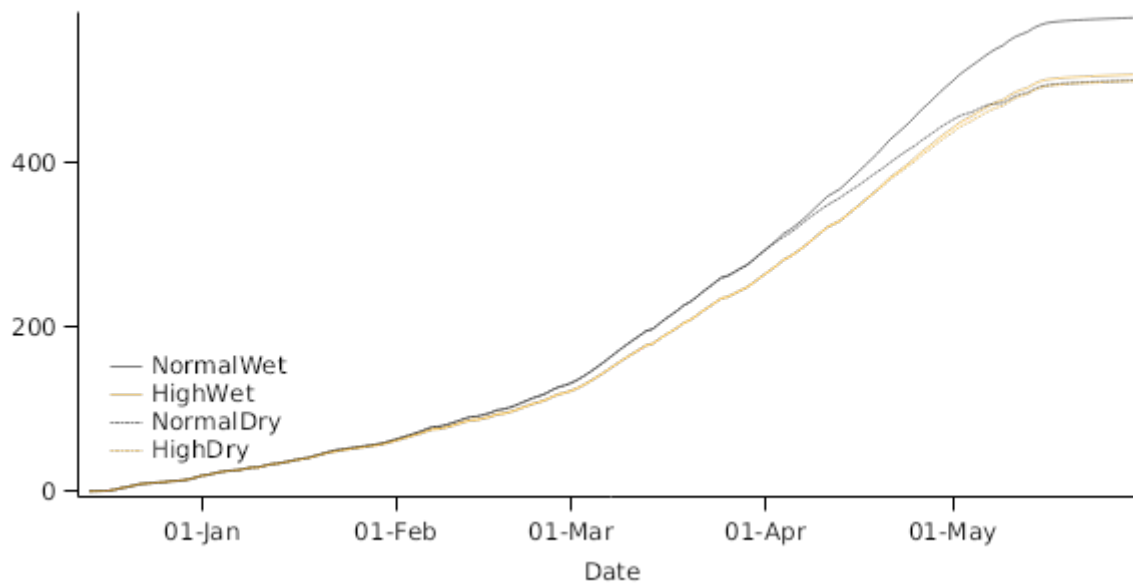
GrainWt



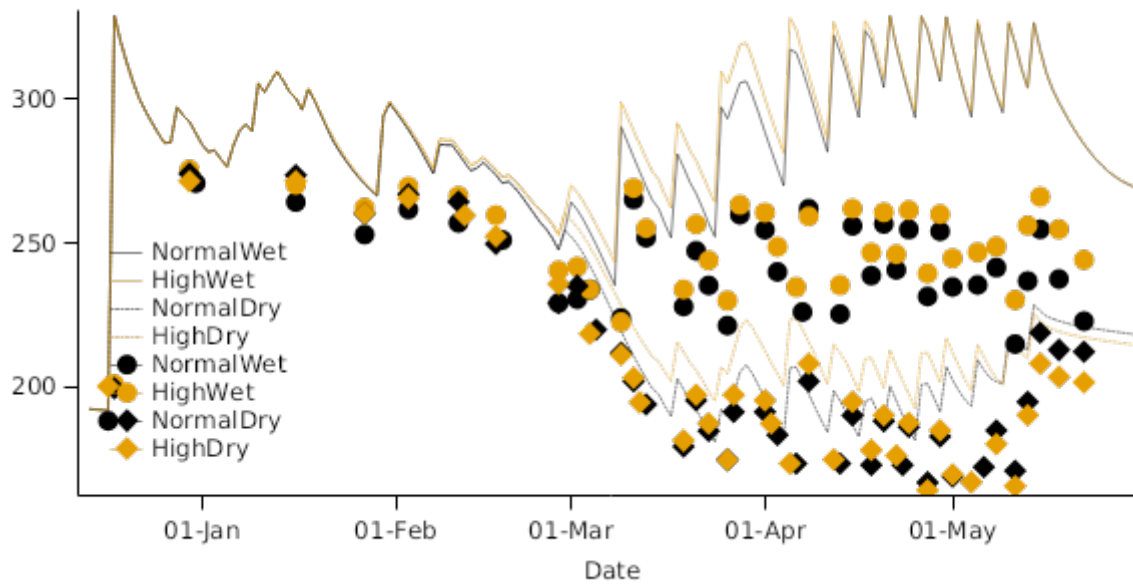
N Stress



ET

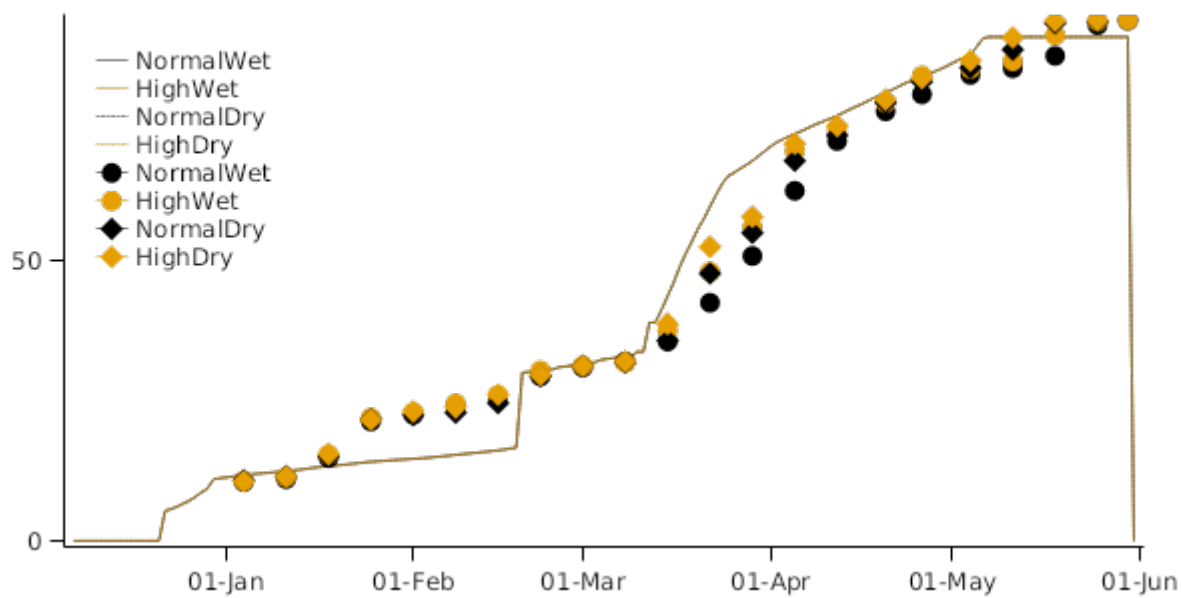


SoilWater

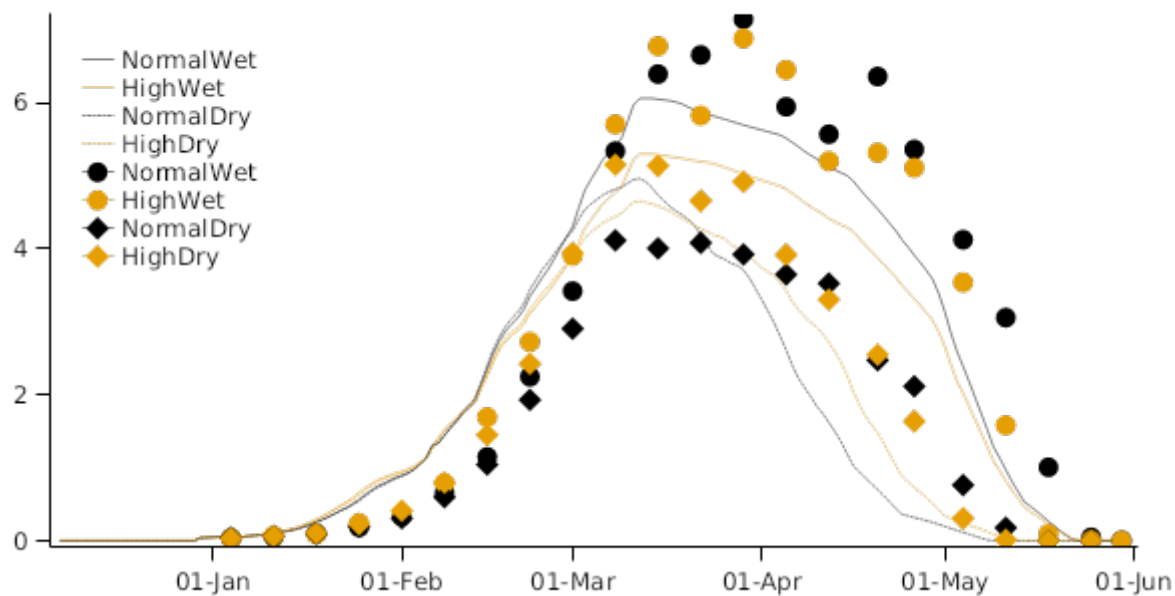


3.8.1.2 ArizonaFACE93

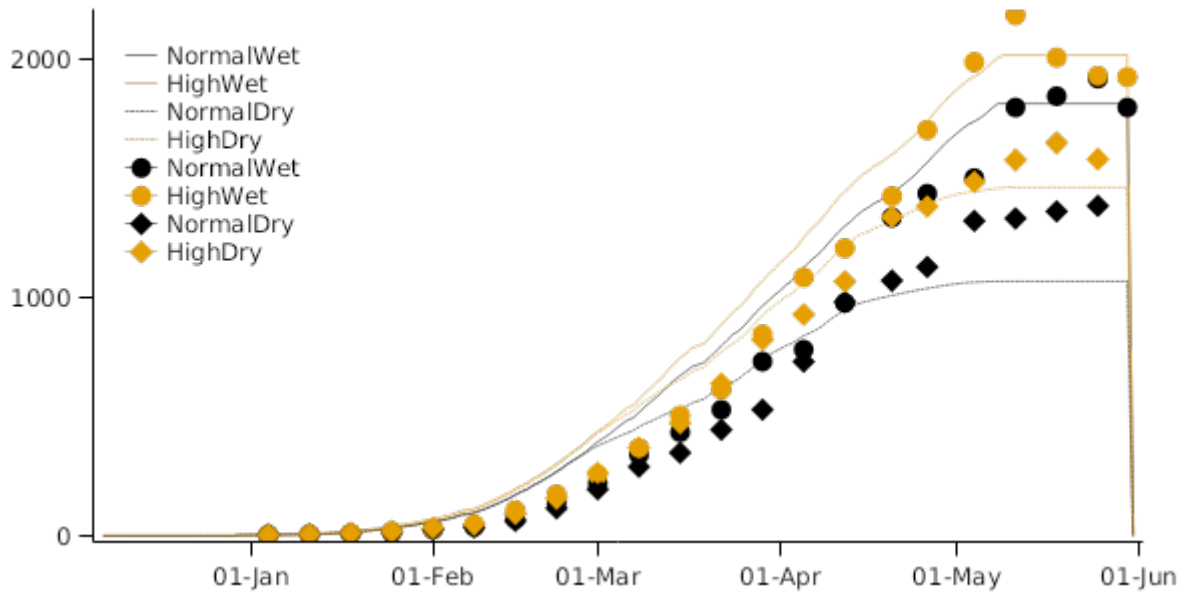
Phenology



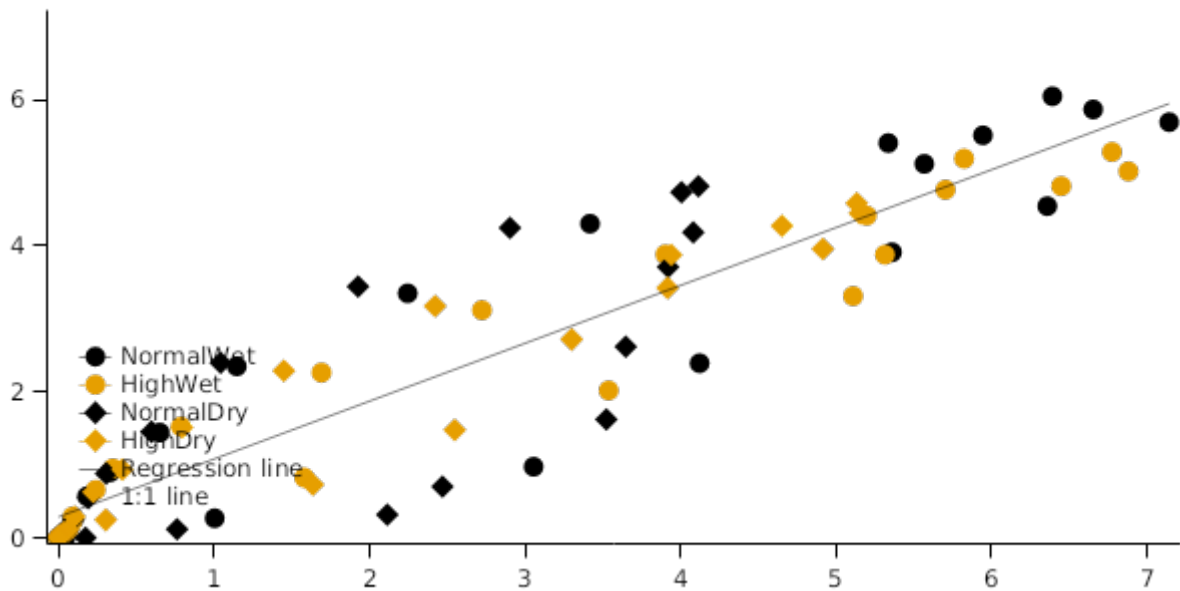
LAI



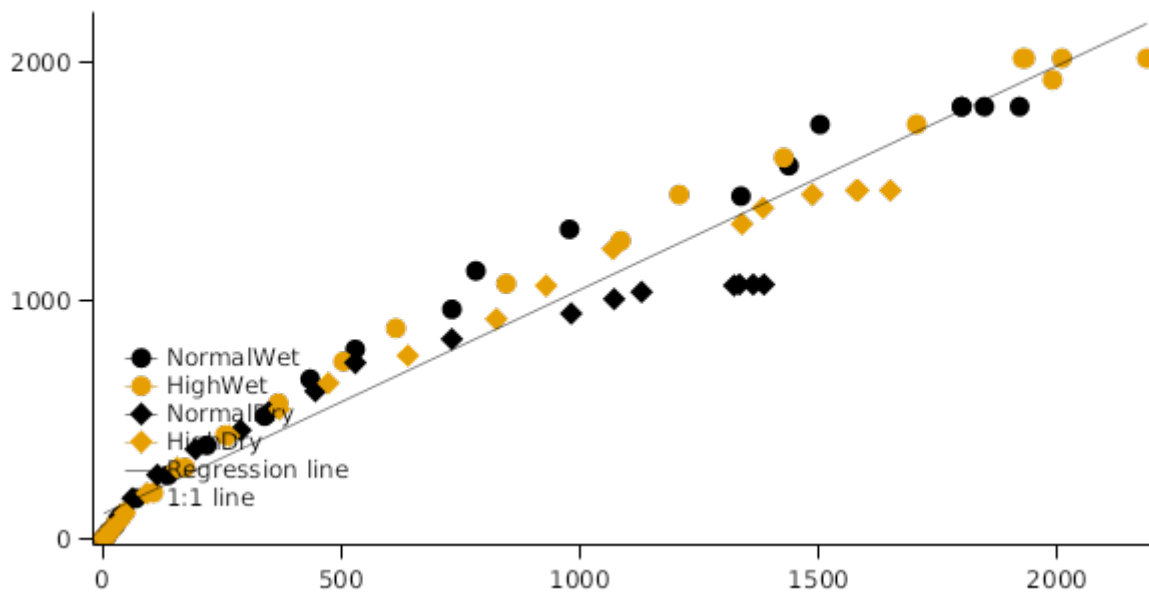
AboveGroundWt



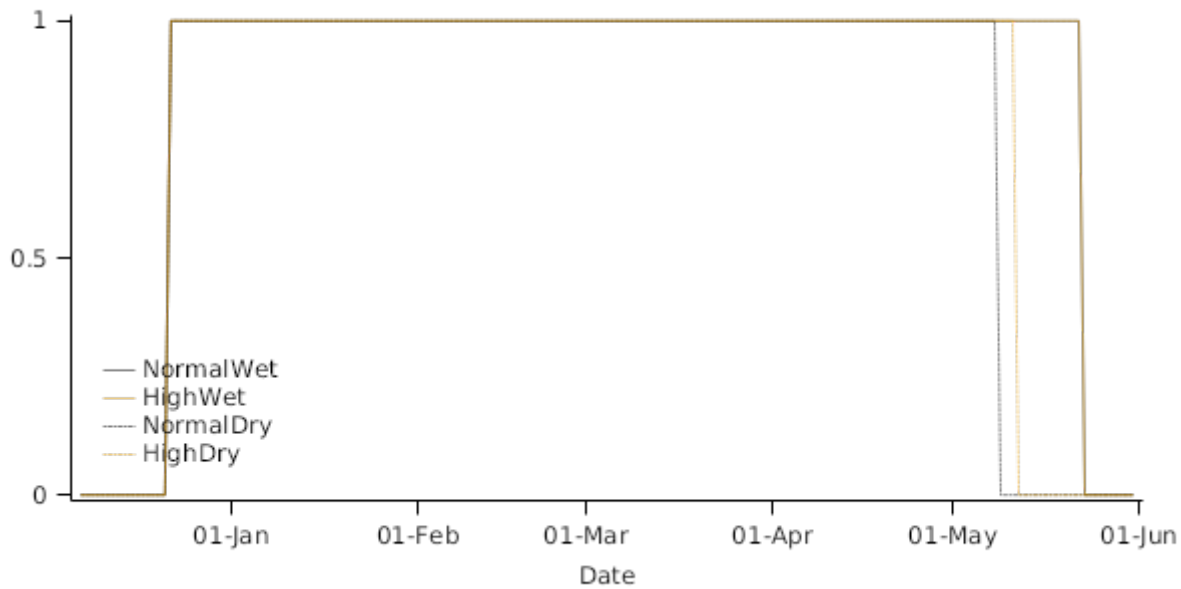
