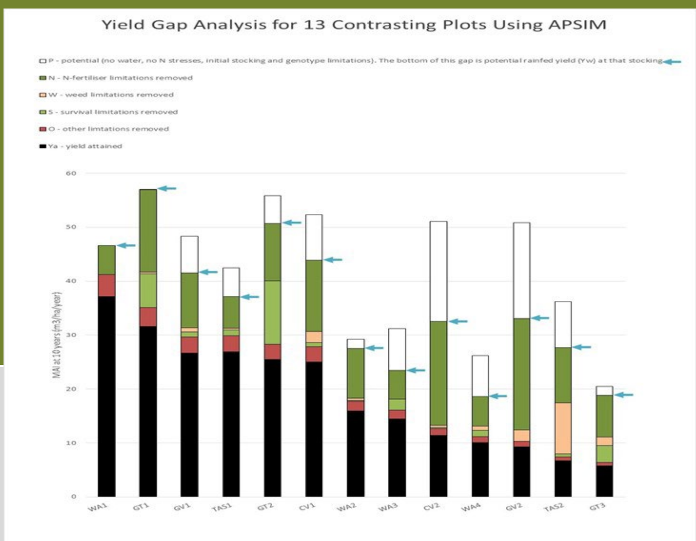
Resources

Optimising productivity of hardwood plantations: yield gap analysis for Eucalyptus globulus plantations in southern Australia

Project number: VNC516-1920

February 2024



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Forest & Wood Products Australia

Optimising productivity of hardwood plantations: yield gap analysis for Eucalyptus globulus plantations in southern Australia

Prepared for

Forest & Wood Products Australia

by

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Executive Summary

The study aimed to improve the knowledge underpinning decisions on the location and management of hardwood plantations across southern Australia by (i) providing estimates of potential productivity (as wood yield), (ii) determining the main causes of differences between potential and actual yields (gaps), and (iii) determining the extent that management practices might reduce gaps. The study was based on (i) empirical analyses, (ii) a forest modelling and prediction framework suited to plot- and regional-scale applications, and (iii) case study demonstrations, focusing on age 10-years yields for planted *Eucalyptus globulus*.

Climate, and particularly water availability, was determined to be the primary limitation to yield across southern Australia. Rain-limited potential yield (posited as 90% quantile yield) varied about 180–380 m^3/ha at age 10 years for mean annual rainfall 600–1200 mm. Regional differences as temperature / evaporation effects were also discerned (e.g. Western Australia cf. Tasmania). Observed greater yields (up to 500 m^3/ha) were attributed to plantations accessing additional water to rain (e.g. run-on, groundwater, deep-profile soil water during first rotation), which were confirmed feasible by modelling. Variation in potential rooting depth as affected by soil properties (observed and/or in modelling) also affected potential yield, including particularly through impact on survival on shallow soils. A soil-fertility effect, as land-use history, was evident for a subset of regions with average yield about 50 m^3/ha less where there had not been a preceding Agriculture phase.

For planted *E. globulus* on former agricultural land, there was an estimated yield gap of up to 150–200 m^3/ha at age 10 years (90% cf. 10% yield quantile). Across regions, and aside from countervailing effects of temperature and evaporation, and the effects of soil depth (10–20 m^3/ha in some modelled examples), this gap might be attributed: (i) in small part to weed competition in well-established plantations, around 10 m^3/ha in modelling, (ii) to stand density (understocking), about 30 m^3/ha, howsoever arising from planting density and subsequent competition-induced mortality, and (iii) largely to low nutrition, with observed responses to N fertiliser application up to 150 m^3/ha.

The APSIM *Eucalyptus* process-based growth model was used in the study because of the ability to include (i) complex soils (deep, with water, C and N), (ii) silvicultural flexibility (particularly the inclusion of N fertiliser, weeds, and slash management), (iii) science and software engineering credentials, and (iv) links to agricultural models and software support. Overall, the model simulations proved to be a useful way to examine the role of individual factors effecting growth and yield without the confounding effects of un-controlled factors that arose in some empirical analyses.

Industry training to use APSIM was provided, including through on-line material. It is envisaged that with on-going support industry will adopt this current modelling capability, and its future enhancements, either in-house or through consultants.

Contents

1. Introduction

1.1 Potential yield and defining the yield gap

A number of FWPA commissioned Investment Plans identified that a capacity to understand the limits to plantation productivity and to estimate the gap between current and potential productivity is critical to optimising plantation performance and profitability.

A yield gap has been described as the deficit in actual production relative to the upper limits to productivity (e.g. van Ittersum *et al.* 2013, Rhebergen *et al.* 2018 (Fig. 1.1). Potential yield is determined by genotype, climate, soil type, management and water supply.

