



1 The APSIM Eucalyptus Model

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.

1.1 Eucalyptus Model Notes

1.2 Plant Modelling Framework

The APSIM Eucalyptus model has been developed using the Plant Modelling Framework (PMF) of [Brown et al., 2014](#) within APSIM Next Generation [Holzworth 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 processes and organ classes (e.g. photosynthesis, leaf) into larger constructions (e.g. maize, wheat, eucalyptus) can be achieved by the model developer without additional coding.

Peculiarities of Eucalyptus and This Model

The Eucalyptus model consists of:

- * a phenology model to simulate development through sequential growth phases
- * 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 forest models such as described by [Huth et al., 2002](#), [Huth et al., 2001](#) and [Huth et al., 2008](#).

Eucalyptus is a reasonably straight forward perennial crop to model. This model has been set up for simulation of even-aged plantations (transplanted seedlings) or native forests (also assumed to start the simulation as a transplanted seedling, but in practice it would be sown from naturally distributed seed). Plants grow in accordance with available resources and conditions, which in this version of the model are temperature, radiation, available soil water, and available soil nitrogen. Leaves, branches and roots senesce, remain attached for some time, then detach to produce litter. Above-ground biomass is the main target of production, which is made up of organs that develop from default partitioning targets that are modified daily in response to organ demand. Forest managers also deal with tree size, which are set in the model as empirical functions of aboveground biomass. During model development, we found that Eucalyptus model performance (plant or stand development) was particularly sensitive to leaf lifespan/longevity, specific leaf area, dead leaf detachment, partitioning to roots and shoots, mortality and thinning, and weeds (if present).

After stem dry weight is determined, it is then empirically split into bark and wood (based on individual stem weight), and the volumes of each set using bark thickness. This enables under and over bark properties to be calculated for BA, Vol and MAI, and finally a the calculation of wood and bark densities. Volume is calculated as a stand rather than summing individual trees. Many of these attributes of stem metrics are highly site, genotype and management specific, and some forestry plantation companies keep their own parameterisations confidential.

There are many Eucalyptus genotypes (species, closely related genera, provenances, families, clones, and hybrids) that can behave differently in response to their growing environment. The Eucalyptus model was calibrated on datasets of species (*E. globulus*, *E. grandis*, *E. nitens*, *E. saligna*), hybrids (*E. grandis* x *E. urophylla*, *E. globulus* x *E. urophylla*), and two clones of the *E. grandis* x *E. urophylla* hybrid.

Including a Eucalyptus crop in an APSIM simulation

An example Eucalyptus simulation is available by clicking the "Open an Example" tab available when APSIM Next Gen is opened. This provides a demonstration of how to simulate a Eucalyptus crop, and it provides some useful graphs as suggestions for viewing model behaviour and performance.

To include a Eucalyptus crop in a simulation the "Eucalyptus" model needs to be added to the paddock, field or zone in which it is to be grown. This can be done by (a) right clicking on the "Paddock", selecting "Add model..." then "PMF", then

selecting "Eucalyptus" from the list that comes up, or (b) copying and pasting the model from the example simulation. A TreeSowingRule needs to be set up to start the crop. Harvesting and replanting are included in the 'EucalyptusRotation' example.

This document provides a more detailed description of the model, describes the validation and test datasets, and model performance.

Major Eucalyptus model developments:

2017-2019

- Developed and released the first version of the Eucalyptus model in APSIM Next Generation. That version was based on Australian and Brazilian datasets covering tropical and sub-tropical genotypes - mainly *E. grandis*. Publications include [Smethurst et al., 2020](#) and [Elli et al., 2020](#).

2020-2022

- Included temperate species, i.e. *E. globulus* and *E. nitens*.
- Included an expansion of stem metrics beyond just diameter at breast height (DBH, cm), height (m), and overbark stem volume (Vol, m³/ha). New stem metrics include underbark parameters of stem volume (Volub) and wood density, and basal area (BA, m²/ha) the mean annual increment of overbark and underbark volumes (m³/ha/year). This required partitioning of stem biomass into bark and wood, calculation of bark thickness, and an estimation of volumes overbark and underbark. All stem metrics are empirically calculated rather than process-based. These metrics are known to be highly affected by stem taper, bark thickness and wood density, which in-turn are highly influenced by site, genetics and management. Few data are available on wood density (underbark, whole tree), so it is included here only as a check that underlying calculations are sensible. Validations of these metrics are included. In comparison, it remains that only DBH, height and overbark stem volume are validated for the tropical and sub-tropical genotypes.

Suggested future developments:

1. Create a set of functional weeds specifically for use with these forestry models, e.g. N-fixing/non-N-fixing X herbaceous/shrub/tree X tropical/sub-tropical/temperate.
2. Coppicing
3. Self-thinning rule or process-based mortality
4. Improve effects of stocking, if necessary. Leaf allocation as a function of aboveground.wt (g/m²) rather than individual tree weight (g/tree) has been included, but further checking of this is required to see that if that is all that is needed for a wide range of stockings.
5. Waterlogging – I (Philip) would have thought it was important, particularly for some euc and pine genotypes, but so far I haven't run into a really need for it amongst our current observed datasets.
6. Add observed data for the tropical and sub-tropical genotypes for the more advanced stem metrics, and recalibrate the model for those genotypes if necessary. This would be a good postgrad project for a Brazilian student with industry collaborators.
7. Soil P (and K) and fertiliser responses
8. Pruning and effects on knot-free wood (wood quality)
9. Geo-locate and interact adjacent plots for predicting area-based metrics like stream flow and wood production
10. Tree and log size class distributions
11. Development of outputs for greenhouse accounting (water use, C sequestration, greenhouse gases, biodiversity indices)
- 12.

Root:shoot ratio, and allometric relationships for height (Ht, m), stem diameter (DBH, cm, over bark at 1.3 m height), and their derivatives (stem volume Vol, and mean annual increment MAI) were developed as a function of above-ground biomass from [Almeida, 2003](#), [Almeida et al., 2004](#), [Borges, 2009](#), [Cromer et al., 1993](#), and [Nogueira, 2005](#). Similarly, above-ground biomass as a function of stem weight or wood weight was developed from the same datasets plus [Turner, 1986](#), [Byrne, 1989](#), [Bradstock, 1981](#), [Polglase et al., 1995](#), [Snow et al., 1999](#), [Snow et al., 1999](#), [Myers et al., 1996](#), [Myers et al., 1998](#), and [Melo et al., 2015](#).

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

1.3 Plant Model Components

Component Name	Component Type
Age	Models.Functions.AccumulateFunction
MortalityRate	Models.Functions.Constant

Component Name	Component Type
SeedMortalityRate	Models.Functions.Constant
Phenology	Models.PMF.Phen.Phenology
Arbitrator	Models.PMF.OrganArbitrator
IndividualTreeLiveWt	Models.Functions.DivideFunction
IndividualTreeStemWt	Models.Functions.DivideFunction
Leaf	Models.PMF.Organs.PerennialLeaf
Branch	Models.PMF.Organs.GenericOrgan
Stem	Models.PMF.Organs.GenericOrgan
CoarseRoot	Models.PMF.Organs.GenericOrgan
FineRoot	Models.PMF.Organs.Root
RootShootRatio	Models.Functions.DivideFunction

1.4 Composite Biomass

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

1.5 Cultivars

Cultivar Name	Alternative Name(s)
grandis	grandis
grandisCoffsHarbour	grandisCoffsHarbour
grandisC15	grandisC15
grandisC22	grandisC22
grandisXurophylla	grandisXurophylla
grandisXurophyllaC3334	grandisXurophyllaC3334
grandisXurophyllaC3336	grandisXurophyllaC3336
urophyllaXglobulus	urophyllaXglobulus
BrazilPlasticClone	BrazilPlasticClone
BrazilTropicalClone	BrazilTropicalClone
BrazilSubTropicalClone	BrazilSubTropicalClone
saligna	saligna
nitens	nitens

Cultivar Name	Alternative Name(s)
nitensLewisham	nitensLewisham
globulus	globulus
globulusShepparton	globulusShepparton
WABlueGum	WABlueGum
FSABlueGum	FSABlueGum

1.6 Child Components

1.6.1 Age

Accumulates a child function between a start and end stage.

1.6.2 MortalityRate

A constant function (name=value)

1.6.3 SeedMortalityRate

A constant function (name=value)

1.6.4 Phenology

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

1.6.5 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.

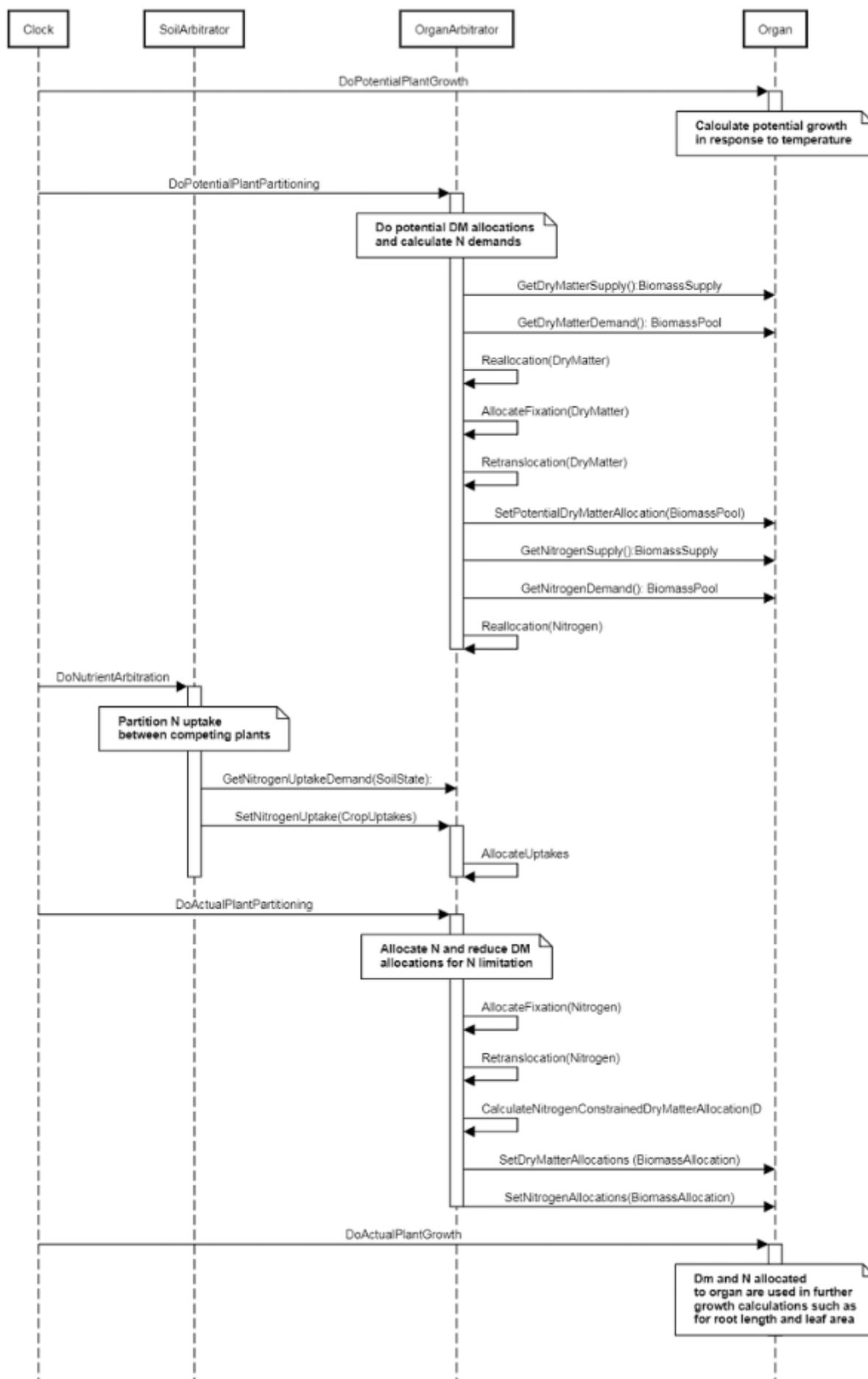


Figure 1: Schematic showing the procedure for arbitration of biomass partitioning. Pink boxes represent events that occur every day and their numbering shows the order of calculations. Blue boxes represent the methods that are called

when these events occur. Orange boxes contain properties that make up the organ/arbitrator interface. Green boxes are organ specific properties.

1.6.6 IndividualTreeLiveWt

A class that divides all child functions.

Note that this property does not include branches. It is used in calculating DM Demands of several plant components.

1.6.7 IndividualTreeStemWt

A class that divides all child functions.

1.6.8 Leaf

This organ is parameterised using a simple leaf organ type which provides the core functions of intercepting radiation, providing a photosynthesis supply and a transpiration demand. It also calculates the growth, senescence and detachment of leaves.

1.6.9 Branch

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.

For many of the parameters in this organ, see comments for similar parameters in the leaf organ.

1.6.10 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.

For many of the parameters in this organ, see comments for similar parameters in the leaf organ.

1.6.11 CoarseRoot

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.

For many of the parameters in this organ, see comments for similar parameters in the leaf organ.

1.6.12 FineRoot

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

For many of the parameters in this organ, see comments for similar parameters in the leaf organ.

1.6.13 RootShootRatio

A class that divides all child functions.

2 Validation

Validation datasets have been included to assist with validation during model development. Validation datasets cover a range of environmental (soil and climate) conditions, management options (populations, nitrogen rates, irrigation) and genetic backgrounds (different regions, provenance, clones). These datasets have been grouped and ordered alphabetically by site within a climatic zone. Graphs of model performance are provided for stocking, canopy development, biomass production, stem metrics, and soil water. Where a tropical or sub-tropical dataset did not include aboveground biomass, but instead a related parameter like stem volume or biomass, the latter was converted to aboveground biomass by a regression based on the rest of the validation dataset for that climatic region. However, this estimation was not conducted for temperate datasets.