Pre vs Obs LAI



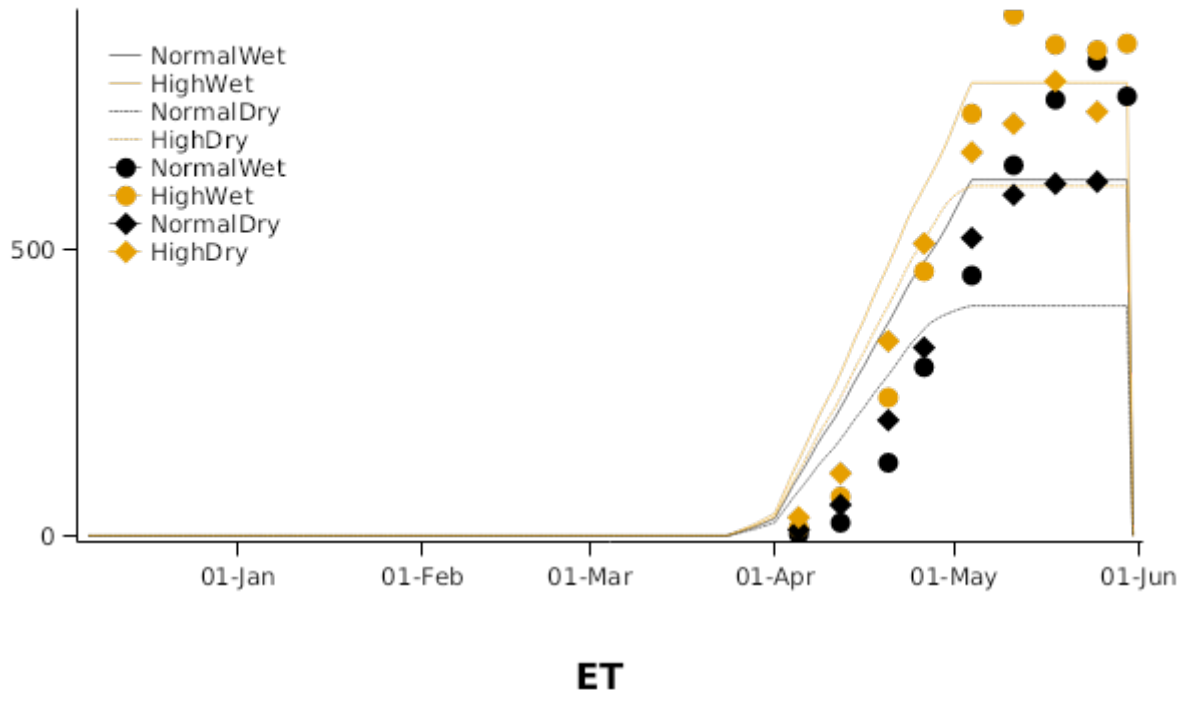
Pre vs Obs AboveGroundWt



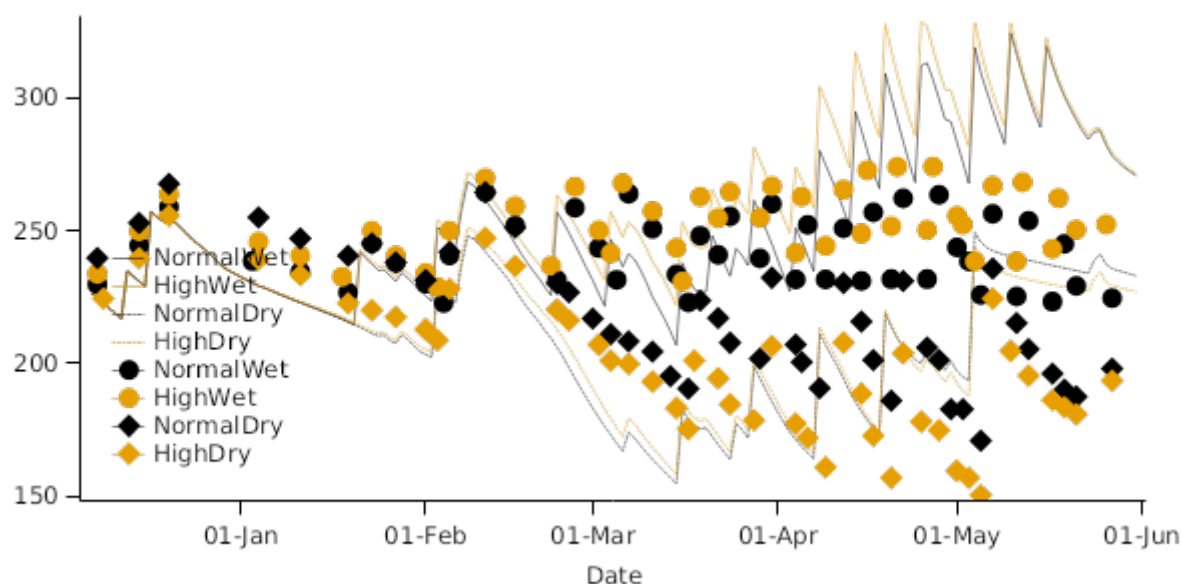
N Stress



GrainWt



SoilWater



3.9 China

3.9.1 ChinaFlux

Yucheng02

Yucheng03

Yucheng04

3.10 Iran

Gorgan05

3.11 Africa

This trial was run in the Jamma district of the Amhara region of the Ethiopia country of the Africa continent and is described in full by [Getu, 2012](#). 