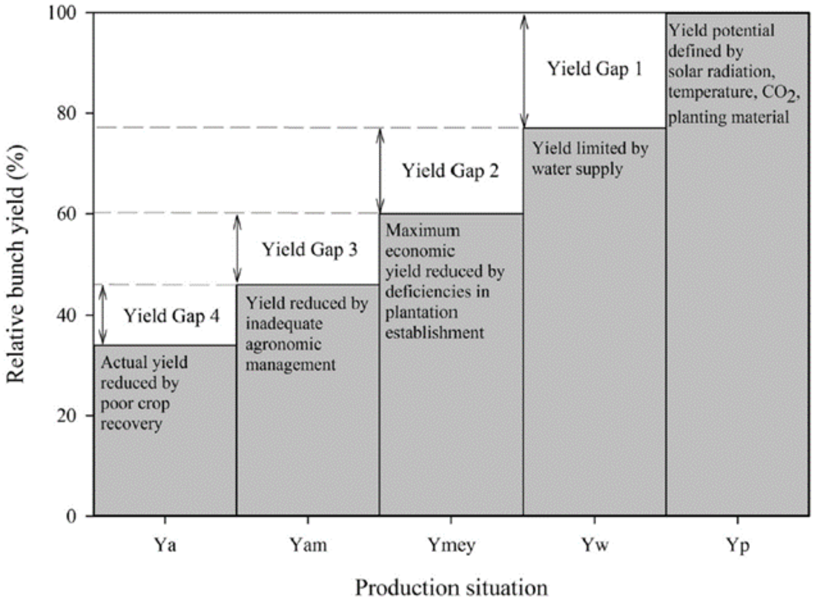


Figure 1.1 Components of yield

Defining the potential yield of plantations and estimating the yield gap provides a framework for decision making based on the potential yield of a site and the improvement in yields due to silvicultural management (competition control, thinning, nutritional management). Yield gap analysis can be based on observations underpinning process-based models, e.g. as recently achieved for Eucalyptus plantations in Brazil (Elli et al. 2019, Attia et al. 2019), or by assessing yield against local observations and empirical models. Such process-based model analysis of yield gaps have generally been scaled to regional or national level analysis, have been restricted to climatic effects, rather than providing a framework for site-specific silvicultural effects as needed in this project.

By necessity the simple model of the influence of the factors that determine yield (Figure 1) does not demonstrate the interactions between these environmental and management factors. There are likely influential interactions between genotype and water supply and various management factors such as weed control, stocking and fertility. The requirement for weed control to ensure satisfactory establishment (survival / stocking) and the effect of fertiliser during establishment on early plantation productivity have been relatively well studied. However, rotation-length effects of weed control / competition, establishment fertiliser, and the effectiveness of later-age fertilization need to be determined.

For most of Australia's plantation resource, potential yield will be the water limited yield, and understanding the interaction between water availability, nutrient supply, and other growth moderating factors (pests and diseases) will be critical in developing the knowledge required to define potential productivity and hence estimate the yield gap. Thus, potential yield varies within and between regions and between rotations with stored water from agriculture increasing the potential yield of first rotation *E. globulus* plantations across much of southern Australia (Mendham *et al*. 2011). Although modelling should be validated for all contexts encountered including irrigation, for virtually all current Australian plantations, additional water available during the first rotation would have been fully exploited and thereafter yield will be linked to current rainfall.

1.2 Potential Australian plantation yield

Nambiar (1995) assembled data for *P. radiata* from a range of silvicultural trials that assessed productivity in relation to water and nutrient supply. These data came from both rainfed and irrigated trials. While the analysis was very useful in identifying the strong influence of both water and nutrient supply in determining plantation productivity, the varied experimental designs and wide range of site conditions made it difficult to define the upper limits to productivity. However, the relationships developed indicated that under some conditions very high productivity could be achieved. The upper limits of growth under rainfed conditions appeared to vary from less than 20 m^3/ha/year to 35 m^3/ha/year over a rainfall gradient of 500-1200 mm/year (Figure 1.2). In the Mount Gambier region of SA, productivity up to 55 m^3/ha.year was measured, however it appears likely that these plantations had access to deep stored water (Benyon *et al.* 2007). In areas with strongly seasonal rainfall, soil water storage capacity appeared to be a critical limitation, however the difficulty in determining soil water storage capacity relevant to deep rooted trees has been described as an intractable issue (Nambiar 1995, Running and Coughlan 1988).