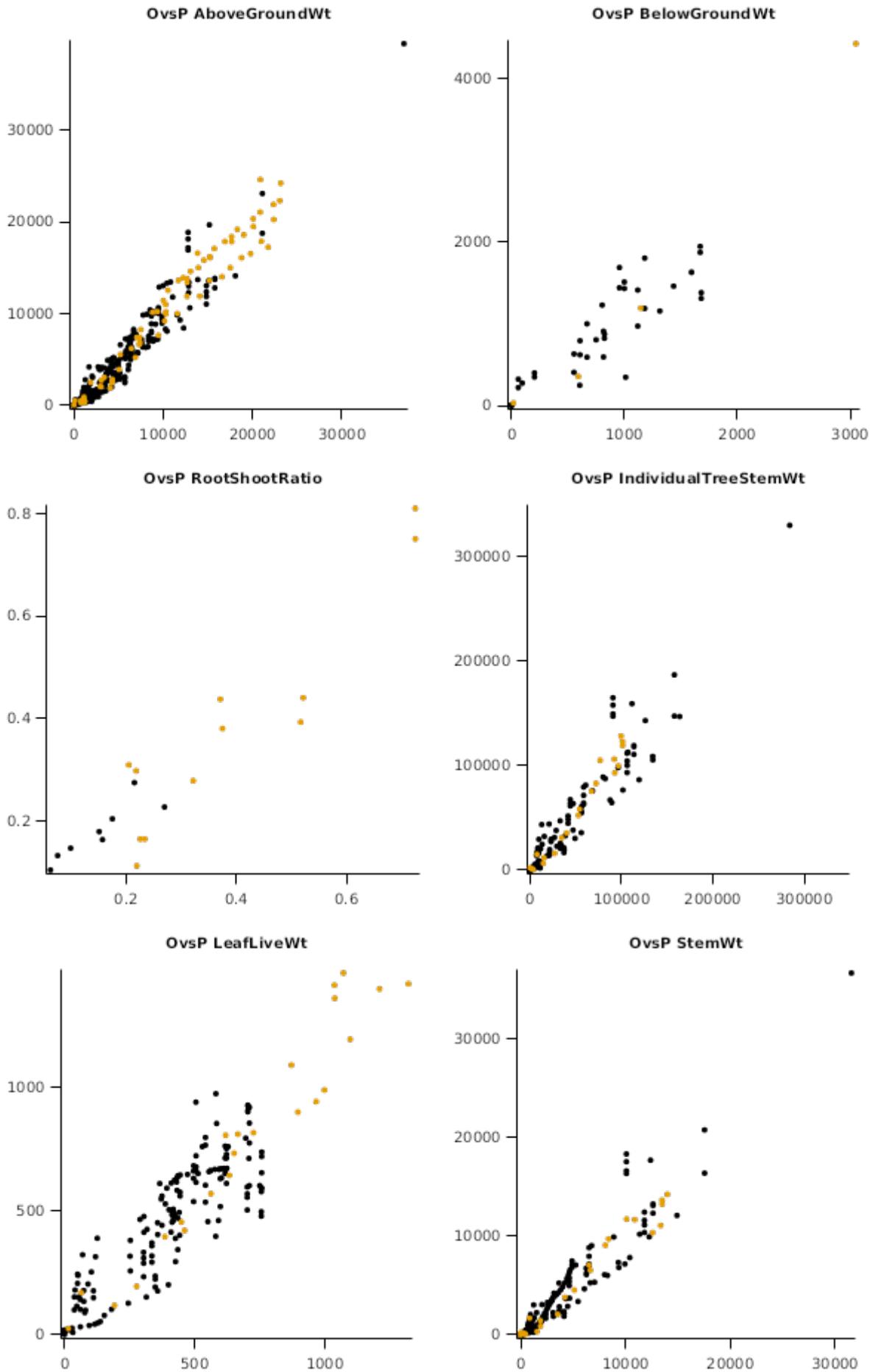
Observed data are shown compared to predictions, with statistics for model skill.

2.1 Combined Validation

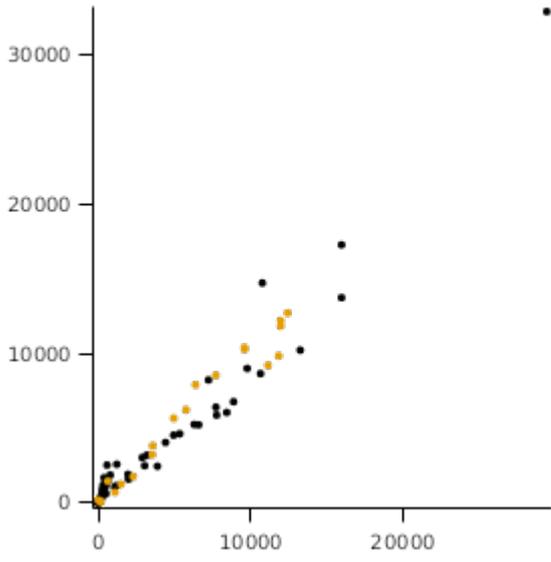
These graphs are for the combined datasets of *Tropical and SubTropical* and *Temperate* climatic zones.

Graphs from individual sites, particularly temporal trends of observed and predicted values, are available but currently

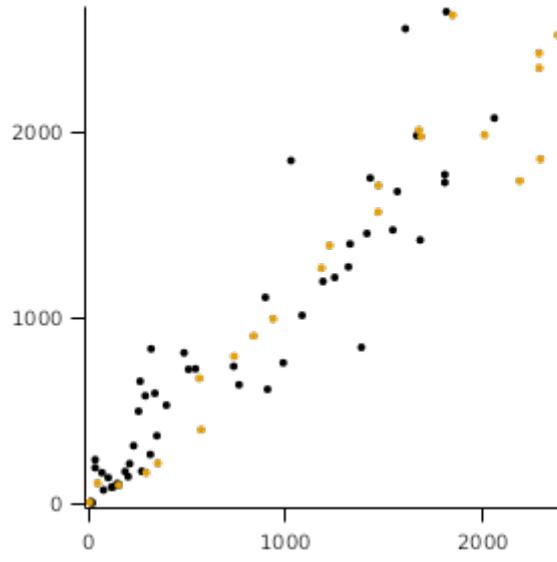
disabled. If you wish to view these graphs, please download the validation from GitHub, run it, and enable those graphs and-or add others.



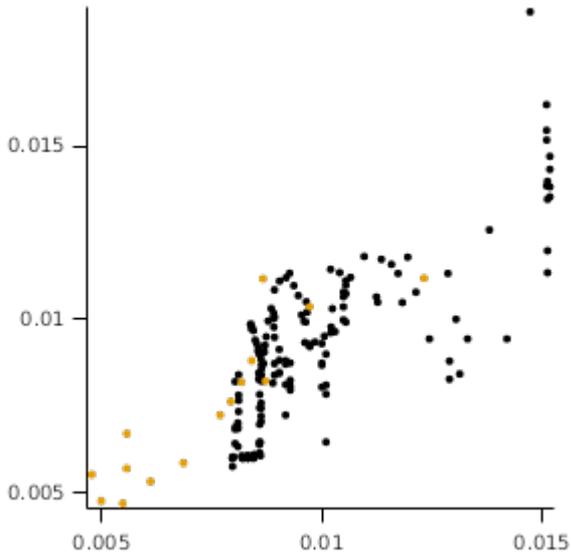
OvsP StemWoodWt



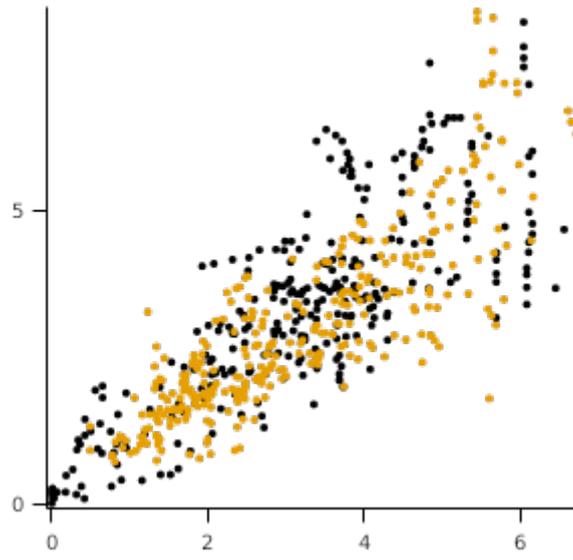
OvsP BranchLiveWt

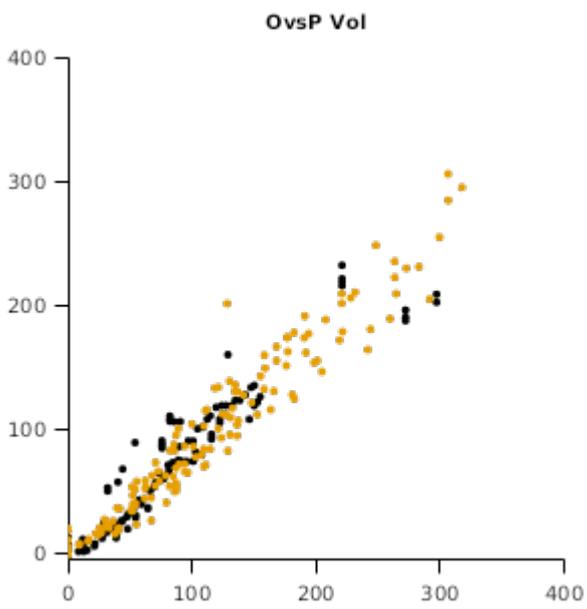
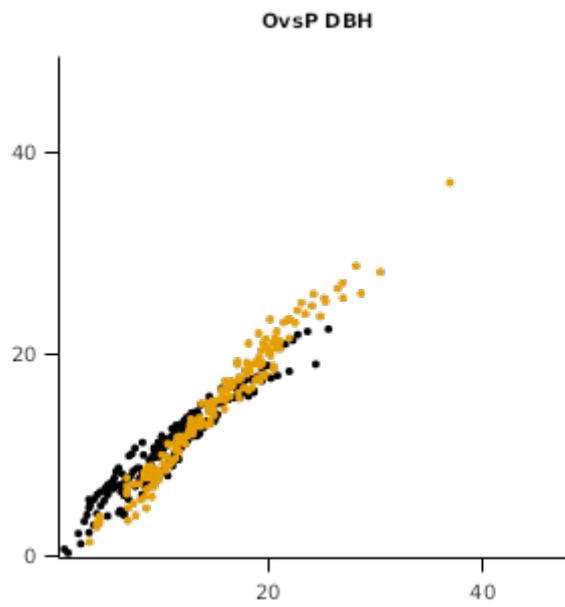
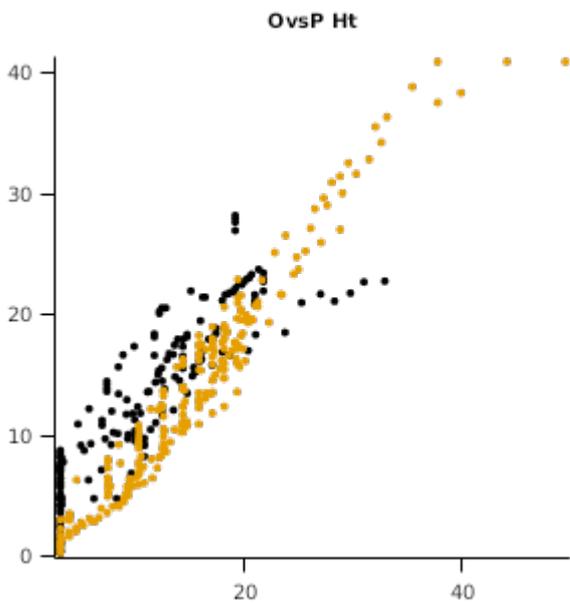


OvsP SLA



OvsP LAI



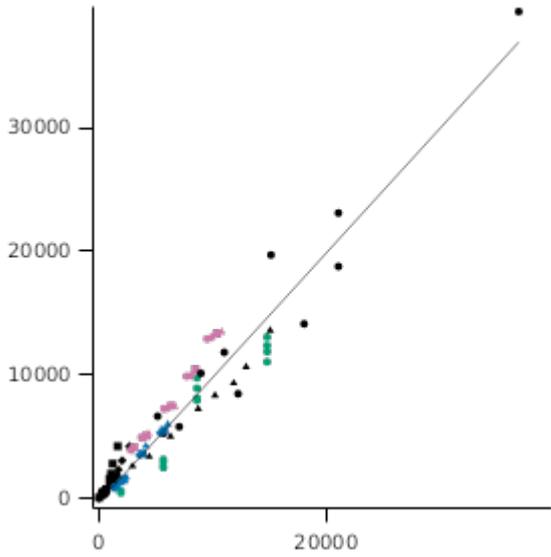


2.2 Tropical and SubTropical

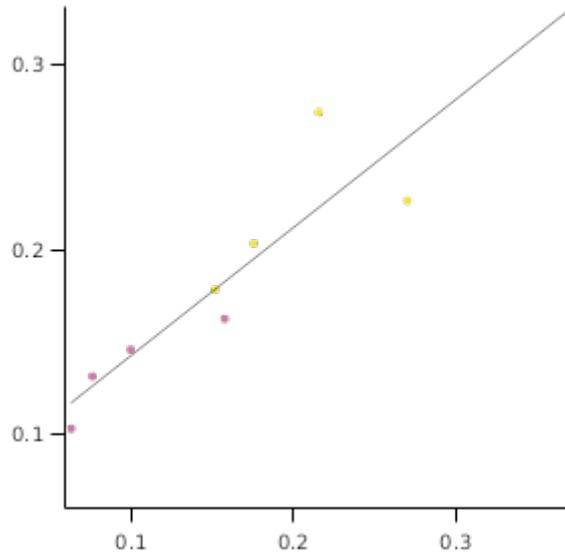
2.2.1 Tropical and SubTropical Validation

These graphs are for the *Tropical and SubTropical* datasets.

