



## 1 The APSIM Mungbean Model

### 1.1 The APSIM Mungbean Model

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

The model consists of:

- \* a phenology model to simulate development between growth 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

•While, when extensively calibrated to specific sites as it was in many papers, the APSIM classic mungbean model can accurately simulate a limited number of targeted scenarios, overall, it has a low level of simulation accuracy (RMSDYield = 470 kg ha<sup>-1</sup>, r<sup>2</sup>yield = 0.13; RMSDBiomass = 1823 kg ha<sup>-1</sup>, r<sup>2</sup>Biomass = 0.2). Therefore, the classic model has limited functionality and performance in forecasting analyses. Likewise, the classic model was built using old cultivars (Berken and King) which bear limited resemblance to the current popular cultivars (e.g., Jade-AU, Crystal, and Celera II-AU). We decided to source some parameter values from the classic model, but otherwise built the new model off of the template of the soybean APSIM NextGen model and Plant Modelling Framework. Parameter-wise, the following are the major ones that were changed:

oThere was an added phase for thermal time accumulation to delay emergence in the spring. The shoot lag was extended from 10 to 25GDD, but now days to emergence is more temperature dependent. oThe base and optimal temperatures for vegetative thermal time were kept the same, but the optimal temperature window was extended to 43C and the max was at 45C, not 40C. This was to reflect the consistency in growth at the October, November, and January sowing dates. Reproductive had the same base, but a lower optimal window and max than Vegetative. oThe node appearance rate was 100 before, but is now 70 (in line with Geetika's work) oThe k and RUE values are higher, sourced from Geetika's work oA water deficit stress induced senescence was added oA photosynthesis respond to higher VPD was added oRoot depth rate was changed to reflect the collected soil water extraction data oWithout root:shoot biomass data, we kept the 0.2 biomass fraction to the root included in the soybean model which had extensive root data included in the model building dataset oThe critical nitrogen concentrations are a smaller range with a lower max and higher min. This data was drawn from Muchow et al., 1993 paper on accumulation (see model documentation)

oThis is not a comprehensive list: We are sure that we are missing other items that were changed (likely the maximum fixation rate and the stem allocation fraction), but it was not always a simple adjustment to the parameters as the model framework itself has changed. The classic model required a good amount of further calibration by the model users in a way that we hope the new model won't. That said, it is still customisable and we welcome any feedback about how it runs or what needs to be added or improved.

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

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

### 1.2 Plant Model Components

Component Name	Component Type
Arbitrator	Models.PMF.OrganArbitrator

Component Name	Component Type
Phenology	Models.PMF.Phen.Phenology
Leaf	Models.PMF.Organs.SimpleLeaf
Grain	Models.PMF.Organs.ReproductiveOrgan
Root	Models.PMF.Organs.Root
Nodule	Models.PMF.Organs.Nodule
Shell	Models.PMF.Organs.GenericOrgan
Stem	Models.PMF.Organs.GenericOrgan
MortalityRate	Models.Functions.Constant
SeedMortalityRate	Models.Functions.Constant

### 1.3 Composite Biomass

Component Name	Component Type
AboveGround	Models.PMF.CompositeBiomass
BelowGround	Models.PMF.CompositeBiomass
AboveGroundLive	Models.PMF.CompositeBiomass
Total	Models.PMF.CompositeBiomass
TotalLive	Models.PMF.CompositeBiomass
TotalDead	Models.PMF.CompositeBiomass
Pod	Models.PMF.CompositeBiomass

### 1.4 Cultivars

Cultivar Name	Alternative Name(s)
Berken	Berken
Emerald	Emerald
Celerall	Celerall
Crystal	Crystal
Jade	Jade
Onyx	Onyx
Opal	Opal
King	King

### 1.5 Child Components

#### 1.5.1 Arbitrator

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

- \* **Structural biomass** which is essential for growth and remains within the organ once it is allocated there.
- \* **Metabolic biomass** which generally remains within an organ but is able to be re allocated when the organ senesces and may be retranslocated when demand is high relative to supply.