'HAR 1685' Wheat was sown in 20 cm row spacing. Different N fertiliser treatments were applied:

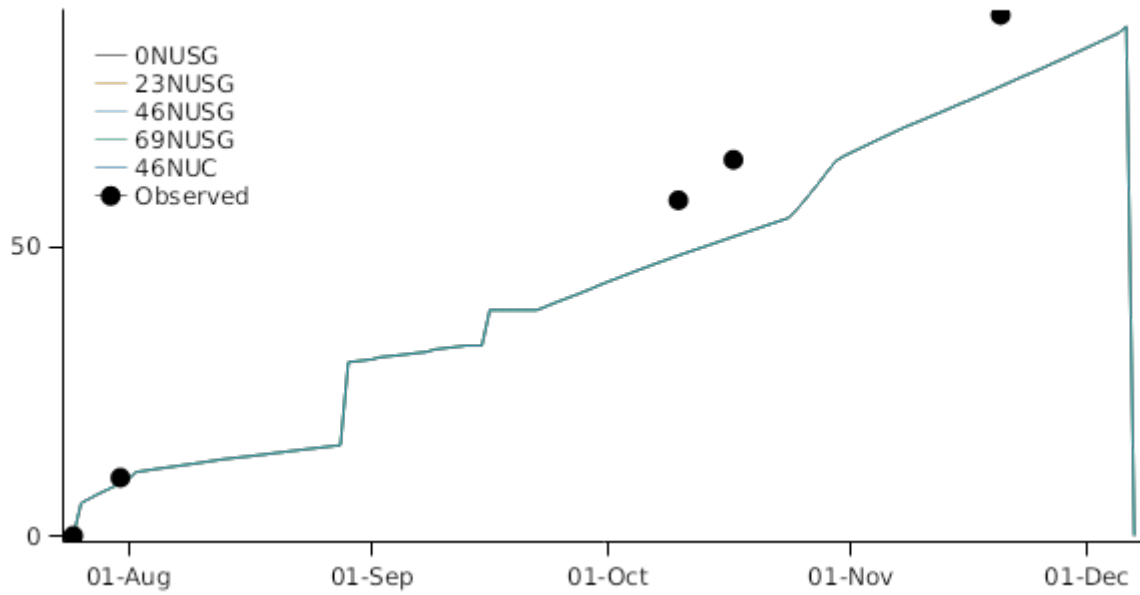
1. 0NUSG = 0 kg N/ha
2. 23NUSG = 23 kg N/ha as Urea Super Granules (a slow release urea product)
3. 46NUSG = 46 kg N/ha as Urea Super Granules
4. 69NUSG = 69 kg N/ha as Urea Super Granules
5. 46NUC = 46 kg N/ha as Uncoated Urea

List of experiments.