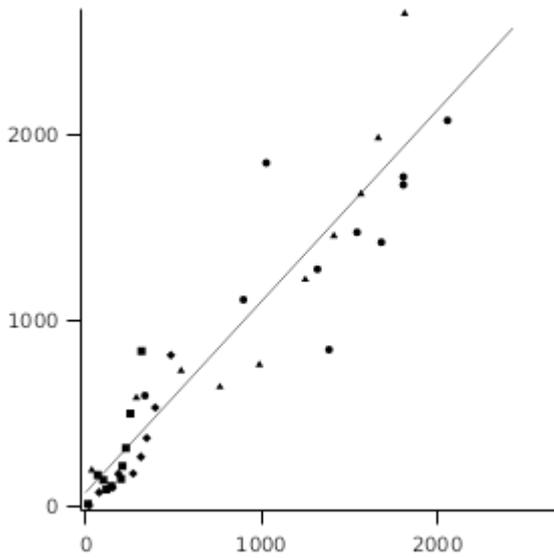
OvsP AboveGroundWt



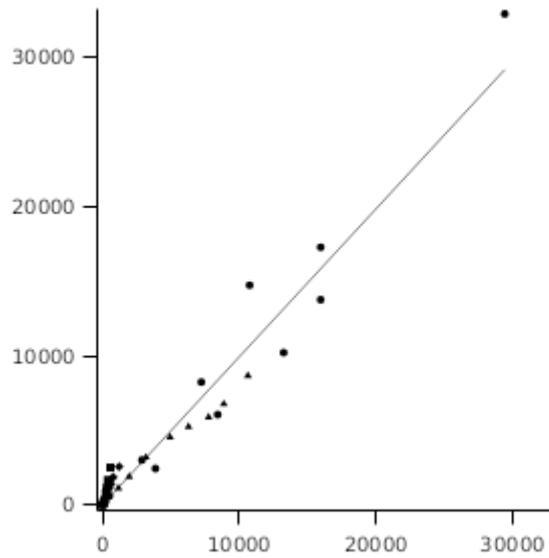
OvsP RootShootRatio



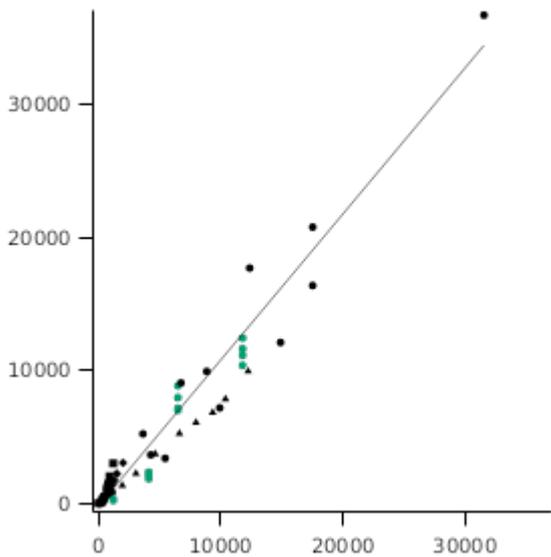
OvsP BranchLiveWt



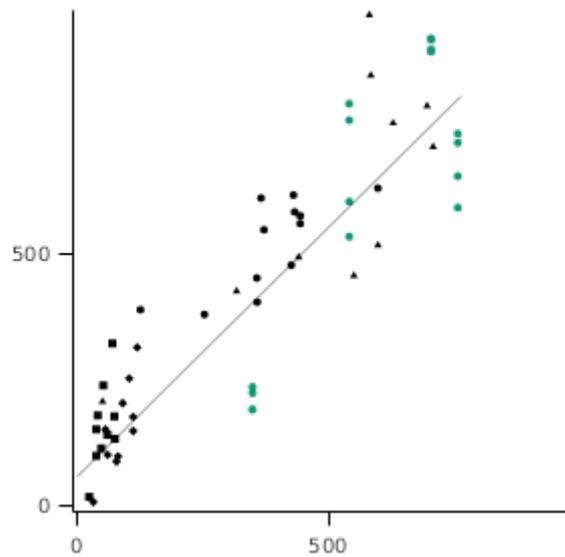
OvsP WoodWt

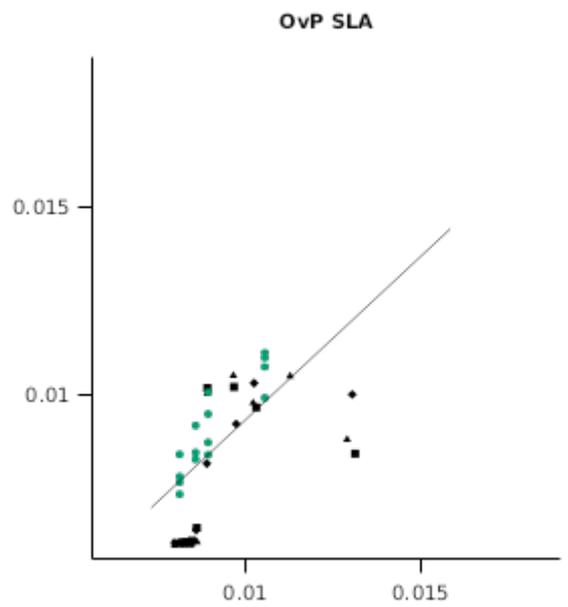
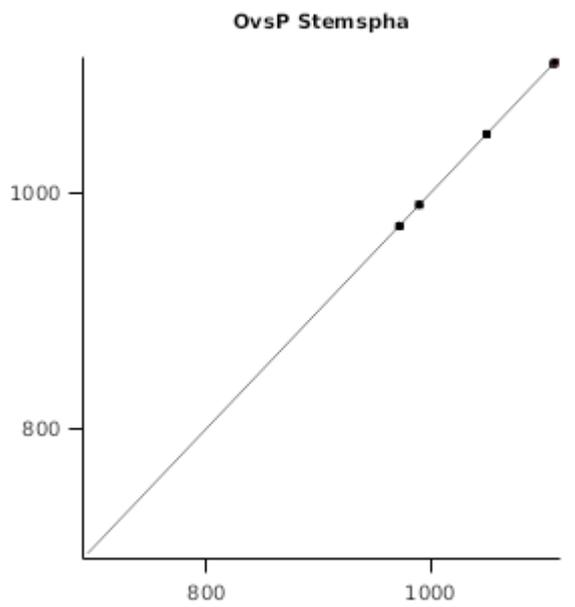
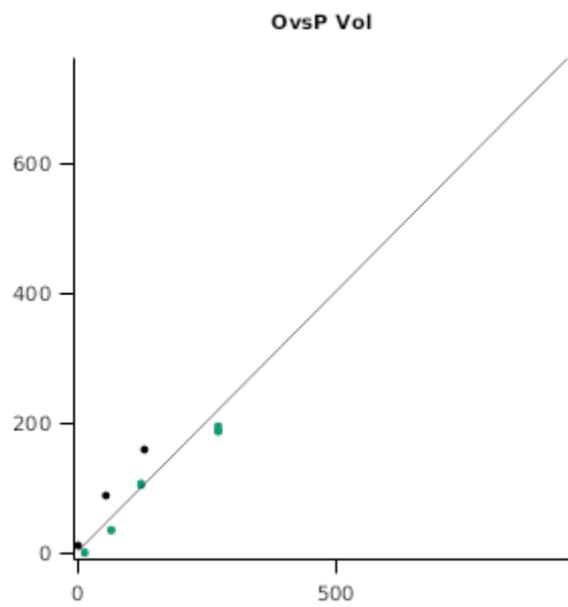
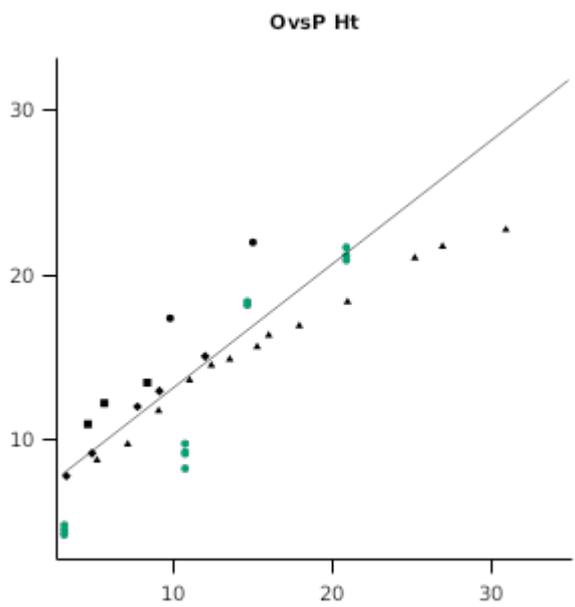
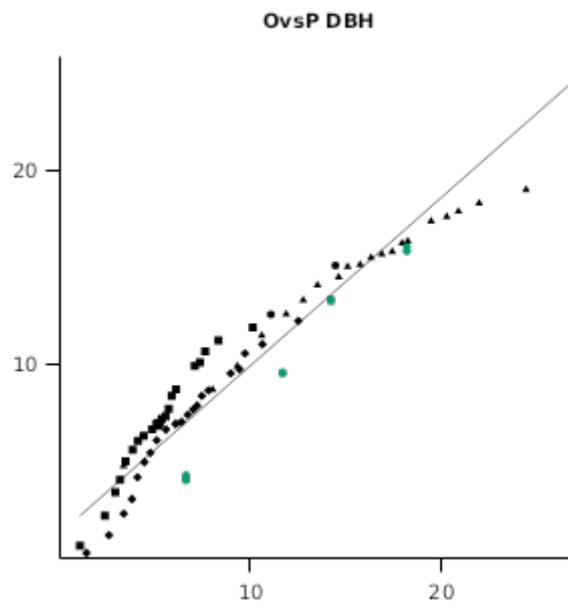
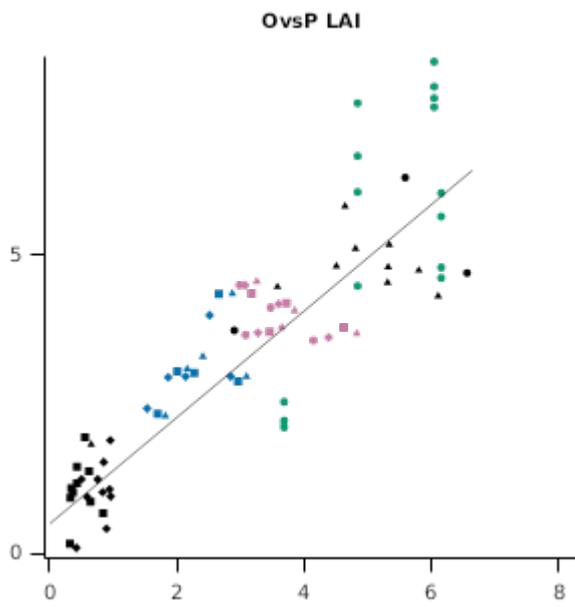


OvsP StemWt



OvsP LeafLiveWt





2.2.2 Australia Egrandis

2.2.2.1 CoffsHarbour

Data are from [Turner, 1986](#). The research is also reported in [Byrne, 1989](#) and [Bradstock, 1981](#). These data are from a chronosequence of approximately even-aged stands of native forests of *E. grandis* and include the oldest stands simulated so far by the APSIM Eucalyptus model. They are the only native forest data in this set of simulations; all other simulations are of plantations.

2.2.2.2 Gympie

This experiment is described in [Cromer et al., 1993](#) and [Cromer et al., 1993](#). Some soil input data are from [Ross, 1991](#). Experimental treatments were factorial combinations of two levels each of irrigation and fertilisation applied to *E. grandis*. Most growth response was to fertiliser, which included NPK, but only N is simulated, which assumes that other nutrients were present at adequate levels.

2.2.2.2.1 List of experiments

Experiment Name	Design (Number of Treatments)
Gympie	Treatment (4)

2.2.2.3 Wagga

This experiment is described in [Polglase et al., 1995](#), [Snow et al., 1999](#), [Snow et al., 1999](#), [Myers et al., 1996](#), and [Myers et al., 1998](#). The experiment included effluent-irrigated *E. grandis* and some weeds; only the irrigated treatment was included here.

2.2.3 Brazil Egrandis and others

2.2.3.1 Aracruz

These data are described in [Almeida, 2003](#) and [Almeida et al., 2004](#). Two clones of *E. grandis* are included that had measured differences in root:shoot ratio. These differences were simulated by specifying partitioning targets as a genetic property.

2.2.3.1.1 List of experiments

Experiment Name	Design (Number of Treatments)
Aracruz	Cult (2)

2.2.3.2 Curvelo

These data are described in [Borges, 2009](#). Two clones of the hybrid *E. grandis* x *E. urophylla* were included (C3334, C3336), but their measured differences were not significantly different. Hence, clonal differences were not simulated by specifying partitioning targets as a genetic property.

2.2.3.2.1 List of experiments

Experiment Name	Design (Number of Treatments)
Curvelo	Site (2)

2.2.3.3 Itacambira

These data are described in [Borges, 2009](#). Two clones of the hybrid *E. grandis* x *E. urophylla* were included (C3334, C3336), but their measured differences were not significantly different. Hence, clonal differences were not simulated by specifying partitioning targets as a genetic property.

2.2.3.3.1 List of experiments

Experiment Name	Design (Number of Treatments)
Itacambira	Site (2)

2.2.3.4 Luisantonio

These data are described in [Melo et al., 2015](#). One clone of the hybrid *E. grandis* x *E. urophylla* was grown with 4 rates of N fertilisation.

2.2.3.4.1 List of experiments

Experiment Name	Design (Number of Treatments)
Luisantonio	N (4)

2.2.3.4.2 Luisantonio

Graph

2.2.3.5 Mogiguacu

These data are described in [Melo et al., 2015](#). One clone of the hybrid *E. grandis* x *E. urophylla* was grown with 4 rates of N fertilisation.

2.2.3.5.1 List of experiments

Experiment Name	Design (Number of Treatments)
Mogiguacu	N (4)

2.2.3.6 MonteDourado

These data are described in [Silva, 2006](#). One clone of the hybrid *E. grandis* x *E. urophylla* was included, and it was grown at two sites on contrasting soils.

2.2.3.7 Paulistania

These data are described in [Melo et al., 2015](#). One clone of the hybrid *E. grandis* x *E. urophylla* was grown with 4 rates of N fertilisation.