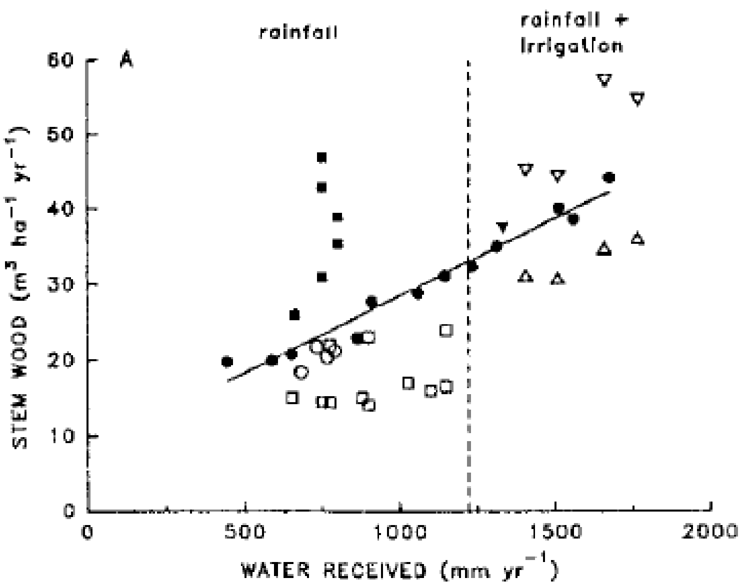


Figure 1.2 The range in amount of water received and mean annual increment (age 11-15 years) in Pinus radiata plantations in Australia

Similarly, the relationships between productivity and water supply for hardwood plantations in WA (White et al. 2009) clearly demonstrated that, in first rotation *E. globulus* plantations, water supply was strongly related to plantation productivity (Fig. 3).

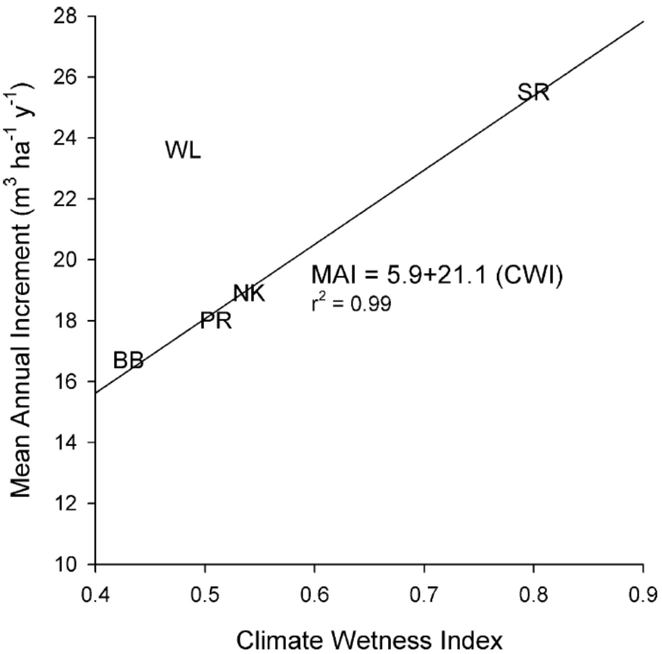


Figure. 1.3. Mean annual increment from 5 sites across southern WA provided with adequate annual fertiliser applications as a function of average annual climate wetness index (CWI = rainfall/potential evaporation) from planting to the time of measurement. The line is a linear relationship fitted by regression to the data for all sites except Wellstead (WL) (From White et al. 2009). The Wellstead site had access to deep stored water.

1.3 Selecting modelling systems

Current yield prediction systems used by the Australian plantation forest industry are local applications of empirical systems that have been referred to as 'growth and yield modelling', an early example of which was described by Clutter et al. (1963) for loblolly pine in the south-eastern USA. In Australia, similar systems were developed for its plantation species, e.g. *Pinus radiata* in South Australia (Lewis et al. 1976) and Victoria (Turvey 1983), *E. globulus* in south-eastern Australia (Wang and Baker 2007). These models require substantial historical data that include historic yield in the same location (soil) that covers a particular range of climate, genotype and management variability. Such systems loose accuracy as growing conditions go outside the historic ranges of inputs, and when predicting plantation yields in untested locations (Almeida 2018). Alternatives for improvement have therefore been sought.

Measurements of stand condition (e.g. leaf area index 'LAI'), or indexes of climate and soil, can be used to refine empirical modelling systems (McGrath et al. 1991, Harper et al. 2005, Scolforo et al. 2019, Waldner et al. 2019. Watt et al. 2016), but these systems require substantial historical data.

Process-based models alone or in combination with more empirical models are now being tested and used internationally in some parts of the industry to meet this need in research and operational conditions, as they have the potential to more reliably predict tree growth in combinations of conditions not represented in historical data (Almeida 2018).

The schematic diagram provided below (Fig. 1.4) outlines how the overall knowledge base relating to plantation productivity could operate in relation to process-based modelling. The current project used only part of this system to develop a yield gap analysis.