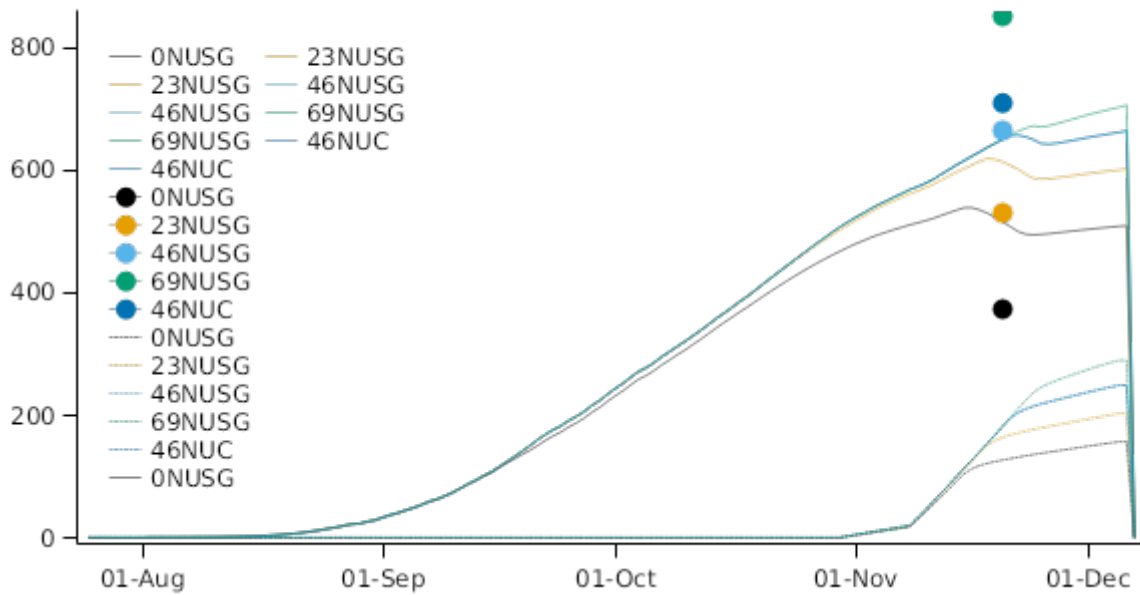
Experiment Name	Design (Number of Treatments)
Jamma	NRate (5)