2.2.3.7.1 List of experiments

Experiment Name	Design (Number of Treatments)
Paulistania	N (4)

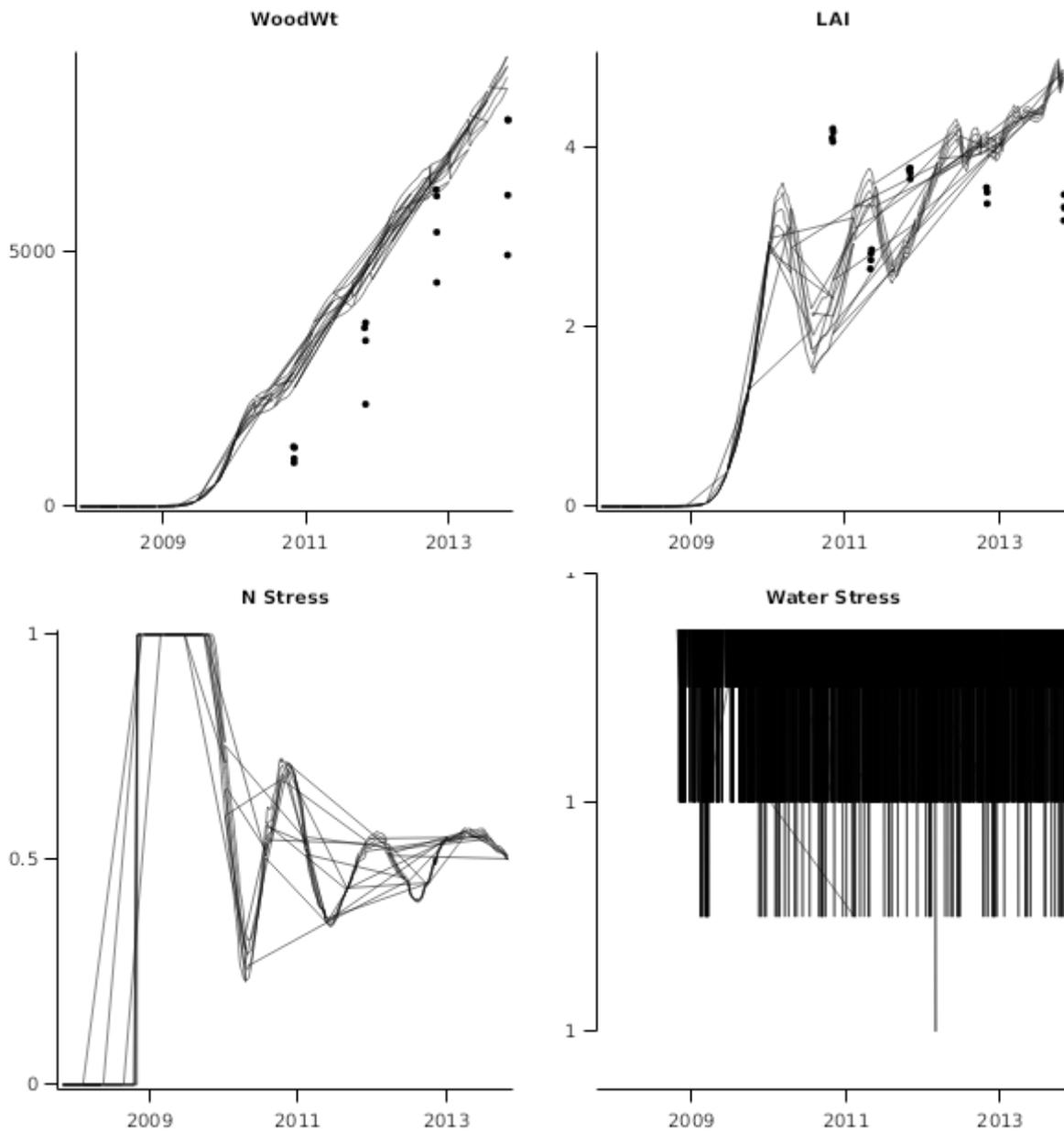
2.2.3.8 Ribasdoriopardo

These data are described in [Melo et al., 2015](#). One clone of the hybrid *E. grandis* x *E. urophylla* was grown with 4 rates of N fertilisation.

2.2.3.8.1 List of experiments

Experiment Name	Design (Number of Treatments)
Ribasdoriopardo	N (4)

2.2.3.8.2 Ribasdoriopardo



2.2.3.9 SantanadoParaiso

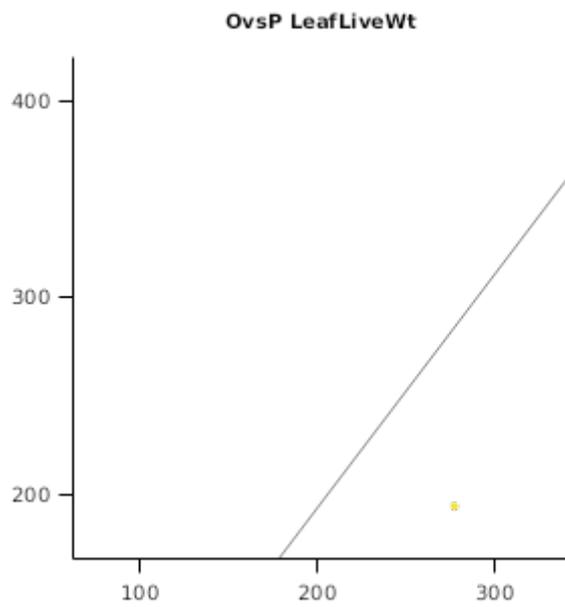
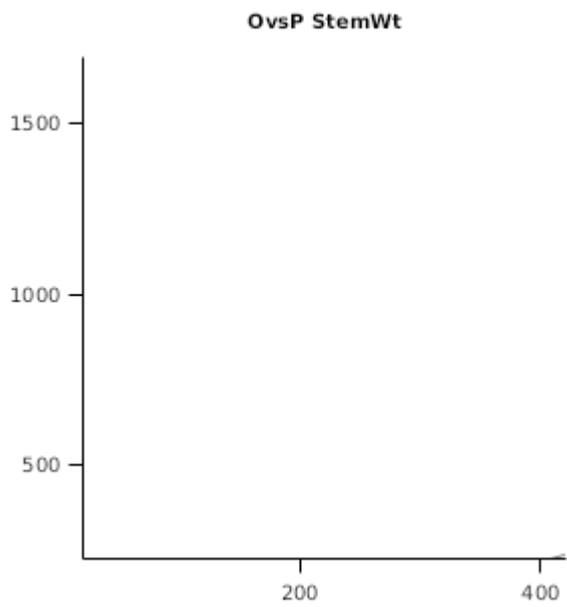
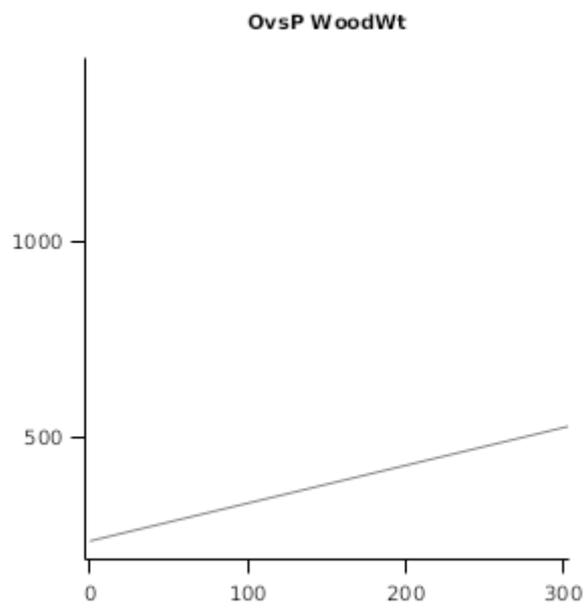
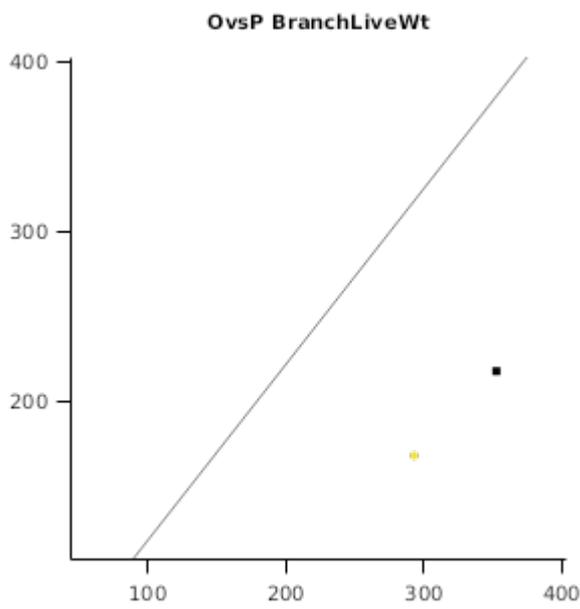
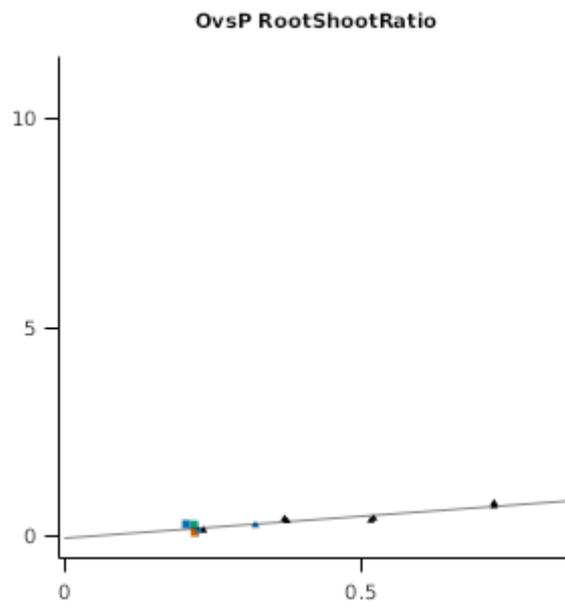
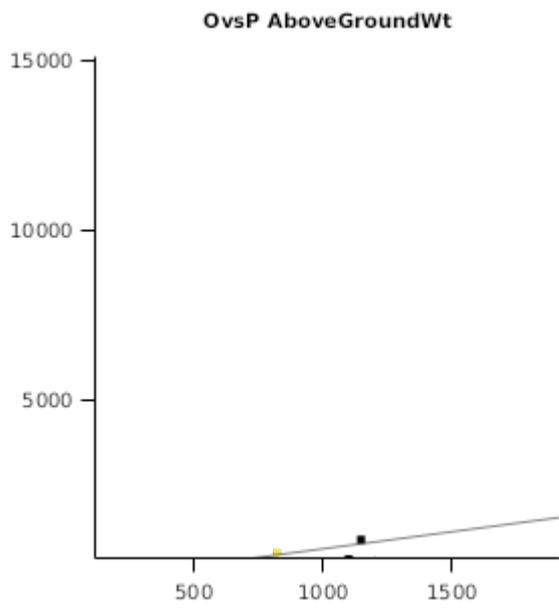
These data are described in [Nogueira, 2005](#). One clone of the hybrid *E. grandis* was included, and it was grown in a factorial experiment of two levels each of irrigation and fertilisation.

2.2.3.9.1 List of experiments

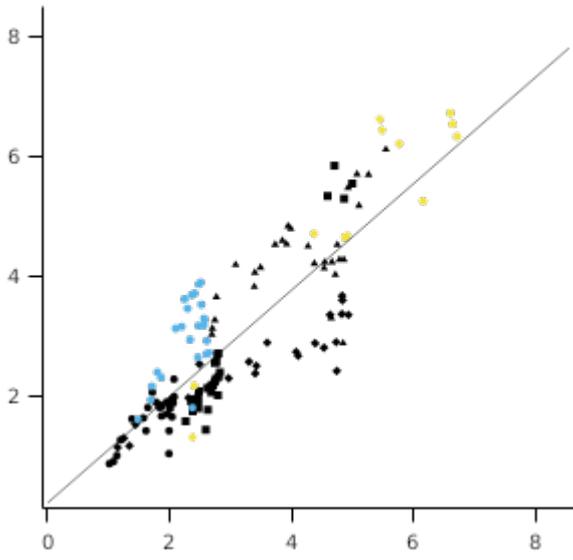
Experiment Name	Design (Number of Treatments)
SantanadoParaiso	Irr x N (4)