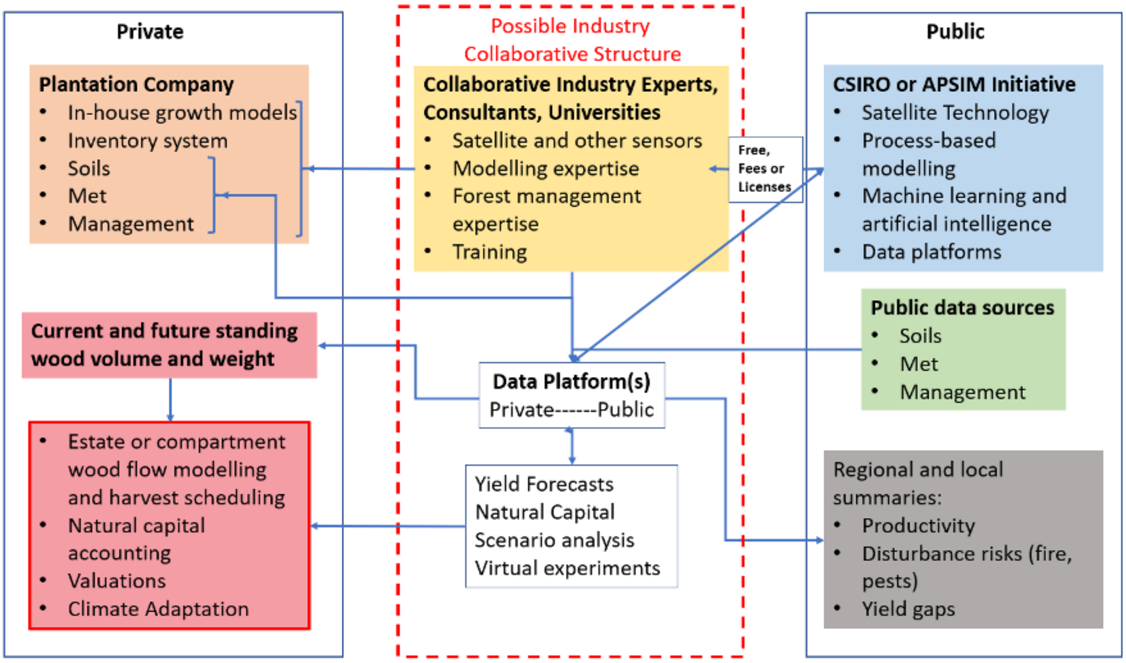


Figure. 1.4. Schematic of a possible industry structure included in the proposal for the FWPA project VNC519-1920 'Next Generation Resource Assessment and Forecasting for Australian Plantation Forestry'.

1.4 Project objectives and major components

The broad objective of the project was to provide hardwood plantation growers with reliable estimates of potential plantation productivity and knowledge to underpin decisions on the location, establishment and management (silvicultural inputs) of plantations to optimise productivity. This was to be delivered through two components:

1. **Developing a forest modelling and prediction framework based on climate and environmental factors that allows the estimation of yield gaps.**

   This component **p**rovides a new methodology for benchmarking Australian plantation performance and assessing investment opportunities and risks associated with environmental factors (e.g. water availability) and management decisions (e.g. fertiliser application).

   Both empirical analyses and process-based modelling approaches were made. The empirical analyses supported the calibration and validation for the process-based modelling.

2. **Demonstrating the utility and robustness of the prediction platform in the form of case study applications.**

   This component provided a thorough test of the accuracy of the modelling and relevance to site-level productivity assessments.

2. Empirical analyses of plantation yield and yield gaps

2.1 Summary – empirical analyses

Using permanent sample plots, silvicultural trials and focussed surveys, plantation yield and site data were used to provide a characterisation of the national estate; explore variation in productivity with site factors (climate, topography, soils) and management practice (fertility, stocking); and provide data to support and validate process-based growth modelling.

The key findings were:

- Climate parameters (rainfall, evaporation and temperature) strongly affected potential yield with rainfall the most influential as volume under bark at age 10 years (Vub 10 y) increased approximately 26 m3/ha per 100 mm increase in mean annual rainfall (MAR).
- Shallow soil depth was associated with lower productivity and in some locations in WA soils <2 m depth was associated with severe mortality.
- An agricultural phase in land use history increasing soil nutrient status was associated with overall increases of about 50 m^3/ha in Vub 10 y.
- Silvicultural manipulations (stand density, coppicing and nutrition) influenced productivity. Vub 10 y increased about 30 m^3/ha as stand density increased from 750 to 1100 stems/ha. Productivity was lower in coppice compared with planted stands. Nitrogen fertiliser application increased yield on many sites and by up to 150 m^3/ha in Vub 10 y where nitrogen supply was maintained by frequent applications.

2.2 Methodology – empirical analyses

Three data sets were contributed by the project partners:

- Operational permanent sample plots (PSPs) across NPI regions
- Silvicultural trials across NPI regions
- Survey plots from the WA region

For all three sets, climate attributes were determined from published continental interpolated surfaces. For most operational PSPs and trials, consistently observed soil morphological, physical or chemical attributes were not available, and consequently, topography and soil attributes were acquired from published continental attribute layers. In contrast, the WA survey plots having observed soil morphology and soil chemistry attributes provided for a more definitive analysis of these factors. While detailed consistent plantation establishment and management information (e.g. genotype, cultivation, weeding, fertiliser application) was not usually available for the PSPs, these were usually known for the trials.