3.11.1 Jamma

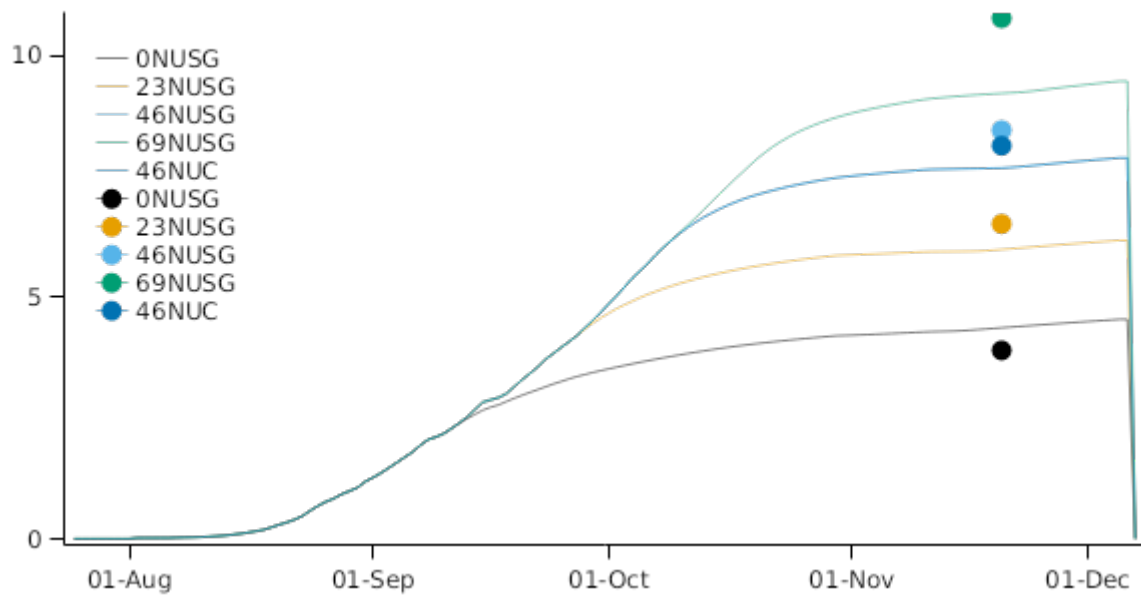
Phenology



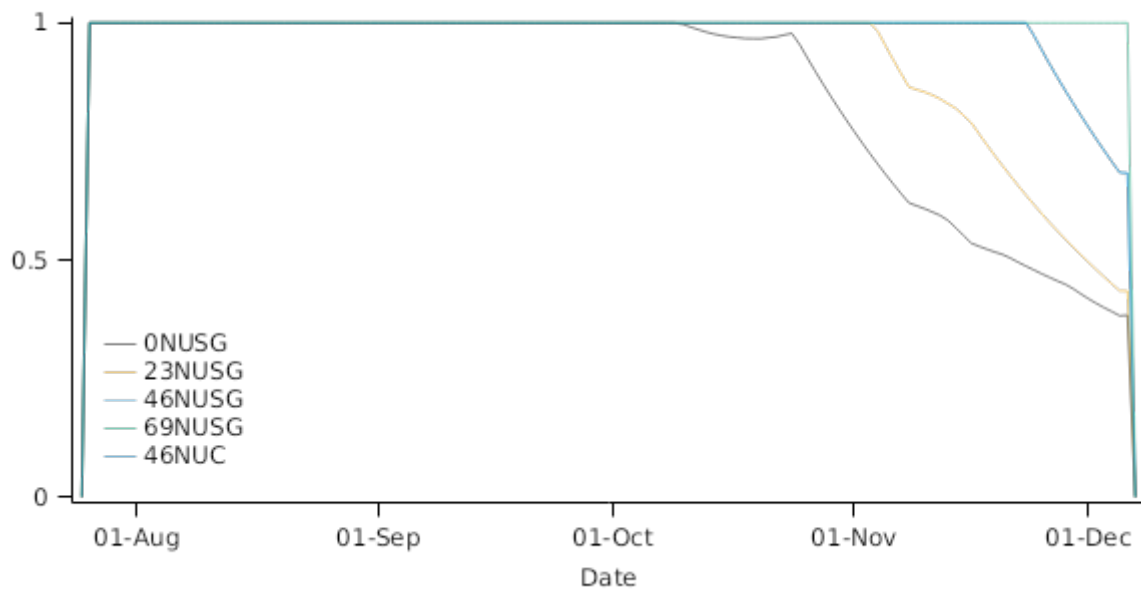
Biomass

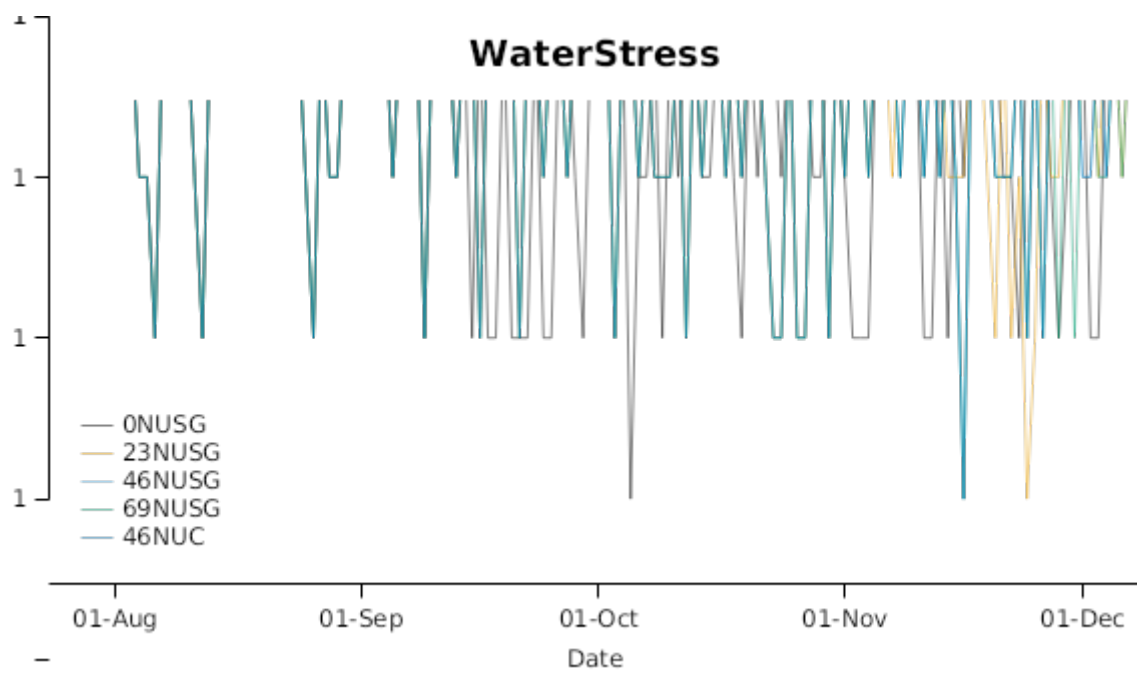


BiomassN



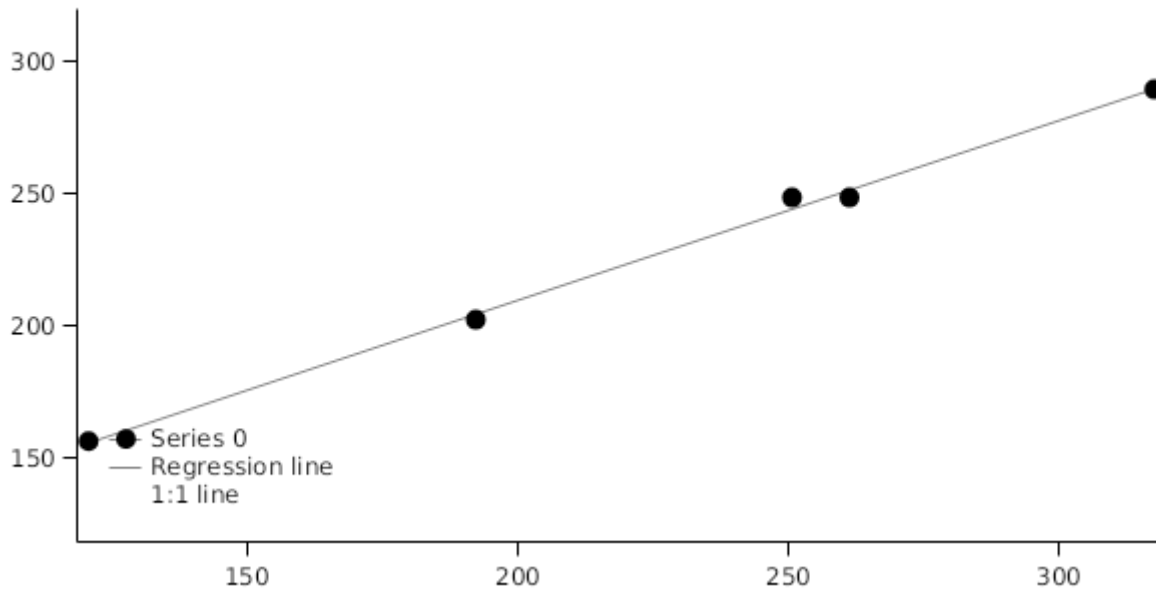
NStress



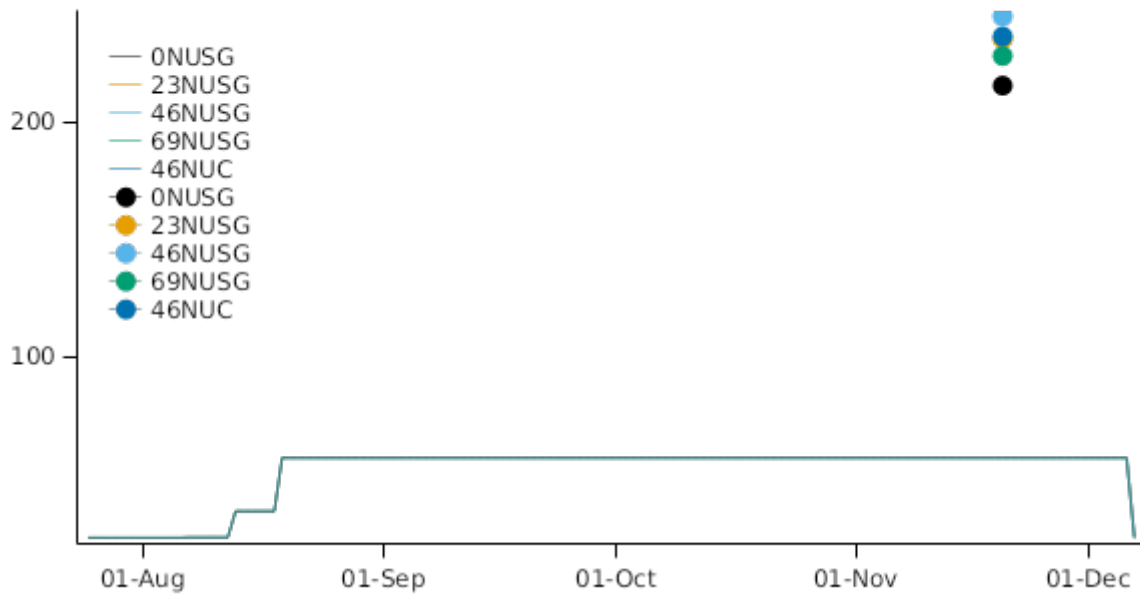


SoilNO3

Harvest Yield



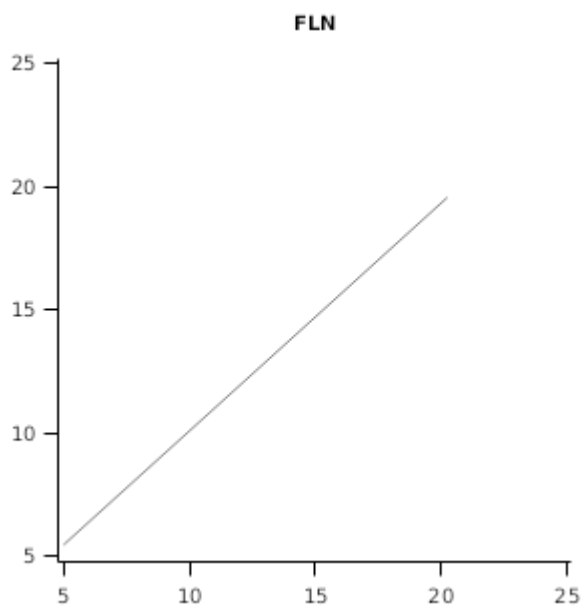
Stems



3.12 ControlledEnvironment

List of experiments.