\* **Storage biomass** which is partitioned to organs when supply is high relative to demand and is available for retranslocation to other organs whenever supply from uptake, fixation, or re allocation is lower than demand.

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

1. **doPotentialPlantGrowth**. When this event occurs, each organ class executes code to determine their potential growth, biomass supplies and demands. In addition to demands for structural, non structural and metabolic biomass (DM and N) each organ may have the following biomass supplies:

\* **Fixation supply**. From photosynthesis (DM) or symbiotic fixation (N)

\* **Uptake supply**. Typically uptake of N from the soil by the roots but could also be uptake by other organs (eg foliage application of N).

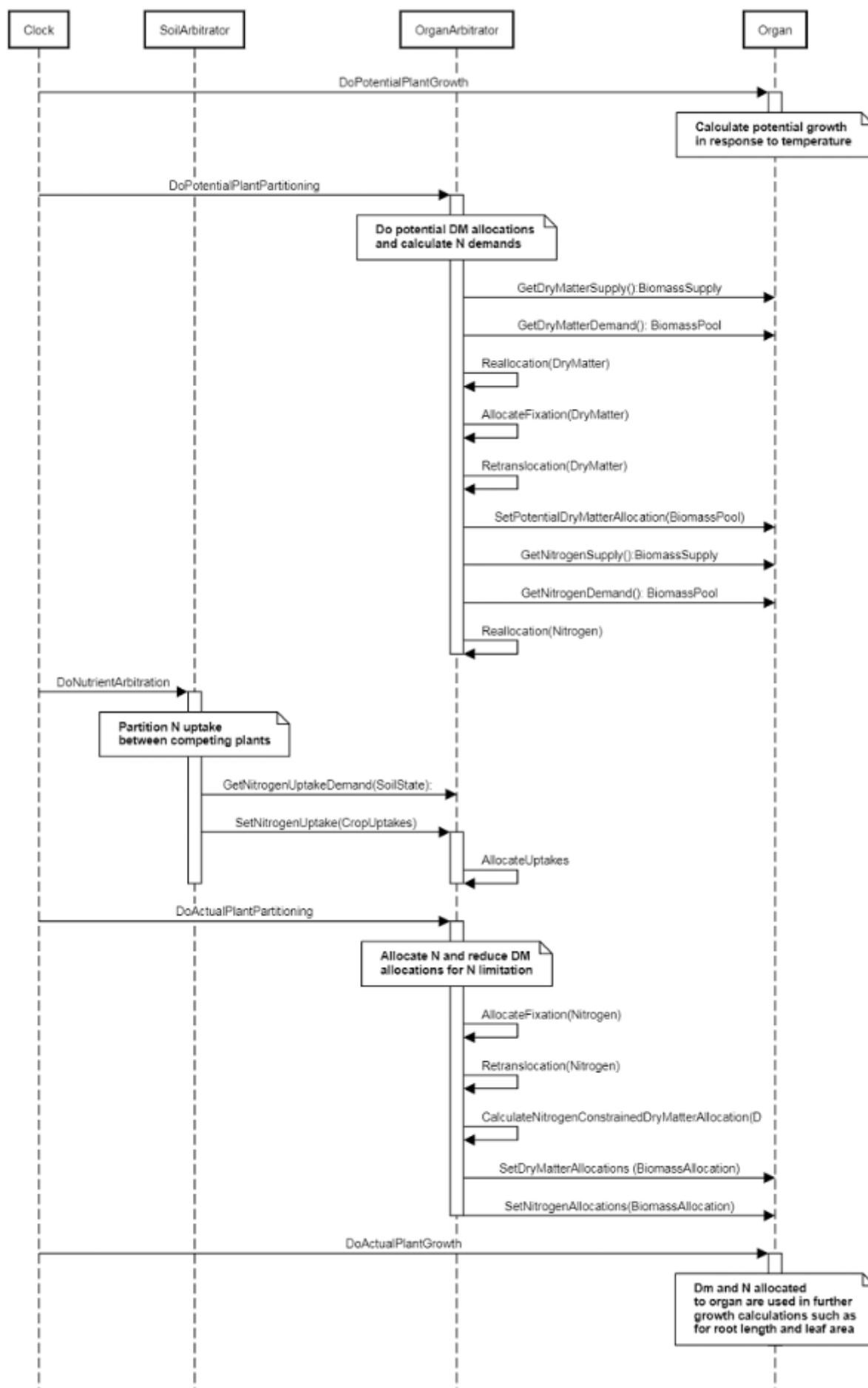
\* **Retranslocation supply**. Storage biomass that may be moved from organs to meet demands of other organs.