2.3 Temperate

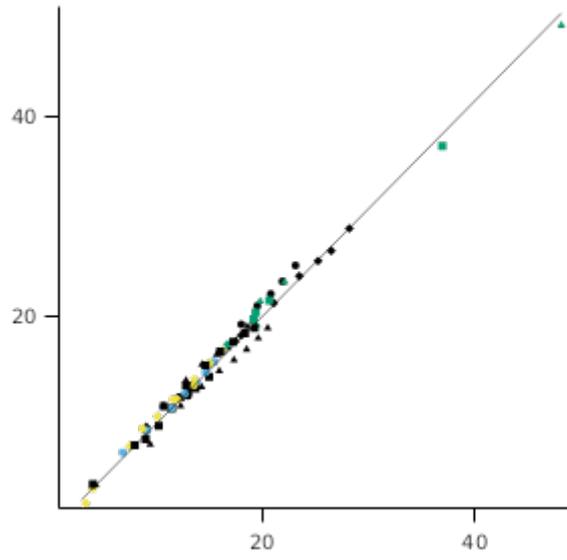
2.3.1 Temperate Validation



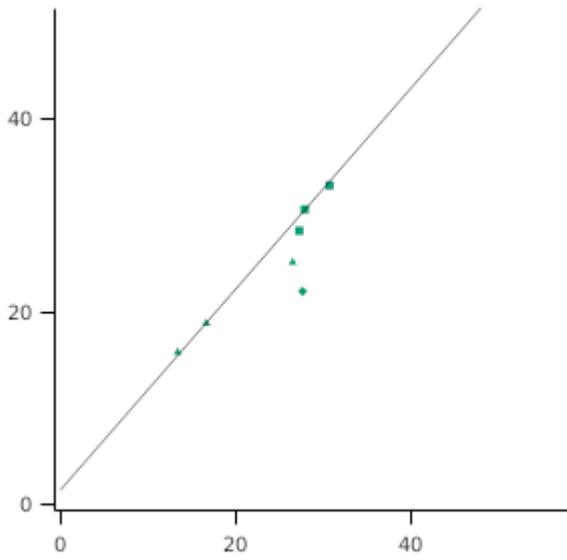
OvsP LAI



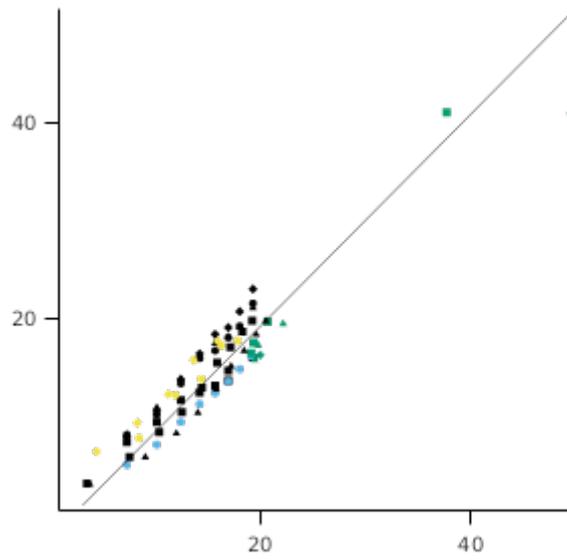
OvsP DBH



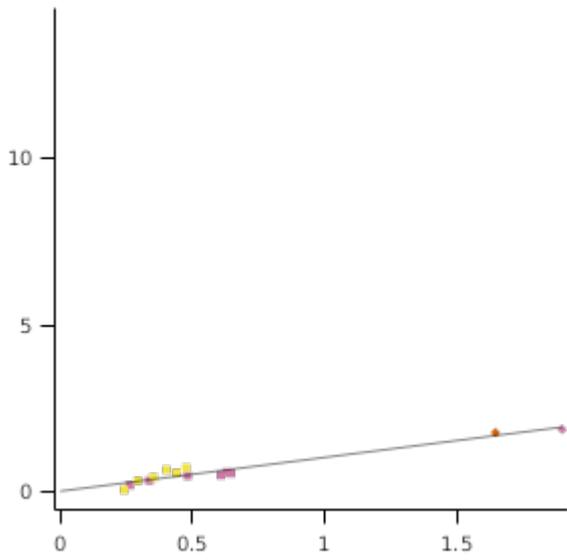
OvsP BA



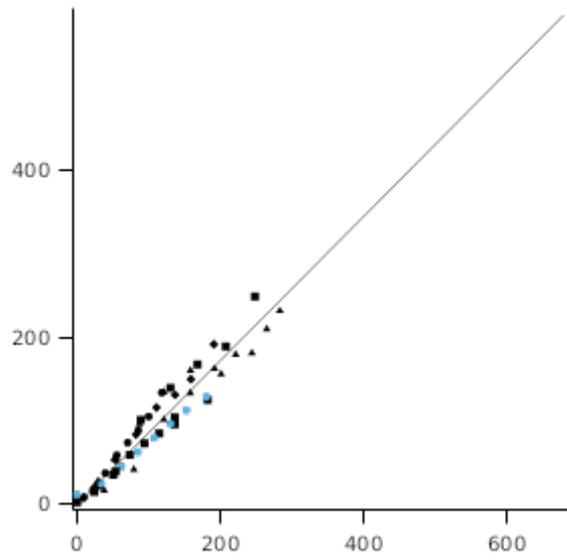
OvsP Ht



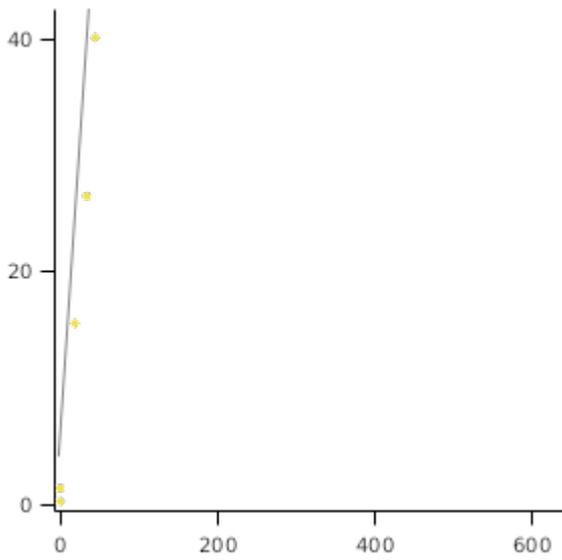
OvsP BarkThickness



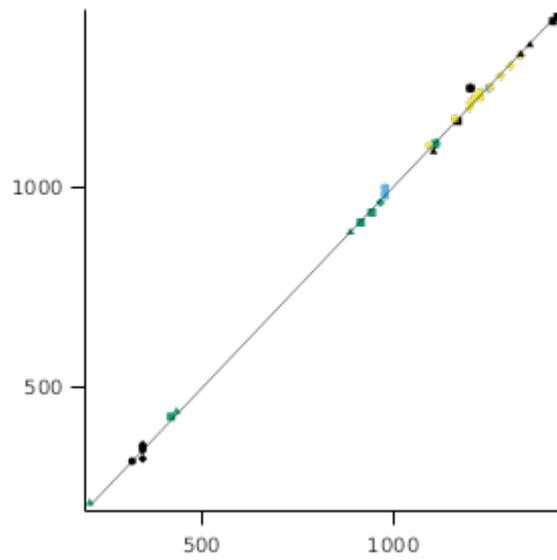
OvsP Vol



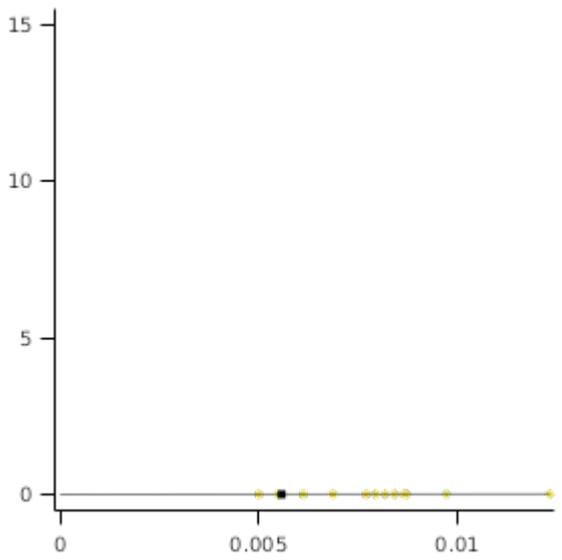
OvsP Volub



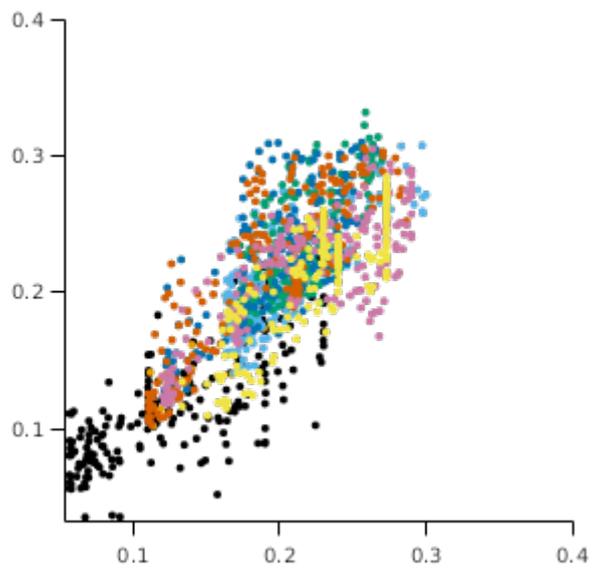
OvsP Stemspha



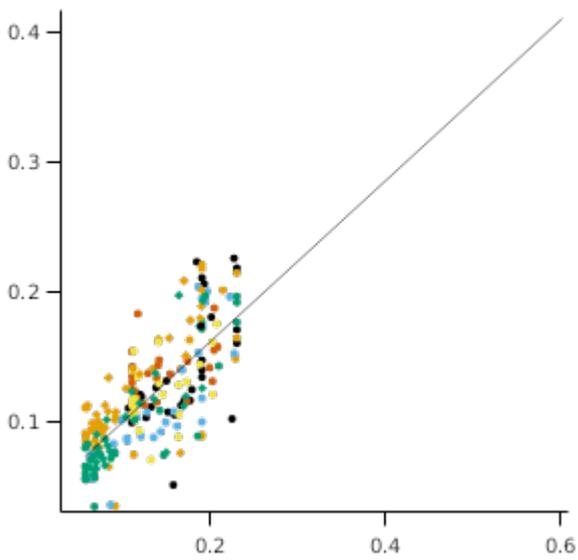
OvP SLA



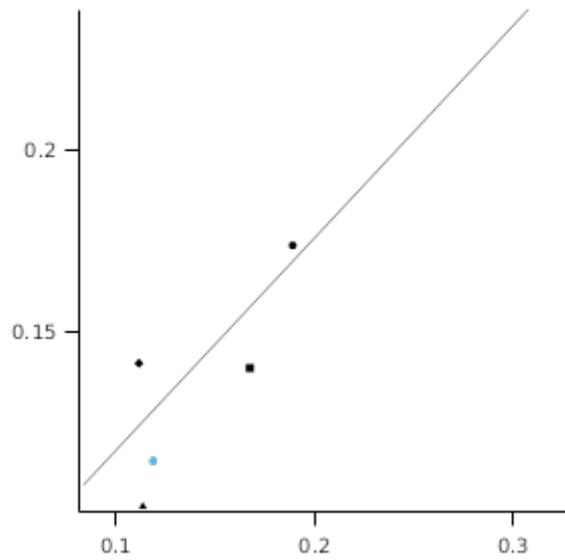
SWALL

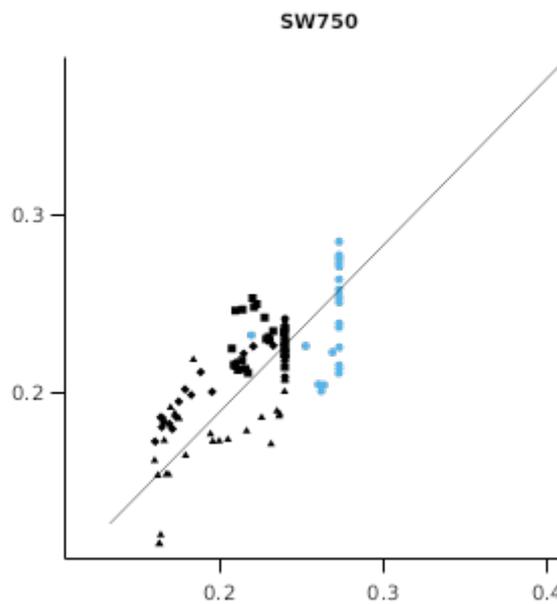
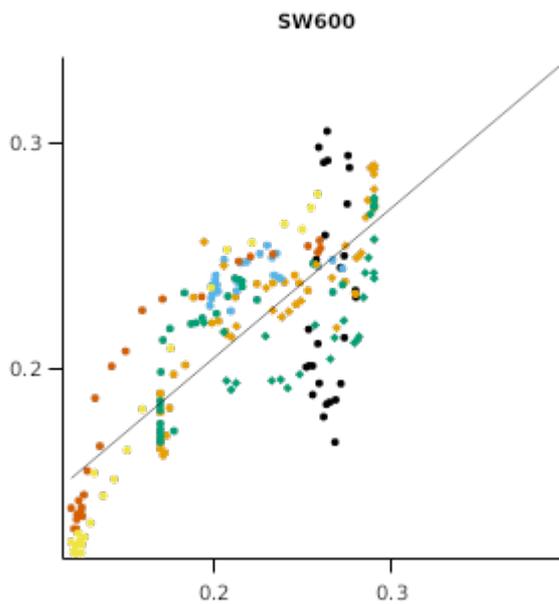
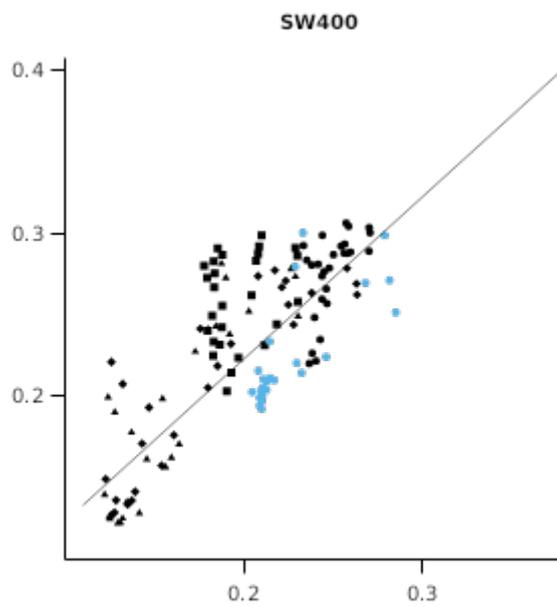
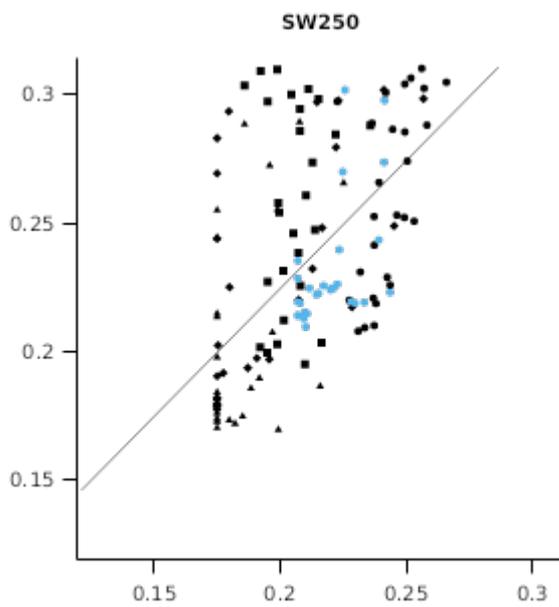
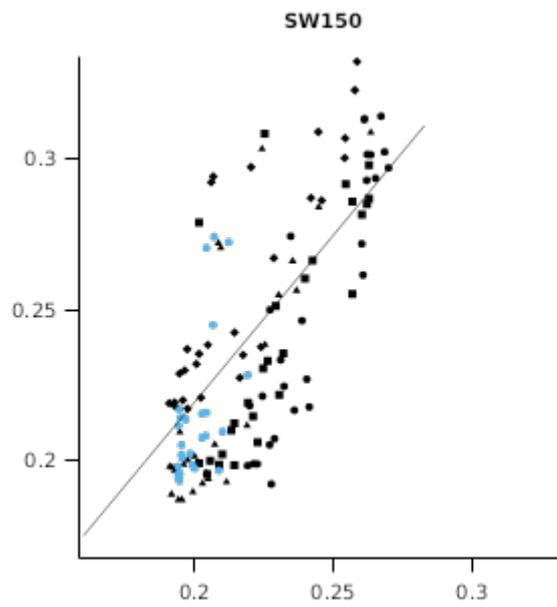
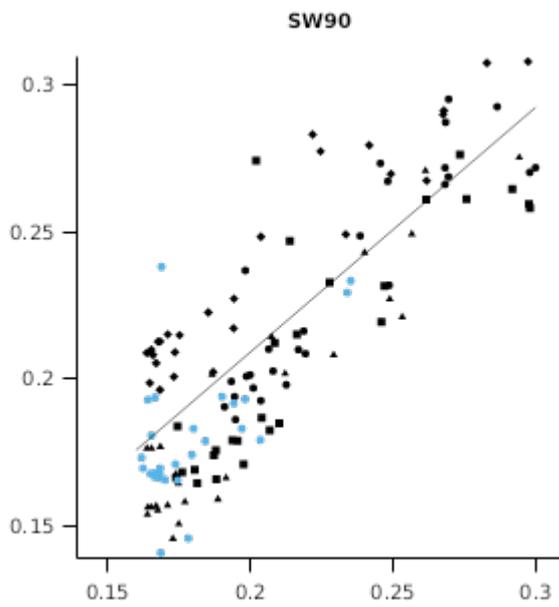