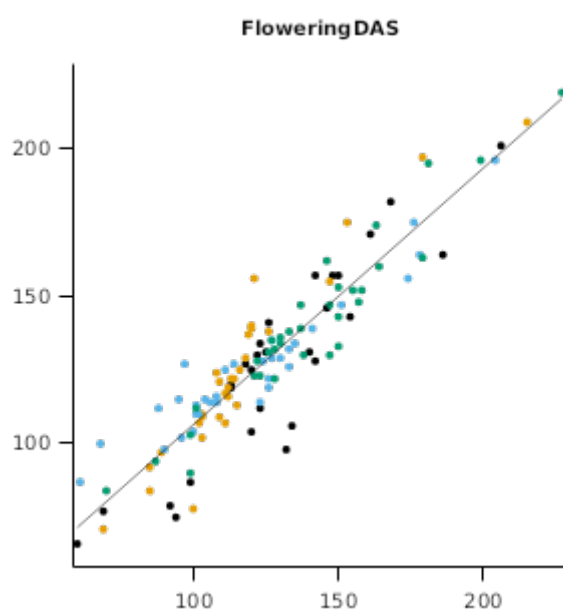
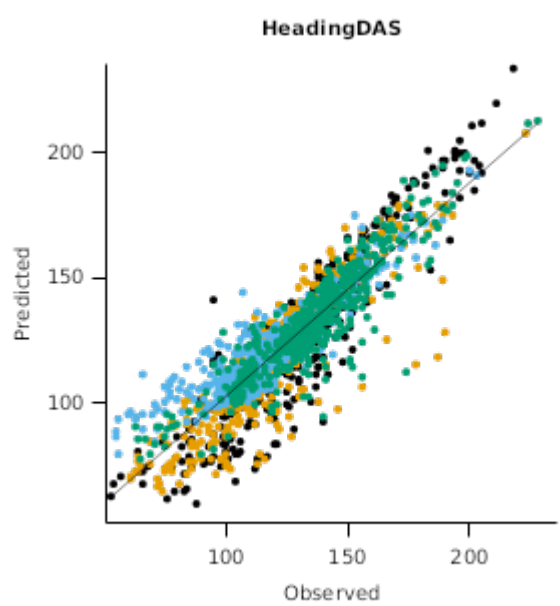
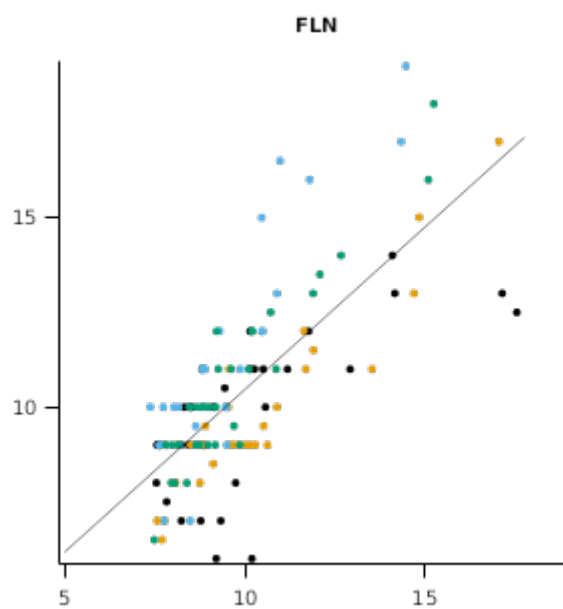
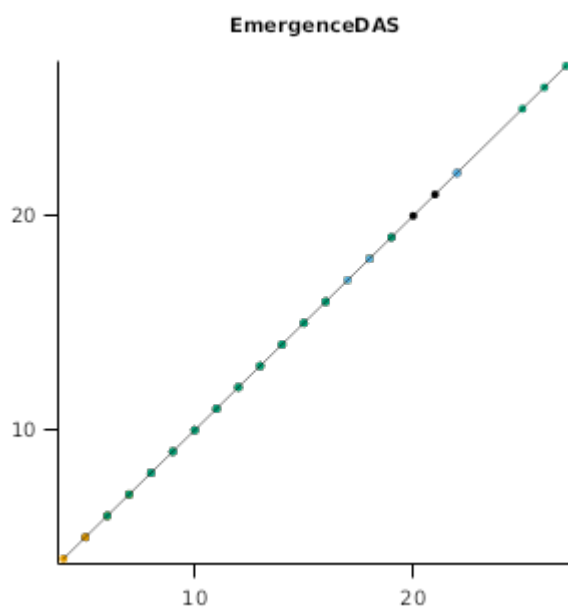
Experiment Name	Design (Number of Treatments)
LaTrobeCE	Treat x CV x Durat (276)
PalmerstonNorthCE	Treat x Cv x Durat (208)
LincolnCE	Treat x Cv x Durat (24)



3.13 NPIField2019

List of experiments.

Experiment Name	Design (Number of Treatments)
WaggaWagga	TOS x Cv (512)
Callington	TOS x Cv (512)
Dale	TOS x Cv (512)
YanYean	TOS x Cv (512)

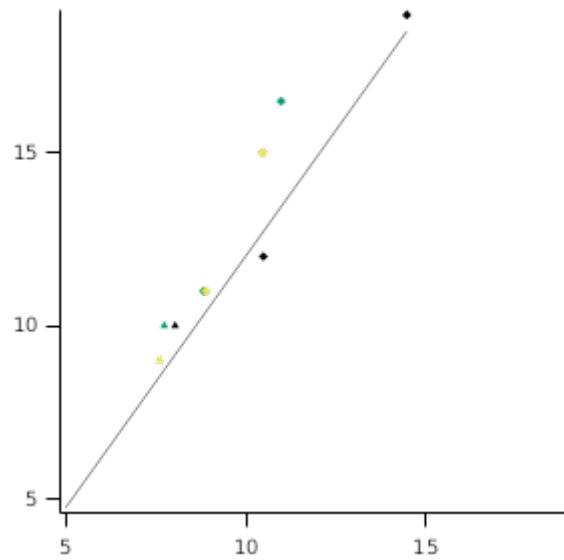


3.13.1 Dale

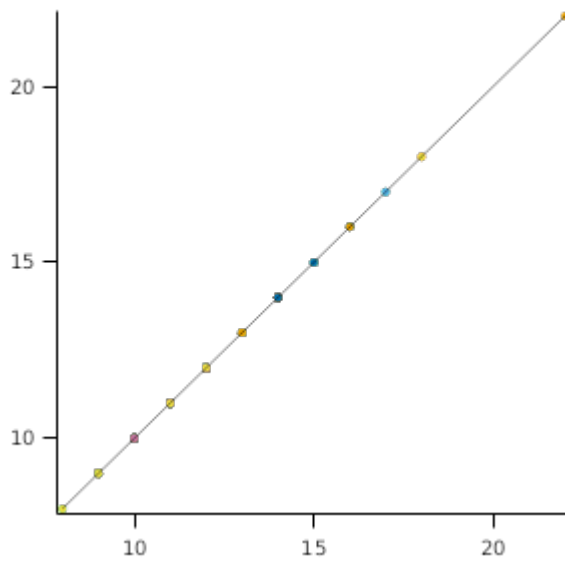
3.13.1.1 PredObs

HaunStage

FLN



EmergenceDAS



3.14 NPValidation

List of experiments.

Experiment Name	Design (Number of Treatments)
SGEHEAT_13GEHEAT-1	Cultivar (6)
SGEHEAT_13GEHEAT-2	Cultivar (6)
14SSOW-1	Cultivar (34)
14SSOW-2	Cultivar (35)
14SSOW-4	Cultivar (34)
14SSOW-5	Cultivar (31)
12JuneJames-1-100	Cultivar (2)
12JuneJames-1-50	Cultivar (1)
12JuneJames-2-100	Cultivar (2)
12JuneJames-2-50	Cultivar (1)

Experiment Name	Design (Number of Treatments)
12JuneJames-3-100	Cultivar (3)
12JuneJames-4-100	Cultivar (2)
BCVT_Ardingly_1992-06-19	Cultivar (1)
BCVT_Badgingarra_2005-05-26	Cultivar (1)
BCVT_Badgingarra_2005-05-28	Cultivar (1)
BCVT_Badjaling_2003-05-30	Cultivar (1)
BCVT_Chapman_1992-06-23	Cultivar (1)
BCVT_Chapman_1992-06-24	Cultivar (1)
BCVT_Chapman_1994-06-10	Cultivar (1)
BCVT_Gairdner_River_2004-06-09	Cultivar (1)
BCVT_Georgina_1992-06-26	Cultivar (1)
BCVT_Konnongorring_1997-06-13	Cultivar (1)
BCVT_Konnongorring_1997-06-27	Cultivar (1)
BCVT_Kumarl_1999-05-22	Cultivar (1)
BCVT_Kunjin_2005-05-26	Cultivar (1)
BCVT_Meckering_2003-06-04	Cultivar (1)
BCVT_Merredin_1995-05-30	Cultivar (1)
BCVT_Merredin_1996-06-25	Cultivar (1)
BCVT_Merredin_1996-07-02	Cultivar (1)
BCVT_Merredin_1998-06-19	Cultivar (1)
BCVT_Merredin_2000-06-19	Cultivar (1)
BCVT_Merredin_2002-06-10	Cultivar (1)
BCVT_Merredin_2003-06-06	Cultivar (2)
BCVT_Mt_Madden_1994-06-13	Cultivar (1)
BCVT_Mukinbudin_2000-06-13	Cultivar (1)
BCVT_Mullewa_1993-06-04	Cultivar (1)
BCVT_Mullewa_2004-05-28	Cultivar (1)
BCVT_Munglinup_1994-06-08	Cultivar (1)
BCVT_Scaddan_1999-05-25	Cultivar (1)
BCVT_Speddingup_2001-05-30	Cultivar (1)
BCVT_Tammin_1999-06-09	Cultivar (1)
BCVT_Wannamal_1992-06-25	Cultivar (1)
BCVT_Wongan_Hills_1998-06-09	Cultivar (1)
BCVT_Wongan_Hills_2001-06-11	Cultivar (1)