\* **Reallocation supply**. Biomass that can be moved from senescing organs to meet the demands of other organs.

1. **doPotentialPlantPartitioning**. On this event the Arbitrator first executes the DoDMSetup() method to gather the DM supplies and demands from each organ, these values are computed at the organ level. It then executes the DoPotentialDMAAllocation() method which works out how much biomass each organ would be allocated assuming N supply is not limiting and sends these allocations to the organs. Each organ then uses their potential DM allocation to determine their N demand (how much N is needed to produce that much DM) and the arbitrator calls DoNSetup() to gather the N supplies and demands from each organ and begin N arbitration. Firstly DoNReallocation() is called to redistribute N that the plant has available from senescing organs. After this step any unmet N demand is considered as plant demand for N uptake from the soil (N Uptake Demand).

2. **doNutrientArbitration**. When this event occurs, the soil arbitrator gets the N uptake demands from each plant (where multiple plants are growing in competition) and their potential uptake from the soil and determines how much of their demand that the soil is able to provide. This value is then passed back to each plant instance as their Nuptake and doNUptakeAllocation() is called to distribute this N between organs.

3. **doActualPlantPartitioning**. On this event the arbitrator call DoNRetranslocation() and DoNFixation() to satisfy any unmet N demands from these sources. Finally, DoActualDMAAllocation is called where DM allocations to each organ are reduced if the N allocation is insufficient to achieve the organs minimum N concentration and final allocations are sent to organs.



**Figure 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.

## 1.5.2 Phenology

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

In the new model we simplified phenology by taking out stages that are not measurable (e.g. end of juvenile stage) and by adding new stages that are measurable (e.g. start pod). The new phenology follows the V/R staging system

For Preemergence thermal time accumulation, a temperature dependent delay in emergence was drawn from Drs. Wenham's recent TOS trial.

For the Vegetative and Reproductive phase thermal time accumulation, the base, optimal, and maximum temperatures from the original generic legume model (Robertson et al., 2002) and a recent paper by Geetika Geetika (Geetika et al., 2021) were 7.5, 30, and 40C, respectively. The values were slightly adjusted to reflect the phenology recorded in Drs. Grant and Pasley's more recent trials.

Photoperiod sensitivity parameters were sourced from a study using the king cultivar (Imrie et al., 1990).

## 1.5.3 Leaf

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

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

These values are then given back to SimpleLeaf which uses them to calculate photosynthesis and soil water demand.

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

Simple leaf approach.

RUE value increased from that of Robertson to reflect higher production levels of more modern varieties in Dr. Kylie Wenham's time of sowing trials (Muchow et al., 1993, Thomas, 2000, Geetika et al., 2021).

The extinction coefficient (k) was sourced from (Thomas, 2000) and (Geetika et al., 2021).

The relative leaf area was sourced from (Geetika et al., 2021).

FVPD decreases at Fw=0.15: Mungbeans have been found to be particularly sensitive to variability in the vapour pressure deficit (VPD), potentially driving their reduced biomass accumulation and yield when sown in the spring in Dr. Kylie Wenham.