SW30



SW50





2.3.2 DroughtRiskSites

These experiments are described in [Mendham et al., 2011](#), [White et al., 1996](#), [White et al., 1998](#), [White et al., 2009](#), [White et al., 2010](#) and [White et al., 2014](#). Experimental treatments were combinations of stocking and N fertilisation starting 2 years after planting. Additional data were provided by D. Mendham. A second rotation is described in these

papers and data included in the observed file, but treatments were reallocated at the beginning of the second rotation, and coppice rather than seedlings were used in most treatments for the second rotation. It would be useful and possible to include coppicing in the Eucalyptus model, but this has not yet been attempted. Other models in APSIM provide a basis for including coppicing, e.g. gliricidia, and lucerne.

2.3.2.1 List of experiments

Experiment Name	Design (Number of Treatments)
ScottRiver	N (4)
Wellstead	N (4)
BoyupBrook	N (4)

2.3.3 Forico

These data describe adjacent plantations of *E. globulus* and *E. nitens*, with part of the *E. nitens* plantation being thinned. The site was known as St Georges Road. We thank G. Holz, K. Joyce, and L. Cannon of Forico for data and other information about the site (formally the site was owned or managed by Gunns, North Forest Products and APPM).

2.3.3.1 List of experiments

Experiment Name	Design (Number of Treatments)
Forico	StGRd (3)

2.3.4 FSAGrowthPlots

These data are for Forestry SA growth plots, and were provided Jim O'Hehir, University of South Australia. As they are in a region with a water table containing nitrate that can be reached by roots, these components were added to the simulation. However, nitrate was not described as a concentration in groundwater, but instead nitrate was applied as nitrate fertiliser at 2.5 m depth or greater four times per year. Thinned and unthinned stands are included.

2.3.4.1 List of experiments

Experiment Name	Design (Number of Treatments)
FSAGPs	A (4)

2.3.5 Furadouro

This experiment is described in [Madeira et al., 1990](#), [Madeira et al., 1995](#), [Pereira et al., 2012](#), [Madeira et al., 2002](#), [Fabião et al., 1995](#), [Klatte et al., 1995](#), [Quilho et al., 2001](#), [Pereira et al., 1994](#), [Pereira et al., 1989](#), and [Fontes et al., 2006](#). Experimental treatments were combinations of irrigation and fertilisation applied to *E. globulus*. Most growth response was to fertiliser, which included NPK, but only the IL treatment was simulated here, which assumes that nutrients other than N were also present at adequate levels.

2.3.5.1 List of experiments

Experiment Name	Design (Number of Treatments)
Furadour	o (1)

2.3.6 Lewisham

This experiment is described in [White et al., 1998](#), [White et al., 1996](#), and [Worledge et al., 1998](#). The experiment included a comparison of *E. globulus* and *E. nitens* under supplemented-rainfed and well-irrigated conditions. Rainfed plots were up-slope of the irrigated plots. Soil was mostly derived from basalt, which was present at a shallow depth.

2.3.6.1 List of experiments

Experiment Name	Design (Number of Treatments)
Lewisham	E (2)

2.3.7 Shepparton

This experiment is described in [Bren et al., 1993](#), [Baker, 1998](#), [Baker et al., 2005](#), [Duncan et al., 1998](#), [Wong et al., 2000](#), [Hopmans et al., 1990](#), and [Stewart et al., 1990](#). Additional data and information were provided by T.G. Baker and H.

Stewart. The experiment included coppiced and seedling *E. grandis* and *E. globulus*, which were irrigated with sewerage effluent. The soil was a duplex, and there for poorly drained. Eearly growth was quite impressive, but by 10 years trees had noticably mortality due to pests and diseases, and also due to other conditions that did not suit these species (poor drainage, frost).

2.3.7.1 List of experiments

Experiment Name	Design (Number of Treatments)
Shepparton	E (2)

2.3.8 Westfield

This experiment is described in [Smethurst et al., 1997](#), [Smethurst et al., 2003](#), [Smethurst et al., 2004](#), [Smethurst et al., 2004](#), [Misra et al., 1998](#), [Misra et al., 1998](#), and [Resh et al., 2003](#). The experiment included nil to high cumulative rates of N and P fertilisers in an *E. nitens* plantation. Other research suggested that three was little or no response to the P component of the fertiliser. Very high rates of fertiliser might have started to induced a base cation deficiency (Ca, Mg or K) by the latter stage of the rotation, as some acidification had occurred, but this was not investigated further.

2.3.8.1 List of experiments

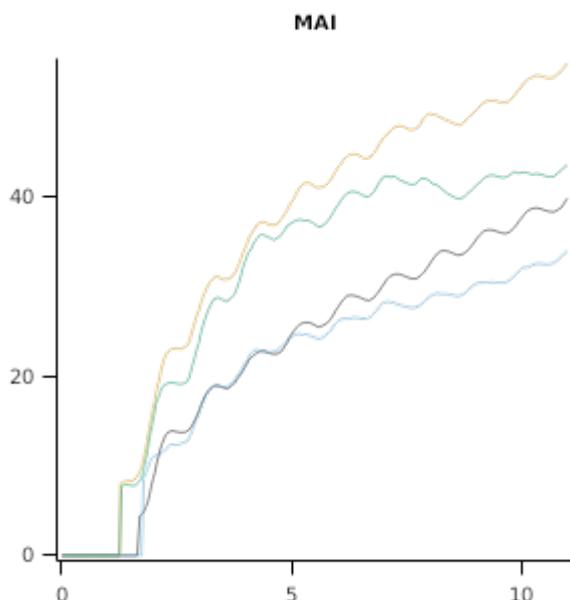
Experiment Name	Design (Number of Treatments)
Westfield	T (6)

3 Sensibility

A series of sensibility tests have been employed to test the behaviour of the model in regions not explicitly included in the previous test set. Furthermore, these tests explore the emergent behaviour of the model under a range of changing climate, fertility and management scenarios to ensure that simulated patterns agree with expected behaviours.

3.1 MAI in SE Australia

Representative growth rates for *Eucalyptus grandis* have been published for south-eastern Australia (Victoria and South Australia) by [Wong2000forecasting]. Some of the sites within this publication had previously been used for improved pasture and had minimal fertility constraints. Simulations for 4 sites have been presented here to capture a range of environmental conditions. Stocking rates used at each site match those obtained at each site within the published study. MAI at age 10 years should be approximately 10 cubic metres per annum for Mount Worth and Stockdale and approximately 20 cubic metres per annum for Tostaree and Mount Lofty. Climate data has been taken from nearby towns and common soil properties have been used for all sites, with soil properties reflecting a relatively high state of fertility.



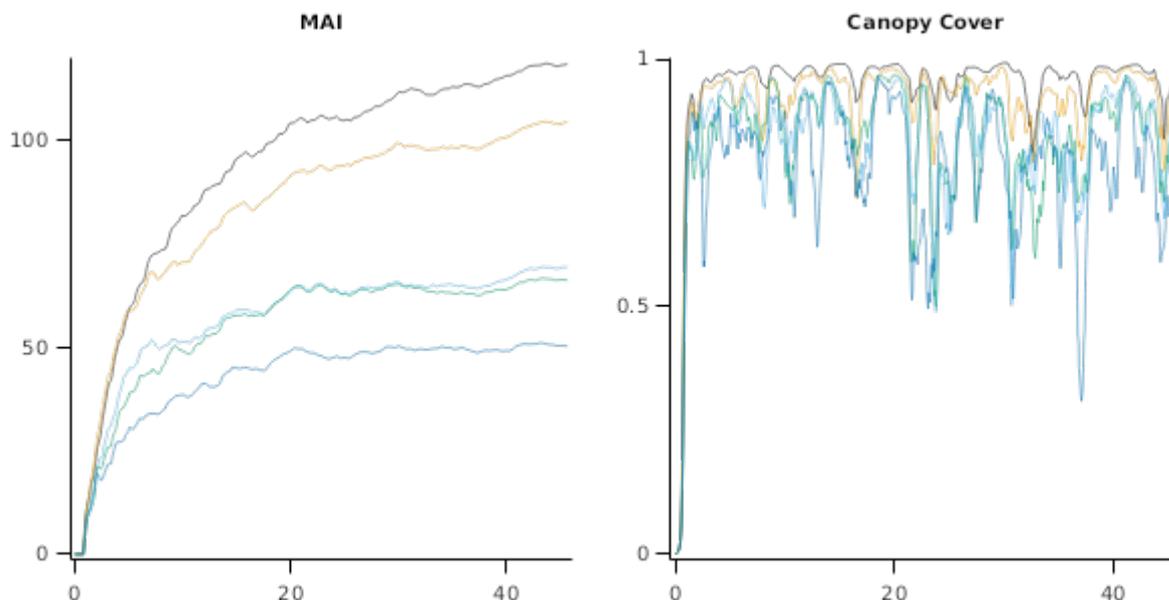
3.2 Response to Rainfall

Eucalyptus should respond to changes in rainfall such that peak MAI should increase with rainfall. Long term "climax LAI" should also increase with mean annual rainfall. This simulation experiment explores the changes in MAI and canopy cover along a rainfall gradient within SE Queensland Australia. Mean annual rainfall decreases from approximately 1200 mm to 660 mm. Fertiliser is applied within the simulations to remove any confounding of results due to site fertility. Data

from [Specht, 1972](#) show that canopy cover should be almost complete for the wetter sites in this study, and decrease to approximately 50% at the drier sites.

3.2.1 List of experiments

Experiment Name	Design (Number of Treatments)
Climate	Site (5)

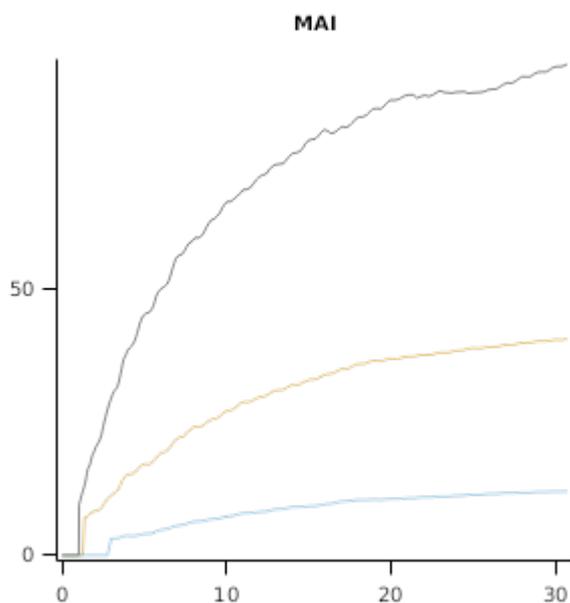


3.3 Response to Soil Fertility

Site fertility is an important driver of the pattern of tree growth rates. As site fertility declines, the long term growth rate (e.g. MAI) should also decrease, but the time to obtaining peak MAI should increase. This sensibility test uses a single location in SE Queensland at which *Eucalyptus grandis* occurs naturally. A range of soil fertility states are applied in this experiment. Peak MAI should decrease with decreasing fertility, but the time required to achieve this should increase.

3.3.1 List of experiments

Experiment Name	Design (Number of Treatments)
Fertility	Level (3)



3.4 Reponse to N Fertilizer

Eucalyptus responses to rate of fertiliser are often asymptotic, the plateau of which is determined by other limiting factors (Rubilar et al., 2018). In the sensibility tests presented here, soil from Wodonga, Australia, was used as the basis for the simulations, except soil organic C and C:N were set to represent site 1 in Columbia in Albaugh et al., 2015 and Rubilar et al., 2018. Two climates are used in these simulations ('Wodonga0ClimateWodonga' and 'Wodonga0ClimateCoffs'). Management was set similar to site 1 in Rubilar et al., 2018, i.e. E grandis was fertilised at 2 years of age and the 3-year stem volume response assessed at 5 years of age. For a highly responsive site in Columbia, a plateau in growth response occurred at about 800 kg N/ha, when it was speculated that other factors became limiting.

In 'Wodonga0ClimateWodonga', a low rainfall site (739 mm/year average longterm), the response to N was simulated to plateau at a rate of about 800 kg N/ha. The N rate inflexion point here is similar to that in Rubilar et al., 2018, but the limiting factor above this N rate in this simulation was mainly water, whereas in Albaugh et al., 2015 we can speculate that it was base cation deficiency.