Experiment Name	Design (Number of Treatments)
BCVT_Wongan_Hills_2002-06-09	Cultivar (1)
BTOS_2008GE1	Cultivar (6)
BTOS_2008GE2	Cultivar (7)
BTOS_2008GE3	Cultivar (8)
BTOS_2008GE4	Cultivar (11)
BTOS_2008KA1	Cultivar (2)
BTOS_2008KA2	Cultivar (1)
BTOS_2008KA3	Cultivar (5)
BTOS_2008KA4	Cultivar (12)
BTOS_2008NM2	Cultivar (1)
BTOS_2008NM3	Cultivar (12)
BTOS_2008NM4	Cultivar (12)
BTOS_2009GE1	Cultivar (5)
BTOS_2009GE2	Cultivar (2)
BTOS_2009GE3	Cultivar (10)
BTOS_2009GE4	Cultivar (12)
BTOS_2009KA3	Cultivar (3)
BYIE_08HIR	Cultivar (4)
BYIE_08KA	Cultivar (7)
BYIE_08NB	Cultivar (13)
BYIE_08RS	Cultivar (13)
BYIE_08WH	Cultivar (13)
BYIE_09ER	Cultivar (12)
BYIE_09GN	Cultivar (13)
BYIE_09HIR	Cultivar (1)
BYIE_09KA	Cultivar (7)
BYIE_09MDL	Cultivar (14)
BYIE_09RS	Cultivar (5)
BYIE_09WH	Cultivar (14)
PTOS_10Kairi-1	Cultivar (8)
PTOS_10Kairi-2	Cultivar (8)
PTOS_10Kairi-3	Cultivar (7)
PTOS_10Kairi-4	Cultivar (7)
PTOS_10Kairi-5	Cultivar (9)

Experiment Name	Design (Number of Treatments)
PTOS_10Mackay-1	Cultivar (8)
PTOS_10Mackay-2	Cultivar (8)
PTOS_10Mackay-3	Cultivar (7)
PTOS_10Mackay-4	Cultivar (7)
PTOS_10Mackay-5	Cultivar (9)
HAGT_09Roseworthy-1	Cultivar (2)
HAGT_09Roseworthy-2	Cultivar (2)
HAGT_09Roseworthy-3	Cultivar (2)
HAGT_09Roseworthy-4	Cultivar (3)
HAGT_09Roseworthy-5	Cultivar (3)
17CuryoMESW-TOS1	Cultivar (5)
17CuryoMESW-TOS2	Cultivar (5)
17CuryoMESW-TOS3	Cultivar (5)
17CuryoMESW-TOS4	Cultivar (5)
17HartMESW-TOS1	Cultivar (5)
17HartMESW-TOS2	Cultivar (5)
17HartMESW-TOS3	Cultivar (5)
17HartMESW-TOS4	Cultivar (5)
17LoxtonMESW-TOS1	Cultivar (5)
17LoxtonMESW-TOS2	Cultivar (5)
17LoxtonMESW-TOS3	Cultivar (5)
17LoxtonMESW-TOS4	Cultivar (5)
17MilduraMESW-TOS1	Cultivar (5)
17MilduraMESW-TOS2	Cultivar (5)
17MilduraMESW-TOS3	Cultivar (5)
17MilduraMESW-TOS4	Cultivar (5)
17MinnipaMESW-TOS1	Cultivar (4)
17MinnipaMESW-TOS2	Cultivar (4)
17MinnipaMESW-TOS3	Cultivar (4)
17MinnipaMESW-TOS4	Cultivar (4)
18HartMESW-TOS1	Cultivar (5)
18HartMESW-TOS2	Cultivar (5)
18HartMESW-TOS3	Cultivar (5)
18HartMESW-TOS4	Cultivar (5)

Experiment Name	Design (Number of Treatments)
18LoxtonMESW-TOS1	Cultivar (5)
18LoxtonMESW-TOS2	Cultivar (5)
18LoxtonMESW-TOS3	Cultivar (5)
18LoxtonMESW-TOS4	Cultivar (5)
18MilduraMESW-TOS1	Cultivar (5)
18MilduraMESW-TOS2	Cultivar (5)
18MilduraMESW-TOS3	Cultivar (5)
18MilduraMESW-TOS4	Cultivar (5)
Inverleigh2013-TOS1	Cultivar (1)
Inverleigh2013-TOS2	Cultivar (1)
Temora2015-TOS1	Cultivar (7)
Temora2015-TOS2	Cultivar (7)
Temora2015-TOS3	Cultivar (7)
Temora2015-TOS4	Cultivar (7)
Brookstead2015-TOS1	Cultivar (3)
Brookstead2015-TOS2	Cultivar (3)
Brookstead2015-TOS3	Cultivar (3)
Emerald2015-TOS1	Cultivar (3)
Emerald2015-TOS2	Cultivar (3)
Emerald2015-TOS3	Cultivar (3)
Minnipa2015-TOS1	Cultivar (4)
Minnipa2015-TOS2	Cultivar (4)
Minnipa2015-TOS3	Cultivar (4)
Temora2016-TOS4	Cultivar (2)
Hart2015-TOS1	Cultivar (2)
Hart2015-TOS2	Cultivar (2)
Hart2015-TOS3	Cultivar (2)
Inverleigh2013-TOS3	Cultivar (1)
Inverleigh2013-TOS4	Cultivar (1)

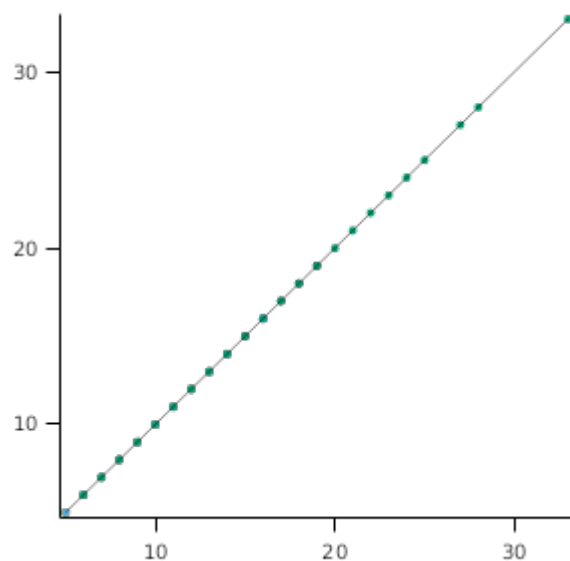
3.15 NPIField2020

List of experiments.

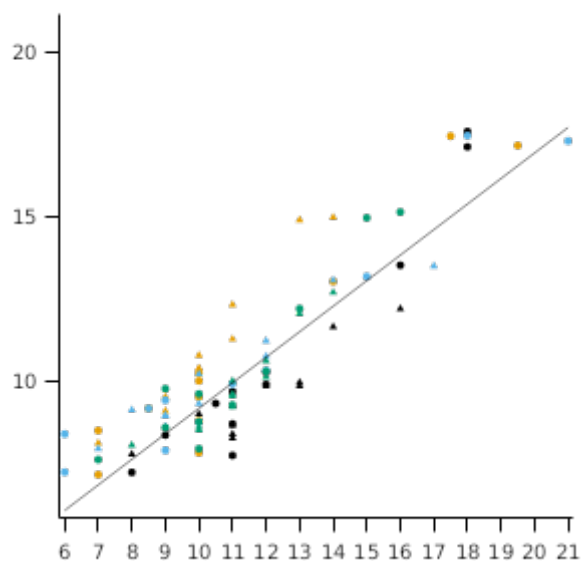
Experiment Name	Design (Number of Treatments)
WaggaWagga2020	TOS x Cv (504)
Urrbrae2020	TOS x Cv (504)

Experiment Name	Design (Number of Treatments)
Dale2020	TOS x Cv (504)
YanYean2020	TOS x Cv (441)