The Phyllochron and branching rates were sourced from trials conducted by Dr. Pasley included in the model testing and from (Geetika et al., 2021).

Specific area and area largest leaf were sources from the APSIM NextGen soybean model.

N concentrations were sourced from (Muchow et al., 1993).

There are two drivers of leaf senescence included in the model: age-driven and water stress-driven. The dominant driver of senescence is the one with the highest rate. Age-driven senescence of the leaves occurs at a constant rate from the end of pod development to ripening. Meanwhile, water stress-driven senescence rate increases with water-deficit stress as quantified by Fw 0.15, starting at the end of canopy development and continuing to ripening. The water-stress driven senescence rate was derived using data from (Thomas, 2000)

## 1.5.4 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).

Muchow and Charles-Edwards 1982 found that the fraction proportioned to the grain is 0.17-0.31 (Muchow et al., 1993). The potential harvest index was estimated to be slightly higher than these values.

N concentrations were sourced from (Muchow et al., 1993).

### 1.5.5 Root

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

Root front velocity values were sourced from Thomas Dissertation that includes 3 experiments that look at different irrigation regimes/timings/cultivars and compares mungbean to soybean. These experiments were used to build the original generic legume model (Robertson et al., 2002, Thomas, 2000).

All other root parameters were sourced from the soybean APSIM NextGen model.

### 1.5.6 Nodule

This organ simulates the root structure associated with symbiotic N fixing bacteria. It provides the core functions of determining N fixation supply and related costs. It also calculates the growth, senescence and detachment of nodules.

The maximum fixation rate (35 g g<sup>-1</sup>) was sourced from (Herridge et al., 2005) and the daily potential fixation rates were sourced from the soybean model for APSIM NextGen. The accuracy of these parameter values was tested via time-series N fixation from the DAF ACRI experiment in the validation dataset.

### 1.5.7 Shell

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.

Muchow and Charles-Edwards 1982 found that the fraction proportioned to the pods is 0.63-0.68 (Muchow et al., 1993).

### 1.5.8 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.

Values for maximum, critical, and minimum N concentrations sourced from Muchow et al., 1993 (Muchow et al., 1993).

Values sourced from graphing leaf vs. stem biomass data from Dr. Kylie Wenham's Time of Sowing trial and Thomas' dissertation (Thomas, 2000).

### 1.5.9 MortalityRate

A constant function (name=value)

### 1.5.10 SeedMortalityRate

A constant function (name=value)

## 2 Validation

### 2.1 Map



## 2.2 ExtraPhenSowOctCvJade

Additional small experiment at Gatton UQ field station on a vertisol. Sown on October 26, 2021. Node, leaf, and branch numbers were counted every week. After the 4th node, biomass samples were taken weekly too and partitioned into leaves and stems. Harvest data was not collected as the aim of the experiment was to nail down phenology.

## 2.3 Thomas Dissertation

Thomas Dissertation includes 3 experiments that look at different irrigation regimes/timings/cultivars and compares mungbean to soybean. These experiments were used to build the original generic legume model ([Robertson et al., 2002](#), [Thomas, 2000](#)).

### 2.3.1 List of experiments

Experiment Name	Design (Number of Treatments)
Experiment_1_Berken	Water (3)
Experiment_1_Emerald	Water (3)
Experiment_2	Water (6)
Experiment_3	_Sow x Cultivar (6)
Experiment_4	_Water x Cultivar (3)

### 2.3.2 Experiment\_1\_Berken

Experiment at Gatton, QLD, sown on November 28 1996 on CSIRO Cooper field station. Soil type was a deep alluvial, weakly-cracking vertisol. There were 3 treatments: 1) well-watered, 2) rainfed and 3) rainfed+irrigation during pod filling. The cultivar used was Berken.

### 2.3.3 Experiment\_1\_Emerald

Experiment at Gatton, QLD, sown on November 28 1996 on CSIRO Cooper field station. Soil type was a deep alluvial, weakly-cracking vertisol. There were 3 treatments: 1) well-watered, 2) rainfed and 3) rainfed+irrigation during pod filling. The cultivar used was Emerald.