The operational PSP set primarily provided for an estimation of yield limited by rain-fed water supply, and a general exploration of climatic and edaphic factors affecting yield. The trial set primarily provided data for exploration of silvicultural factors / treatments (e.g. density, fertiliser application) affecting yield. The WA survey set provided data to assess the role of climate, observed soil attributes and stand characteristics in determining productivity.

Some definitions and abbreviations used in this section, and elsewhere, include:

- Australian National Plantation Inventory (NPI) regions: Western Australia (**WA**); Green Triangle (**GT**); Central Victoria (**CV**); Murray Valley (**MV**); Central Gippsland (**CG**); East Gippsland and Bombala (**EG**); Tasmania (**TAS**) (Legg et al. 2021)
- Species: *Eucalyptus globulus* Labill.; *E. nitens* (Deane & Maiden) Maiden
- Rotation type: Planted (**P**); Coppice (**C**)
- Land-use history: A sequence of land uses/phases/rotations, including current use, denoted **F** = native forest (an assumed origin), **A** = agriculture, **P** = pine plantation, **E** = eucalypt plantation (e.g. FAE, FAEE)
- Permanent Sample Plot (PSP): An areal measurement plot, commonly about 0.04 ha, measured at 2 or more ages.
- Trial type: Variously comparing species/seedlots (**s**), planting density (**n**), and/or treatments such as soil cultivation (**c**), weeding (**w**), and fertiliser application (**f**) at establishment (**e**) and/or later in the rotation (**t**) (e.g. e – f).
- Plantation productivity as total under-bark stem volume yield at age 10 years (**Vub 10 y**, m^3/ha)

2.2.1 Operational PSP data

Data from almost 3400 geopositioned PSPs in operational *E. globulus* and *E. nitens* plantations in six NPI regions were contributed by industry partners — most (87%) with yield measurements between 8–12 years (most 9–11 years). The PSPs represented 1005 plantations as deemed by plantation / property / tree farm name or coding thereof, by year of establishment (i.e. planting, coppicing), by species, by rotation type (planted, coppice) (Table 2.1, Fig. 2.1a). About half the plantations were represented by 1 PSP and about three-quarters by 1–3 PSPs; the balance mostly represented by up to 10 PSPs depending on plantation size and particularly for some contributed data sets a high sampling intensity. The plantations were established 1970–2019, most (96%) 1987–2015.

Table 2.1. Distribution of the represented plantations between NPI regions

Region	*E. globulus*		*E. nitens*	Total
	Planted	Coppice	Planted	
CG	65			65
CV	144	3	23	170
GT	145	62		207
MV	19	1		20
TAS	30		26	56
WA	400	87		487
Total	803	153	49	1005