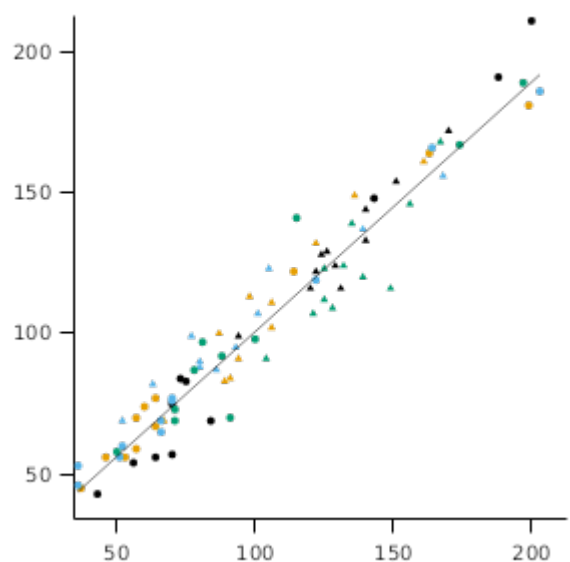
EmergenceDAS



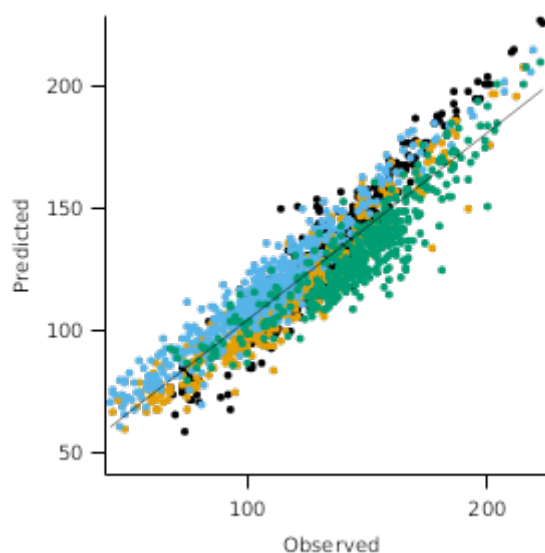
FLN



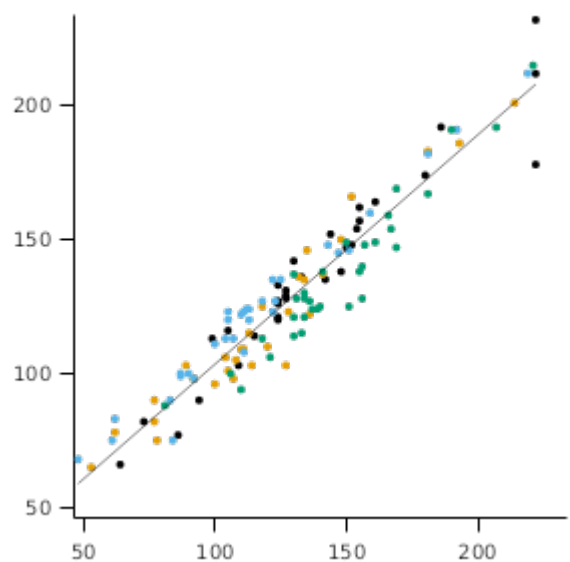
FlagleafDAS



HeadingDAS



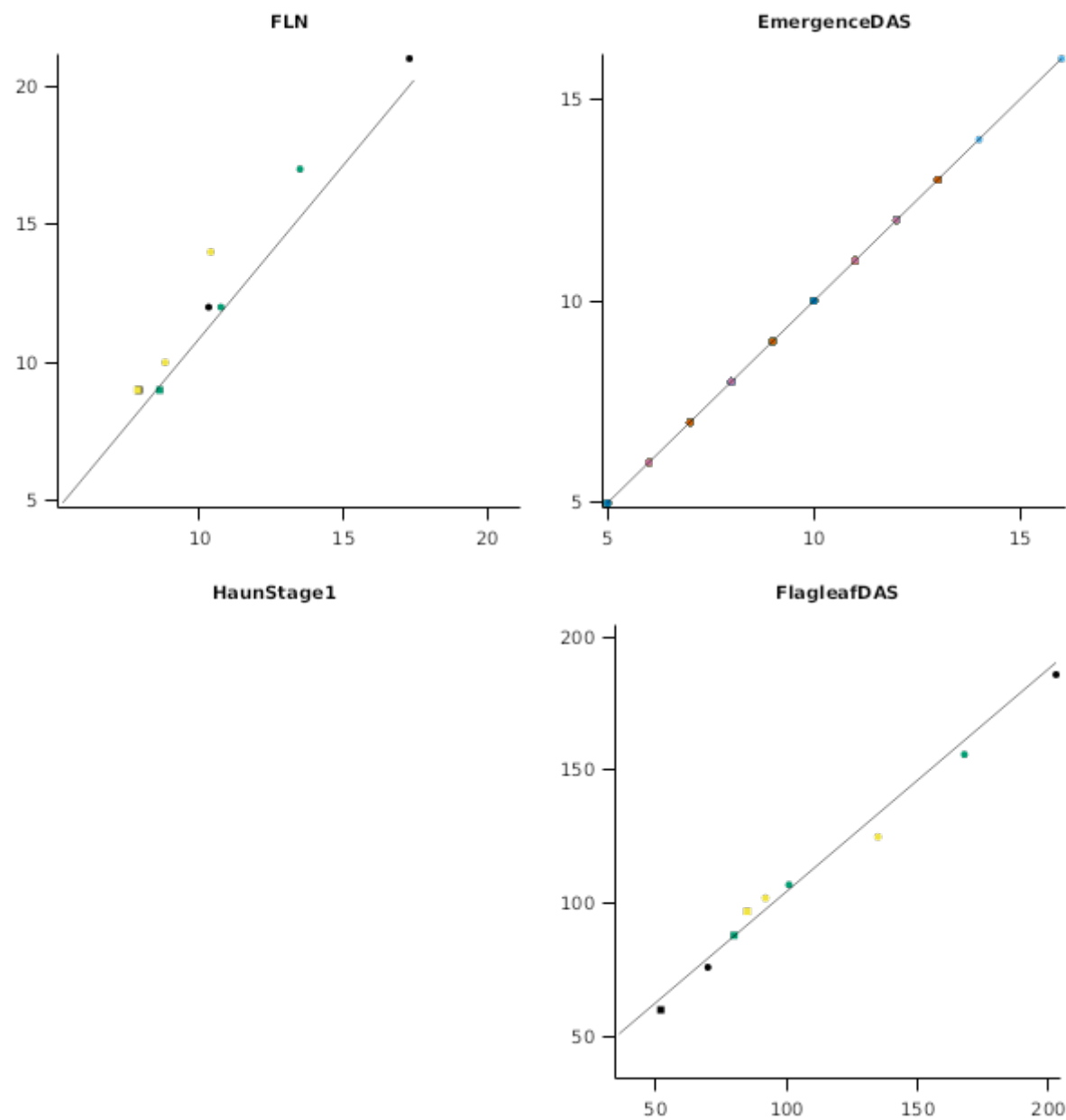
FloweringDAS



HaunStage

3.15.1 Dale2020

3.15.1.1 PredObs



4 Sensibility

4.1 CO2AndTranspirationEfficiency

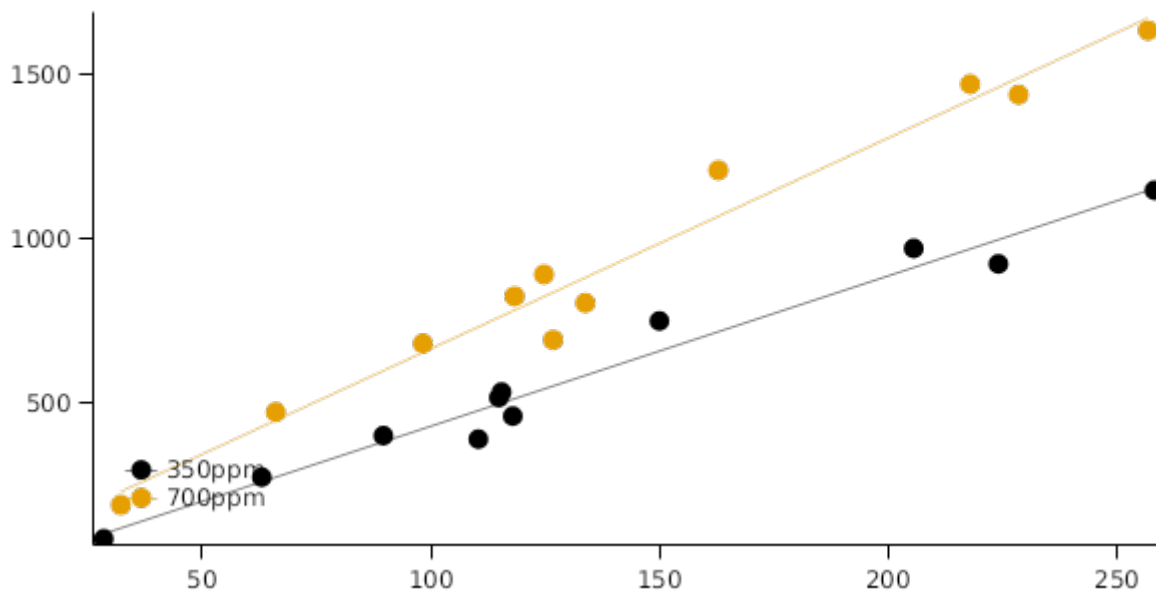
List of experiments.

Experiment Name	Design (Number of Treatments)
CO2TE	CO2 (2)

4.1.1 CO2TE

This test examines the impact of a doubling of CO2 from historical (350ppm) on Transpiration Efficiency. [Reyenga et al., 1999](#) suggest an increase of approximately 37% in Transpiration Efficiency over this range in CO2 concentration. In this test, a series of wheat crops are simulated for Dalby, Queensland, Australia. Nitrogen limitation is removed. The slope of plots of biomass production vs crop water use is used to quantify a gross seasonal TE. The change in slope should approximate the response suggested by [Reyenga et al., 1999](#).

Biomass production vs Crop water Use



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