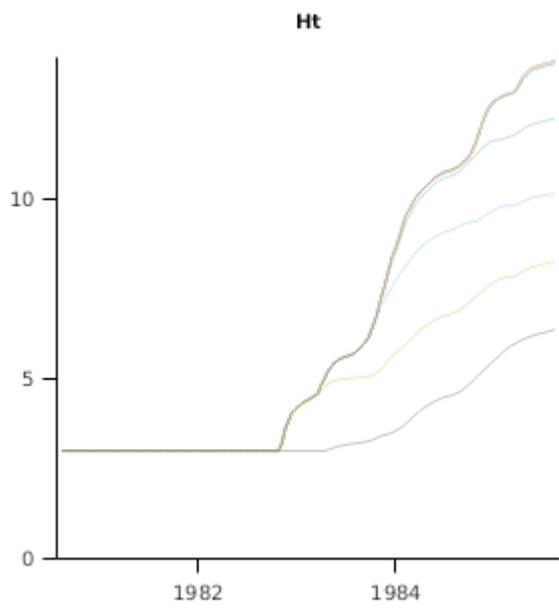
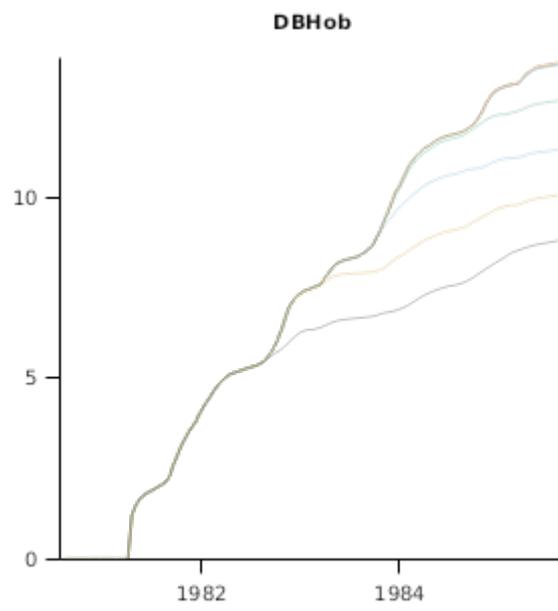
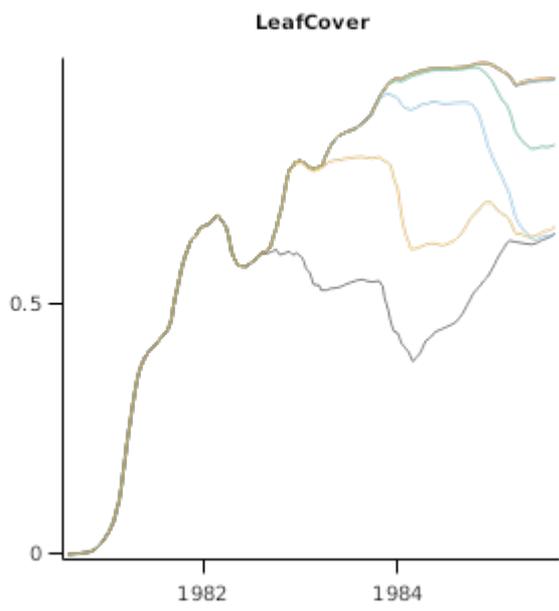
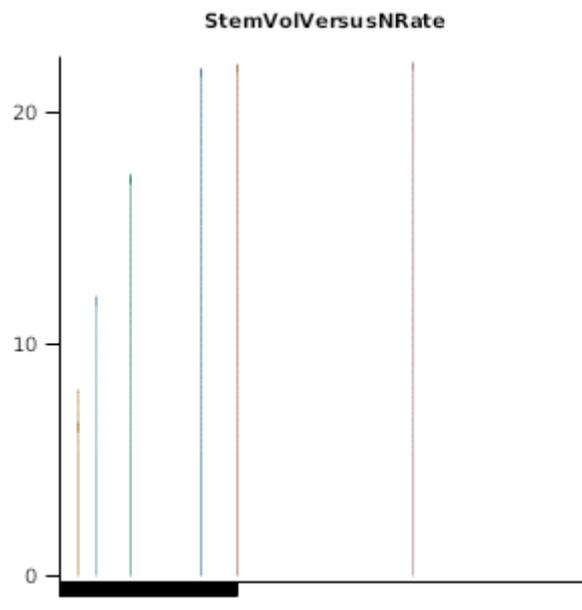
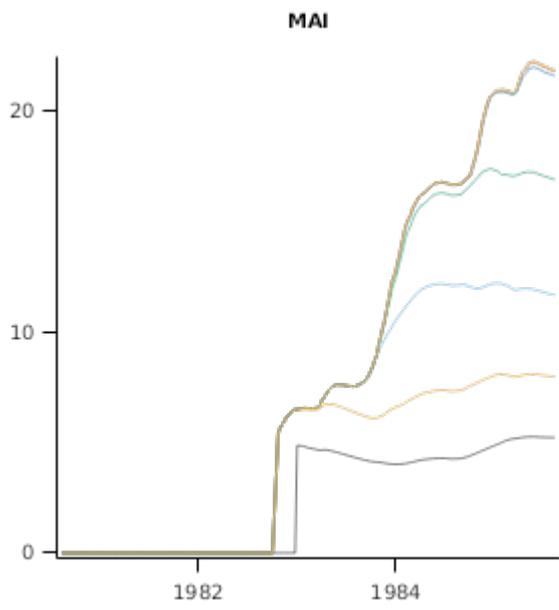
In 'Wodonga0ClimateCoffs', a high rainfall site (1635 mm/year average longterm), the water limitation was removed and the response to N has not plateaued even at a rate of 3000 kg N/ha.

Values of MAI and other outputs are in the range of expectation.

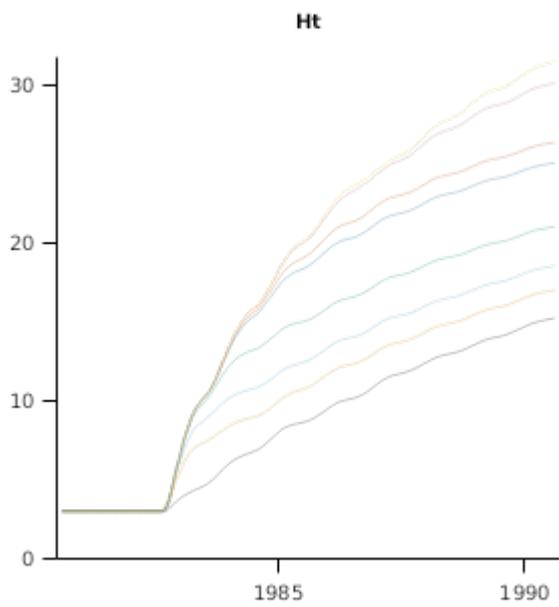
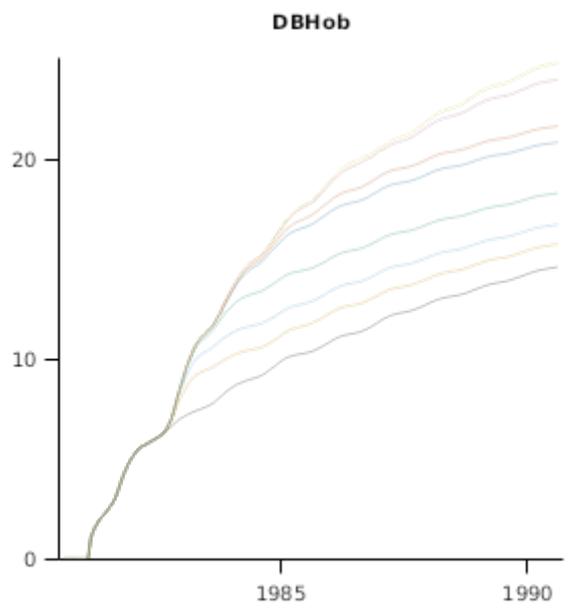
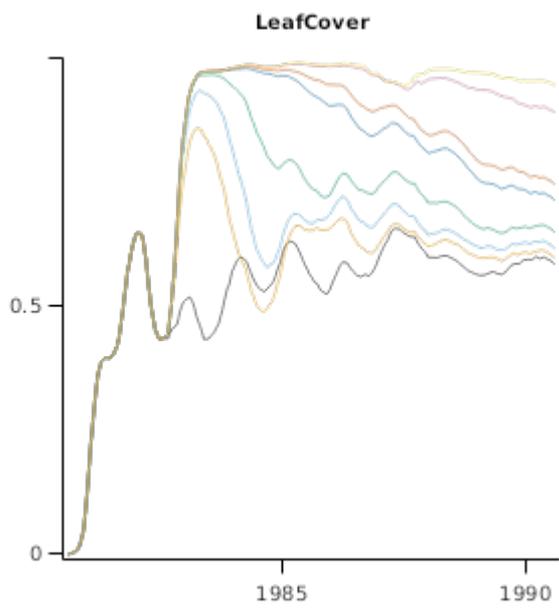
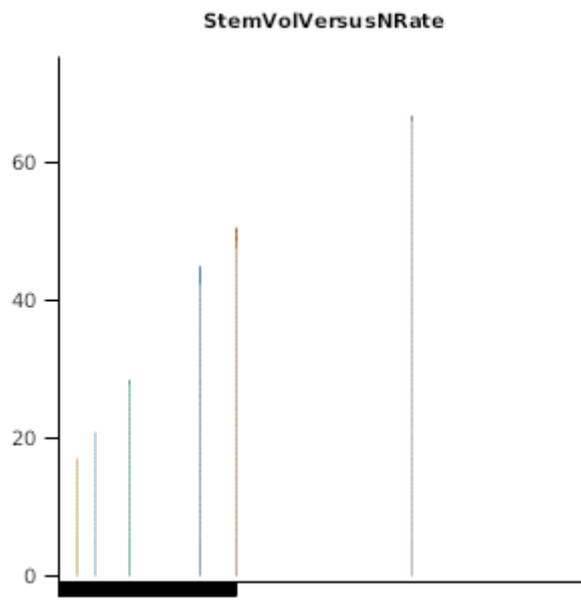
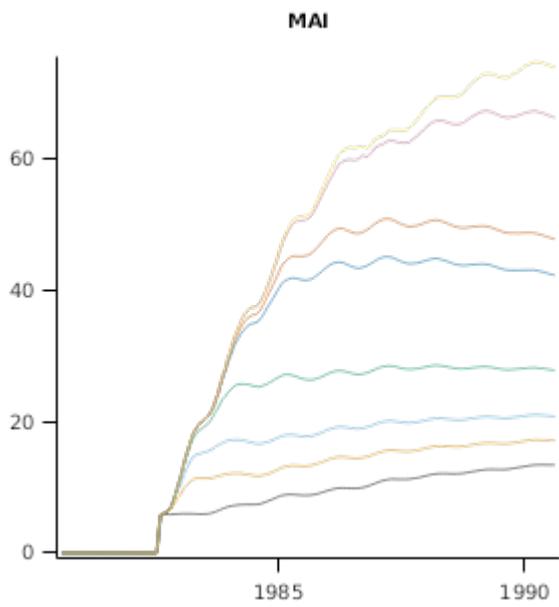
3.4.1 List of experiments

Experiment Name	Design (Number of Treatments)
Wodonga0ClimateWodonga	N (8)
Wodonga0ClimateCoffs	N (8)

3.4.2 Wodonga0ClimateWodonga



3.4.3 Wodongal0ClimateCoffs

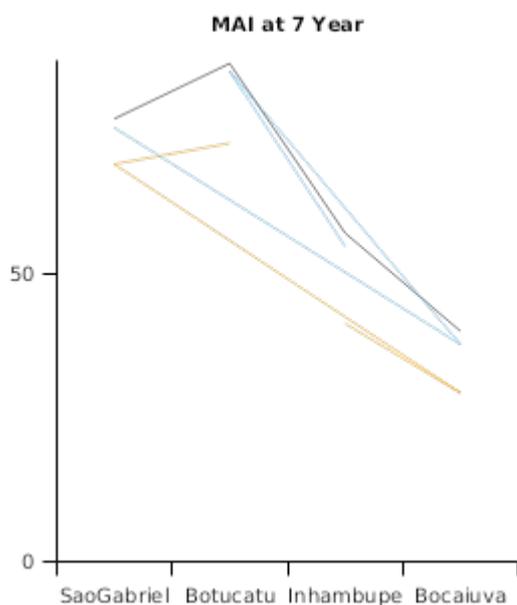


3.5 GXE Brazil

The graphs shown here demonstrate a genotype \times site interaction. Inhambupe is a dry site in NE Brazil. Botucatu is a highly productive site in SE Brazil. Sao Gabriel is a wet site in S Brazil. Bocaiuve is a dry site in SE Brazil.

3.5.1 List of experiments

Experiment Name	Design (Number of Treatments)
GxEBrazil	Site x Clone (12)



3.6 ScottRiverNResponse

This experiment is described in [Cromer et al., 1993](#) and [Cromer et al., 1993](#). Some soil input data are from [Ross, 1991](#). Experimental treatments were factorial combinations of two levels each of irrigation and fertilisation applied to *E. grandis*. Most growth response was to fertiliser, which included NPK, but only N is simulated, which assumes that other nutrients were present at adequate levels.