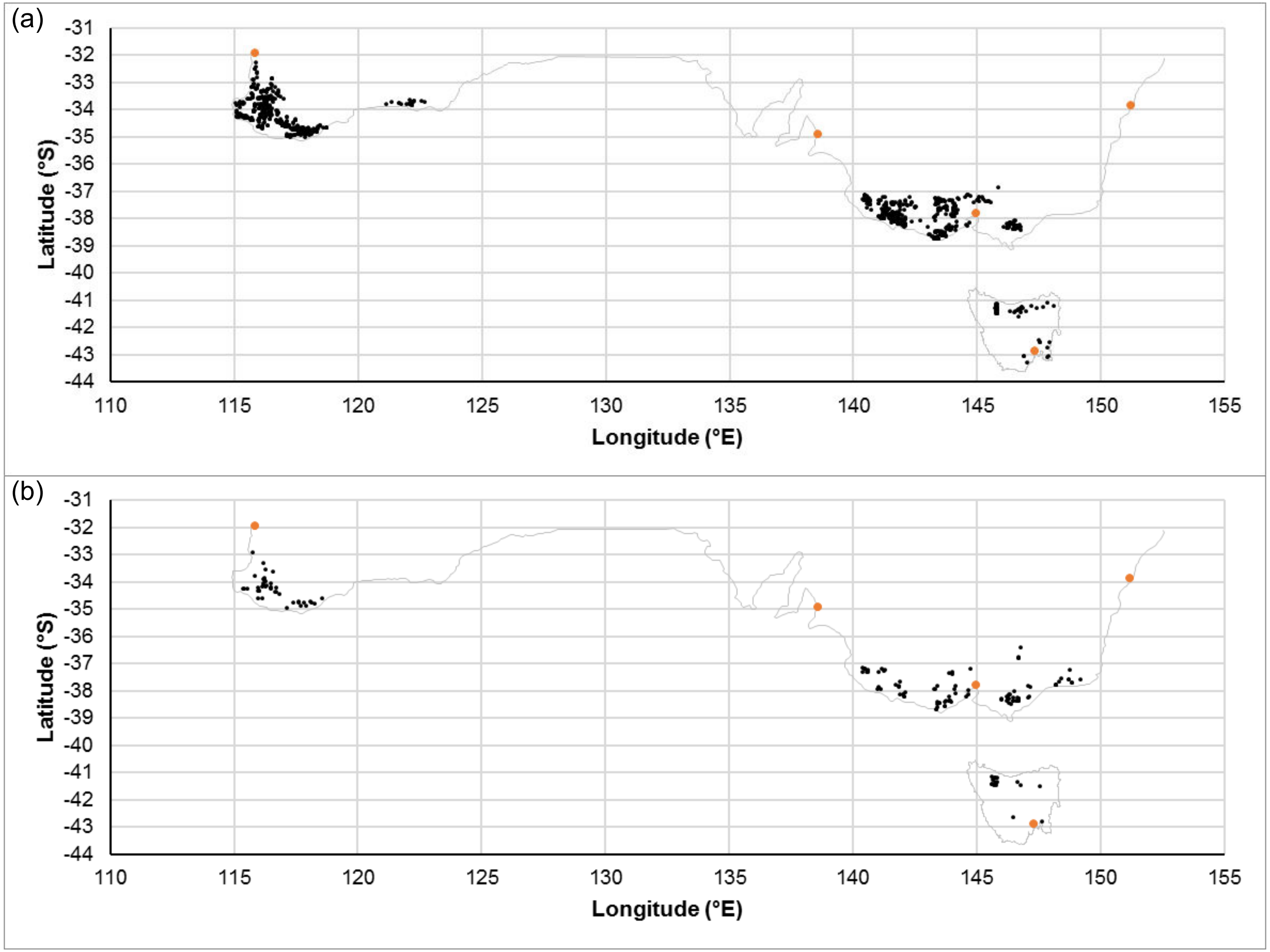


Figure 2.1. Locations of represented plantations, n =1005 (a); and trials, n =163 (b). State capital cities indicated (orange points).

Most represented plantations were planted *E. globulus* rotations on sites with some agricultural land-use history (74%, Table 2.2). No plantations from EG were represented. Nationally, southern *E. nitens* plantations are confined to CV, CG, EG and TAS, but no plantations from CG and EG were represented, and the TAS plantations represented an altitudinal gradient rather than the Tasmanian estate more generally.

Table 2.2. Land use history for the represented plantations. See text for explanation.

Land-use history	*E. globulus*		*E. nitens*	Total
	Planted	Coppice	Planted	
FAE	616		4	620
FAEE	87	148	3	238
FAEEE	8	5	1	14
FAPE	31		20	51
FAPEE	2		1	3
FE	5		6	11
FEE	9		10	19
FEEE	1		1	2
FPE	41		1	42
FPEE			2	2
Unknown	3			3
Total	803	153	49	1005

The geopositioned PSPs provided for a somewhat comprehensive sample (n =956 plantations) of growing conditions for the national *E. globulus* estate (Table 2.3). However, (i) the Mt Lofty Ranges and Kangaroo Island region was not represented; and (ii) given the year of establishment of the plantations the growing conditions sampled may extend wider than the current estate since there has been a substantial reduction in plantation area from a maximum 2009/10.

Table 2.3. Area (ha) of *E. globulus* plantation by NPI region 2009/10 and 2019/20. From Gavran and Parsons (2011) and Legg et al. (2021).

NPI region	2009/10	2019/20
Central Gippsland	14,000	4,315
Central Victoria	33,000	12,383
East Gippsland-Bombala	1,000	
Green Triangle	168,000	128,702
Mount Lofty Ranges and Kangaroo Island	12,000	14,686
Murray Valley	6,000	4,889
North Coast	1,000	
Tasmania	20,000	13,009
Western Australia	283,000	166,410
TOTAL	538,000	344,393

For PSP point locations (i) climate attributes (1976–2005) were determined using ANUCLIM v.6.1.1 MTHCLIM (https://fennerschool.anu.edu.au/research/products/anuclim; Xu and Hutchinson, 2011), and (ii) landscape and soil attributes were acquired from the Soil and Landscape Grid Australia (SLGA; https://www.clw.csiro.au/aclep/soillandlandscapegrid; Grundy et al., 2015). The climate attributes are from interpolated surfaces across the continent (i) the landscape attributes are (mostly) derived from digital elevation model measurements; and (ii) the soil attributes from interpolated / modelled data (Gallant and Austin, 2015; Viscarra Rossel et al., 2015), and consequently there is significant uncertainty in these values at specific locations. While some soil attribute values may also be biased to agricultural soils which form the bulk of the underpinning data, the national *E. globulus* estate has been largely established on such soils (see earlier).