### 2.3.4 Experiment\_2

Experiment at Gatton, QLD, sown on January 7 1997 on CSIRO Cooper field station. Soil type was a deep alluvial, weakly-cracking vertisol. There were 3 treatments: 1) well-watered, 2) rainfed and 3) terminal water stress with a rainout shelter. The cultivars used were Berken and Emerald.

### 2.3.5 Experiment\_3

Experiment at Gatton, QLD, CSIRO Cooper field station. Soil type was a deep alluvial, weakly-cracking vertisol. There were 3 treatments: 1) well-watered, 2) rainfed and 3) stress with a rainout shelter for 4 weeks starting at different stages of mungbean growth imposed by having 3 sowing dates (3, 17, 30 December 1997). The cultivar used was Emerald.

### 2.3.6 Experiment\_4

Experiment at Gatton, QLD, CSIRO Cooper field station. Soil type was a deep alluvial, weakly-cracking vertisol. There were 3 treatments: 1) well-watered, 2) rainfed and 3) rainfed+irrigated for first 3 weeks and at podfilling. The cultivar used was Emerald.

## 2.4 TOS

These trials took place in Gatton on a vertisol at the Gilbert Site 2018-2021 looking at 6 cultivars (Jade, Crystal, Celerall, Opal, Onyx, Berken) planted at 5-6 times in rainfed and irrigated (one year). The data has not been published yet, but was collected and will be published by Kylie Wenham. Berken was likely not a pure seed and cannot be compared to the results of Thomas' dissertation and so was removed from the model-building dataset. The first and second years of the experiment were entirely or partially excluded from the model dataset because the data was concluded to be unreliable.

### 2.4.1 List of experiments

Experiment Name	Design (Number of Treatments)
TOSyear2Opal	Sow x Cv (2)
TOSyear3	Sow x Cv (25)

## 2.5 Muchow

This dataset ([Muchow et al., 1993](#)) includes the cultivar "King" grown under irrigated conditions in a subtropical environment at the Gatton Research Station in southeastern Queensland, Australia and Kimberly, NT, Australia. Plants were sampled almost weekly for biomass partitioning, nitrogen and plant development.

### 2.5.1 List of experiments

Experiment Name	Design (Number of Treatments)
Kimberly1980	Dens (3)

## 2.6 Mungbean\_DAF

These trials were done by DAF in 2019 and 2020, largely looking at the impact of applying N and inoculating seeds. Data is recorded in annual reports but not published. Jade was the cultivar used on all. It is unclear why the recorded harvest date is so much later than the simulated as the simulated was confirmed within 10 days by the Thomas Dissertation and Dr. Wenham's TOS trials. Perhaps, like the Yield Gap studies, the crop was harvested much later than the earliest harvest date possible or else, as was seen in one experiment in the Thomas Dissertation, the crop was semi-indeterminant and didn't reach a natural harvest ripe point when anticipated (the crop keeps growing if there is enough water) and so the date of the harvest recorded in the field corresponds to a date at which the crop was chemically or mechanically desiccated.

### 2.6.1 List of experiments



Experiment Name	Design (Number of Treatments)
ACRI	N (2)
Emerald2020	N (2)
HopelandSpring	N (2)
HopelandSummer	N (2)

### 2.6.2 ACRI

ACRI trial in Narrabri with cultivars Opal and Jade. Detailed soil water measurements. Was supposed to be an N fertilizer trial, but not a priority in the model so we just looked at ON rainfed.

### 2.6.3 Emerald2020

DAF trial in Emerald, QLD with cultivar Jade. Was supposed to be an N fertilizer trial, but not a priority in the model so we just looked at ON.

### 2.6.4 HopelandSpring

DAF trial in Hopeland, QLD with cultivar Jade planted in Spring. Was supposed to be an N fertilizer trial, but not a priority in the model so we just looked at ON.