3.6.1 List of experiments

Experiment Name	Design (Number of Treatments)
ScottRiverNResponse	N (7)

4 References

- Albaugh, Timothy J, Rubilar, Rafael A, Fox, Thomas R, Allen, H Lee, Urrego, John B, Zapata, Marcela, Stape, Jose L, 2015. Response of *Eucalyptus grandis* in Colombia to mid-rotation fertilization is dependent on site and rate but not frequency of application. *Forest Ecology and Management* 350, 30-39.
- Almeida, AC, 2003. Application of a process-based model for predicting and explaining growth in *Eucalyptus* plantation..
- Almeida, Auro C, Landsberg, Joe J, Sands, Peter J, 2004. Parameterisation of 3-PG model for fast-growing *Eucalyptus grandis* plantations. *Forest Ecology and Management* 193 (1-2), 179-195.
- Baker, T, Duncan, M, Stackpole, D, others, 2005. Growth and silvicultural management of irrigated plantations. *New forests: wood production and environmental services*, 113-134.
- Baker, TG, 1998. Tree growth in irrigated plantations at Wodonga and Kyabran, Victoria (1976-1994)..
- Borges, JS, 2009. Parameterization calibration and validation of the 3PG model for the cerrado of Minas Gerais..
- Bradstock, R, 1981. Biomass in an age series of *Eucalyptus grandis* plantations. *Australian Forest Research* 11 (2), 111-127.
- Bren, L, Hopmans, P, Gill, B, Baker, T, Stackpole, D, 1993. Commercial tree-growing for land and water care. 1. Soil and Groundwater Characteristics of the Pilot Sites. *Trees for Profit Research Centre, University of Melbourne*, 46.
- [Brown, Hamish E., Huth, Neil I., Holzworth, Dean P., Teixeira, Edmar I., Zyskowski, Rob F., Hargreaves, John N. G., Moot, Derrick J., 2014. Plant Modelling Framework: Software for building and running crop models on the APSIM platform. *Environmental Modelling and Software* 62, 385-398.](#)

- Byrne, GF, 1989. Above-ground dry matter accumulation by *Eucalyptus grandis* and its relation to standard meteorological data. *Agricultural and forest meteorology* 46 (1-2), 65-73.
- Cromer, RN, Cameron, DM, Rance, SJ, Ryan, PA, Brown, M, 1993. Response to nutrients in *Eucalyptus grandis*. 1. Biomass accumulation. *Forest Ecology and Management* 62 (1-4), 211-230.
- Cromer, RN, Cameron, DM, Rance, SJ, Ryan, PA, Brown, M, 1993. Response to nutrients in *Eucalyptus grandis*. 2. Nitrogen accumulation. *Forest Ecology and Management* 62 (1-4), 231-243.
- Duncan, M, Baker, TG, Wall, G, 1998. Wastewater irrigated tree plantations: productivity and sustainability. *Proceedings of the 61st Annual Water Industry Engineers and Operators' Conference*, 18-26.
- Elli, Elvis, Huth, Neil, Sentelhas, Paulo, Carneiro, Rafaela, Alcarde Alvares, Clayton, 2020. Global sensitivity-based modelling approach to identify suitable *Eucalyptus* traits for adaptation to climate variability and change. *in silico plants* 2.
- Fabiao, António, Madeira, Manuel, Steen, E, Klatte, T, Ribeiro, C, Araújo, C, 1995. Development of root biomass in an *Eucalyptus globulus* plantation under different water and nutrient regimes. *Plant and Soil* 168 (1), 215-223.
- Fontes, Luis, Landsberg, Joe, Tomé, José, Tomé, Margarida, Pacheco, Carlos A, Soares, Paula, Araújo, Clara, 2006. Calibration and testing of a generalized process-based model for use in Portuguese eucalyptus plantations. *Canadian Journal of Forest Research* 36 (12), 3209-3221.
- Holzworth, Dean P., Huth, Neil I., deVoil, Peter G., Zurcher, Eric J., Herrmann, Neville I., McLean, Greg, Chenu, Karine, van Oosterom, Erik J., Snow, Val, Murphy, Chris, Moore, Andrew D., Brown, Hamish, Whish, Jeremy P. M., Verrall, Shaun, Fainges, Justin, Bell, Lindsay W., Peake, Allan S., Poulton, Perry L., Hochman, Zvi, Thorburn, Peter J., Gaydon, Donald S., Dalgliesh, Neal P., Rodriguez, Daniel, Cox, Howard, Chapman, Scott, Doherty, Alastair, Teixeira, Edmar, Sharp, Joanna, Cichota, Rogerio, Vogeler, Iris, Li, Frank Y., Wang, Enli, Hammer, Graeme L., Robertson, Michael J., Dimes, John P., Whitbread, Anthony M., Hunt, James, van Rees, Harm, McClelland, Tim, Carberry, Peter S., Hargreaves, John N. G., MacLeod, Neil, McDonald, Cam, Harsdorf, Justin, Wedgwood, Sara, Keating, Brian A., 2014. APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling and Software* 62, 327-350.
- Hopmans, P, Stewart, HTL, Flinn, DW, Hillman, TJ, 1990. Growth, biomass production and nutrient accumulation by seven tree species irrigated with municipal effluent at Wodonga, Australia. *Forest Ecology and Management* 30 (1-4), 203-211.
- Huth, N. I., Carberry, P. S., Cocks, B., Graham, S., McGinness, H. M., O'Connell, D. A., 2008. Managing drought risk in eucalypt seedling establishment: An analysis using experiment and model. *Forest Ecology and Management* 255 (8-9), 3307-3317.
- Huth, N. I., Snow, V. O., Keating, B. A., 2001. Integrating a forest modelling capability into an agricultural production systems modelling environment-current applications and future possibilities.. Eds: Zerger, A. and Argent, R.M., 1895-1900.
- Huth, Neil Ian, Carberry, P.S., Poulton, P.L., Brennan, L.E., Keating, Brian A., 2002. A framework for simulating agroforestry options for the low rainfall areas of Australia using APSIM. *European Journal of Agronomy* 18, 171-185.
- Klatte, Thomas, Fabiao, António, Madeira, Manuel, Ribeiro, Carlos, Steen, Eliel, 1995. Fine-root dynamics, soil moisture and soil carbon content in a *Eucalyptus globulus* plantation under different irrigation and fertilisation regimes. *Forest Ecology and Management* 74 (1-3), 1-12.
- Madeira, M, Araújo, MC, Pereira, JS, 1995. Effects of water and nutrient supply on amount and on nutrient concentration of litterfall and forest floor litter in *Eucalyptus globulus* plantations. *Plant and Soil* 168 (1), 287-295.
- Madeira, M, Pereira, JS, 1990. Productivity, nutrient immobilization and soil chemical properties in an *Eucalyptus globulus* plantation under different irrigation and fertilization regimes. *Water, Air, and Soil Pollution* 54 (4), 621-634.
- Madeira, MV, Fabiao, A, Pereira, JS, Araújo, MC, Ribeiro, C, 2002. Changes in carbon stocks in *Eucalyptus globulus* Labill. plantations induced by different water and nutrient availability. *Forest Ecology and Management* 171 (1-2), 75-85.
- Melo, Eduardo Aparecido Sereguin Cabral de, Gonçalves, José Leonardo de Moraes, Rocha, José Henrique Tertulino, Hakamada, Rodrigo Eiji, Bazani, José Henrique, Wenzel, Andrea Virginia Athayde, Arthur, José Carlos, Borges, Jarbas Silva, Malheiros, Rogério, Lemos, Cristiane Camargo Zani de, others, 2015. Responses of clonal eucalypt plantations to N, P and K fertilizer application in different edaphoclimatic conditions. *Forests* 7 (1), 2.

- Mendham, DS, White, DA, Battaglia, M, McGrath, JF, Short, TM, Ogden, GN, Kinal, J, 2011. Soil water depletion and replenishment during first-and early second-rotation *Eucalyptus globulus* plantations with deep soil profiles. *Agricultural and Forest Meteorology* 151 (12), 1568-1579.
- Misra, RK, Turnbull, CRA, Cromer, RN, Gibbons, AK, LaSala, AV, 1998. Below-and above-ground growth of *Eucalyptus nitens* in a young plantation: I. Biomass. *Forest Ecology and Management* 106 (2-3), 283-293.
- Myers, BJ, Benyon, RG, Theiveyanathan, S, Criddle, RS, Smith, CJ, Falkiner, RA, 1998. Response of effluent-irrigated *Eucalyptus grandis* and *Pinus radiata* to salinity and vapor pressure deficits. *Tree physiology* 18 (8-9), 565-573.
- Myers, BJ, Theiveyanathan, S, O'brien, ND, Bond, Warren J, 1996. Growth and water use of *Eucalyptus grandis* and *Pinus radiata* plantations irrigated with effluent. *Tree Physiology* 16 (1-2), 211-219.
- Nogueira, CAS, 2005. Estado nutricional e produtividade de plantios de clones híbridos de *Eucalyptus grandis* x *E. urophylla* submetidos a diferentes níveis de adubação no vale do Rio Jari, Pará e Amapá..
- Pereira, João S, Landsberg, Joseph John, 2012. Biomass production by fast-growing trees. 166.
- Pereira, JS, Linder, S, Araújo, MC, Pereira, H, Ericsson, T, Borralho, N, Leal, LC, 1989. Optimization of Biomass Production in *Eucalyptus Globulus* Plantations.—A Case Study. *Biomass production by fast-growing trees*, 101-121.
- Pereira, JS, Madeira, MV, Linder, S, Ericsson, T, Tomé, M, Araújo, MC, 1994. Biomass production with optimised nutrition in *Eucalyptus globulus* plantations. *Eucalyptus for biomass production*, 13-30.
- Polglase, PJ, Tompkins, D, Stewart, LG, Falkiner, RA, 1995. Mineralization and leaching of nitrogen in an effluent-irrigated pine plantation. *Journal of Environmental Quality* 24 (5), 911-920.
- Quilhó, Teresa, Pereira, Helena, 2001. Within and between-tree variation of bark content and wood density of *Eucalyptus globulus* in commercial plantations. *Iawa Journal* 22 (3), 255-265.
- Resh, Sigrid C, Battaglia, Michael, Worledge, Dale, Ladiges, Sven, 2003. Coarse root biomass for eucalypt plantations in Tasmania, Australia: sources of variation and methods for assessment. *Trees* 17 (5), 389-399.
- Ross, DJ, 1991. Soils at sites selected for eucalypt research in Toolara State Forest, Gympie, Queensland..
- Rubilar, Rafael A, Allen, H Lee, Fox, Thomas R, Cook, Rachel L, Albaugh, Timothy J, Campoe, Otávio C, 2018. Advances in Silviculture of Intensively Managed Plantations. *Current Forestry Reports* 4 (1), 23-34.
- Silva, GGC, 2006. Nutrição, crescimento e sua modelagem em povoamentos de eucalipto em resposta a disponibilidade de água e nutrientes..
- Smethurst, Philip J, Valadares, Rafael V, Huth, Neil I, Almeida, Auro C, Elli, Elvis F, Neves, Júlio CL, 2020. Generalized model for plantation production of *Eucalyptus grandis* and hybrids for genotype-site-management applications. *Forest Ecology and Management* 469, 118164.
- Smethurst, Philip, Baillie, Craig, Cherry, Maria, Holz, Greg, 2003. Fertilizer effects on LAI and growth of four *Eucalyptus nitens* plantations. *Forest ecology and management* 176 (1-3), 531-542.
- Smethurst, Philip, Holz, Greg, Moroni, Martin, Baillie, Craig, 2004. Nitrogen management in *Eucalyptus nitens* plantations. *Forest Ecology and Management* 193 (1-2), 63-80.
- Smethurst, PJ, Herbert, AM, Ballard, LM, 1997. A paste method for estimating concentrations of. *Australian journal of soil research* 35 (1), 209-225.
- Smethurst, PJ, Mendham, DS, Battaglia, M, Misra, R, 2004. Simultaneous prediction of nitrogen and phosphorus dynamics in a *Eucalyptus nitens* plantation using linked CABALA and PCATS models..
- Snow, VO, Bond, Warren J, Myers, BJ, Theiveyanathan, S, Smith, CJ, Benyon, RG, 1999. Modelling the water balance of effluent-irrigated trees. *Agricultural Water Management* 39 (1), 47-67.
- Snow, VO, Smith, CJ, Polglase, PJ, Probert, ME, 1999. Nitrogen dynamics in a eucalypt plantation irrigated with sewage effluent or bore water. *Soil Research* 37 (3), 527-544.
- Specht, RL, 1972. Water use by perennial evergreen plant communities in Australia and Papua New Guinea. *Australian Journal of Botany* 20 (3), 273-299.
- Stewart, HTL, Hopmans, P, Flinn, DW, Hillman, TJ, 1990. Nutrient accumulation in trees and soil following irrigation with municipal effluent in Australia. *Environmental pollution* 63 (2), 155-177.

- Turner, John, 1986. Organic matter accumulation in a series of Eucalyptus grandis plantations. Forest Ecology and Management 17 (2-3), 231-242.
- White, DA, Beadle, CL, Worledge, D, 1996. Leaf water relations of Eucalyptus globulus ssp. globulus and E. nitens: seasonal, drought and species effects. Tree physiology 16 (5), 469-476.
- White, Don, Beadle, Chris, Worledge, Dale, Honeysett, John, Cherry, Maria, 1998. The influence of drought on the relationship between leaf and conducting sapwood area in Eucalyptus globulus and Eucalyptus nitens. Trees 12 (7), 406-414.
- White, Donald A, Battaglia, Micheal, Mendham, Daniel S, Crombie, D Stuart, Kinal, JOE, McGrath, John F, 2010. Observed and modelled leaf area index in Eucalyptus globulus plantations: tests of optimality and equilibrium hypotheses. Tree physiology 30 (7), 831-844.
- White, Donald A, Crombie, D Stuart, Kinal, Joe, Battaglia, Michael, McGrath, John F, Mendham, Daniel S, Walker, Scott N, 2009. Managing productivity and drought risk in Eucalyptus globulus plantations in south-western Australia. Forest Ecology and Management 259 (1), 33-44.
- White, Donald A, McGrath, John F, Ryan, Michael G, Battaglia, Michael, Mendham, Daniel S, Kinal, Joe, Downes, Geoffrey M, Crombie, D Stuart, Hunt, Mark E, 2014. Managing for water-use efficient wood production in Eucalyptus globulus plantations. Forest ecology and management 331, 272-280.
- [Wong, J., Baker, T., Duncan, M., McGuire, D., Bulman, P., 2000. Forecasting Growth of Key Agroforestry Species in South-Eastern Australia. \(Publication 00/68\).](#)
- Worledge, D, Honeysett, JL, White, DA, Beadle, CL, Hetherington, SJ, 1998. Scheduling irrigation in plantations of Eucalyptus globulus and E. nitens: a practical guide. TASFORESTS-HOBART- 10, 91-102.