Selected climate, landscape and soil attributes for the represented *E. globulus* plantations are presented by NPI region (Figure. 2.2, Table 2.4) for descriptive purposes and to support further analysis of plantation yield data. From west to east / north to south across the continent some trends or differences are well-recognized, including those primarily driven by effects of latitude and elevation on temperature underpinned by differences in geology / soil parent material. Notably across regions, based on upper/lower values from interquartile ranges:

- MAT decreases from about 16 ºC (WA) to 10.5 ºC (TAS).
- MAR varies about 650–1050 mm (WA to TAS), and MAE about 1000–1450 mm (TAS to WA).
- Climate wetness index (CWI, as MAR / MAE) increases from about 0.5 (WA) to 1.3 (TAS).
- WA surface and subsoils are sandier than elsewhere, and there is an over-all trend of decreasing sand and concomitant increase in clay content – silt being a minor component of soil – across the continent (Figs 2.2i–l).
- Deeper regoliths occur on Quaternary and other Cenozoic sediments (WA, GT, CG) compared with those on other geologies particularly on higher elevation / steeper landscapes (CV, MV, TAS) (Fig. 2.2m).
- There is relatively little variation in soil A&B (horizon) depth, with values (0.85–1.05 m, Fig. 2.2n); although this attribute may not be reflective of the depth of the regolith that might be exploited by tree roots (i.e. including A, B, C and D horizons).
- Despite marked differences in soil textures across the continent, there is relatively little variation (170–210 mm, Fig 2.2p) or trend in PAWC 0–100 cm, in part because of the countervailing effect of soil bulk density (as VM soil 0–100 cm, Fig2.2o).
- Soil organic C 0–30 cm and total N 0–30 cm contents (Figs 2.2r&s) increase monotonically from WA to TAS, attributable to increasing rainfall, decreasing temperature and increasing soil clay content.
- Soil CN ratio 0–30 cm (varying overall 15–30, Fig. 2.2t) was relatively constant across regions, but perhaps higher in WA and TAS because of texture / temperature interactions.