### 2.6.5 HopelandSummer

DAF trial in Hopeland, QLD with cultivar Jade planted in Summer. Was supposed to be an N fertilizer trial, but not a priority in the model so we just looked at ON.

### 2.6.6 BreezaN0N

DAF trial on the Liverpool plains at the Liverpool Plains Research Station with cultivar Jade. Was supposed to be an N fertilizer trial, but not a priority in the model so we just looked at ON.

### 2.6.7 Emerald2019N0N

DAF trial in Emerald, QLD with cultivar Jade. Was supposed to be an N fertilizer trial, but not a priority in the model so we just looked at ON.

### 2.6.8 IrvingdaleN0N

DAF trial in Irvingdale, QLD with cultivar Jade planted. Was supposed to be an N fertilizer trial, but not a priority in the model so we just looked at ON.

## 2.7 Yield\_Gap

CSIRO large-scale, primarily single year field studies that were looking to see what the leading yield limiters were. The data was organized by Brook Anderson (CSIRO) and is being written up by Marisa Collins (LaTrobe) and Lindsay Bell (CSIRO). The cultivar used was Jade with the exception of one site year where they used Crystal. Total biomass and days to maturity data were removed from the model-building dataset as well as a few treatments from the Pampas site after discussion with Lindsay Bell about the unreliability of this data. In some of the studies, the harvesting date in the field is much later than the simulated dates. These discrepancies are for the same reason the biomass and days to maturity data was removed: the crop was left in the ground for later than its maturity or earliest harvesting date, so the harvest date recorded by the field technicians are for that later date.

### 2.7.1 List of experiments

Experiment Name	Design (Number of Treatments)
Billa_Billa	Sow (3)
Emerald	Sow (6)
HRS	Sow (3)
Pampas	Sow (5)
Warra	Sow (2)

### 3 Sensibility

A factorial simulation of different sowing times by initial soil water level at three sites was run for 55 years, from 1963 to 2018, resetting the soil organic matter, N, and water on July 1 of each year. The baseline simulations for Gatton, Katherine, and Narrabri (-30.2 S, 147.6 E) were sourced from the calibration/testing dataset. Jade-AU was sown at early (September 15), mid (December 15), and late (February 15) in the growing season with initial soil water profile at 20%, 60%, and 100% of full representing a low, mid, high water status, respectively. The site descriptions of the three sites can be categorised according to their soils and climate: Gatton is a vertisol (195mm plant available water when the profile is full), with a temperate climate where the hot temperatures (20-30°C) ideal for mungbeans occur during a short window (early sowing results in potential heat stress at flowering and grain fill, late sowing results in low temperatures hindering grain fill) and so is termed in this study as “Short Season Temperate Vertisol.” Narrabri is also a vertisol (321mm plant available water when the profile is full), with a long hot (20-30°C) and dry growing season for mungbeans and so, is termed “Long Season Arid Vertisol.” Katherine soil is an alfisol (195mm plant available water when the profile is full), with very hot (30-35°C) conditions where average monthly rainfall only exceeded 40mm starting in November, suggesting that mungbeans need to be planted later there, and so, is termed “Late Season Arid Alfisol.” Probability analyses were then run on the resulting grain yields to test if the model outputs changed in a sensible way relative to the environment and growing conditions and in their response to more extreme environments. We expect the model to output a greater sensitivity to sowing date irrespective of water conditions in a “Short Season Temperate Vertisol,” to water conditions irrespective of sowing date in a “Long Season Arid Vertisol,” and to not be able to grow mungbeans at all at the early sowing date and when there is little initial water in the “Late Season Arid Alfisol.”

#### 3.1 List of experiments

Experiment Name	Design (Number of Treatments)
Gatton	Water x Sow (9)
Katherine	Water x Sow (9)
Narrabri	Water x Sow (9)

### 4 References

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