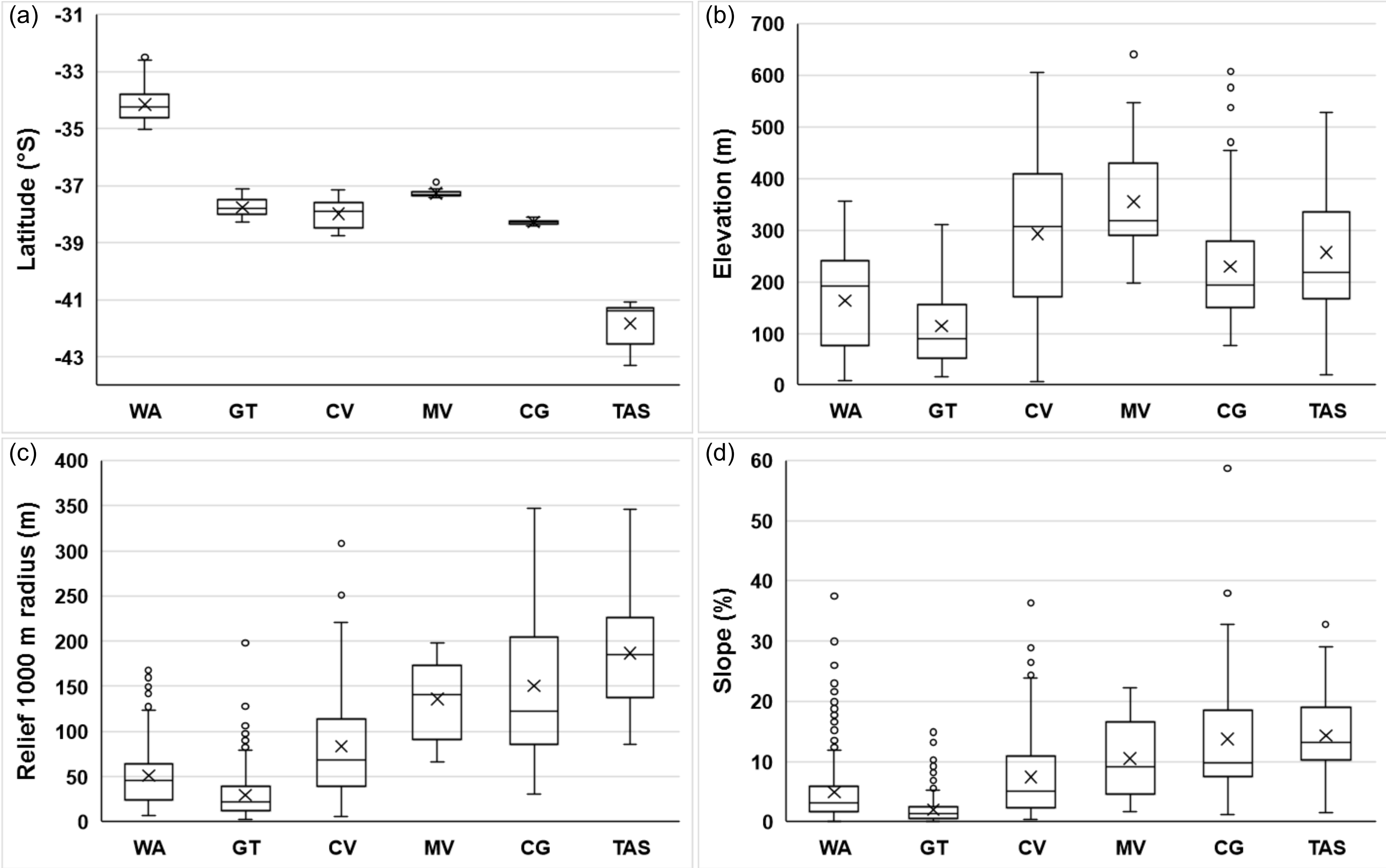
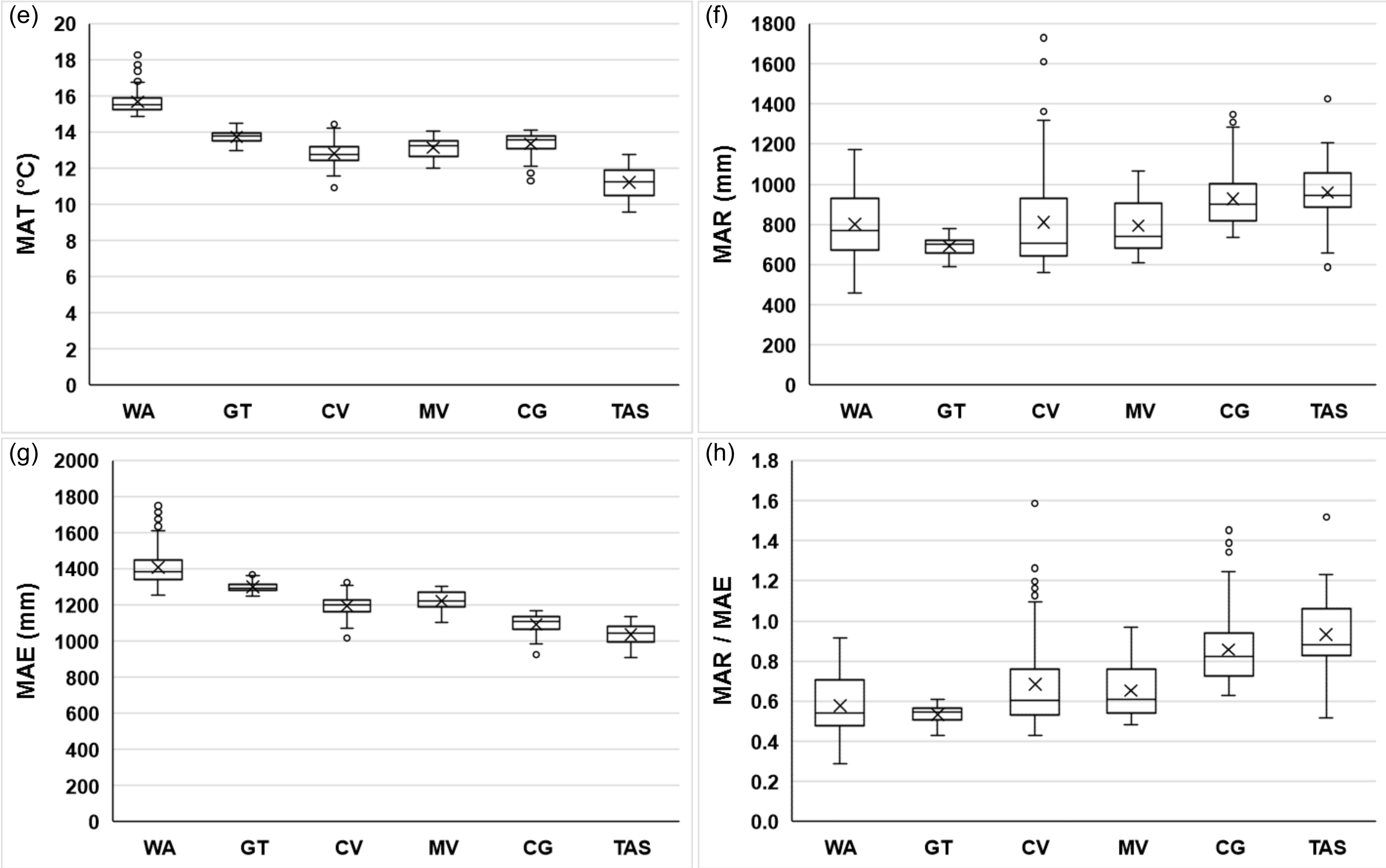


Figure 2.2. Box & Whisker plots of selected site climate, landscape and soil attribute values for represented *E. globulus* plantations in NPI regions (n =956). See Table 2.4 for attribute names / abbreviations and explanation.



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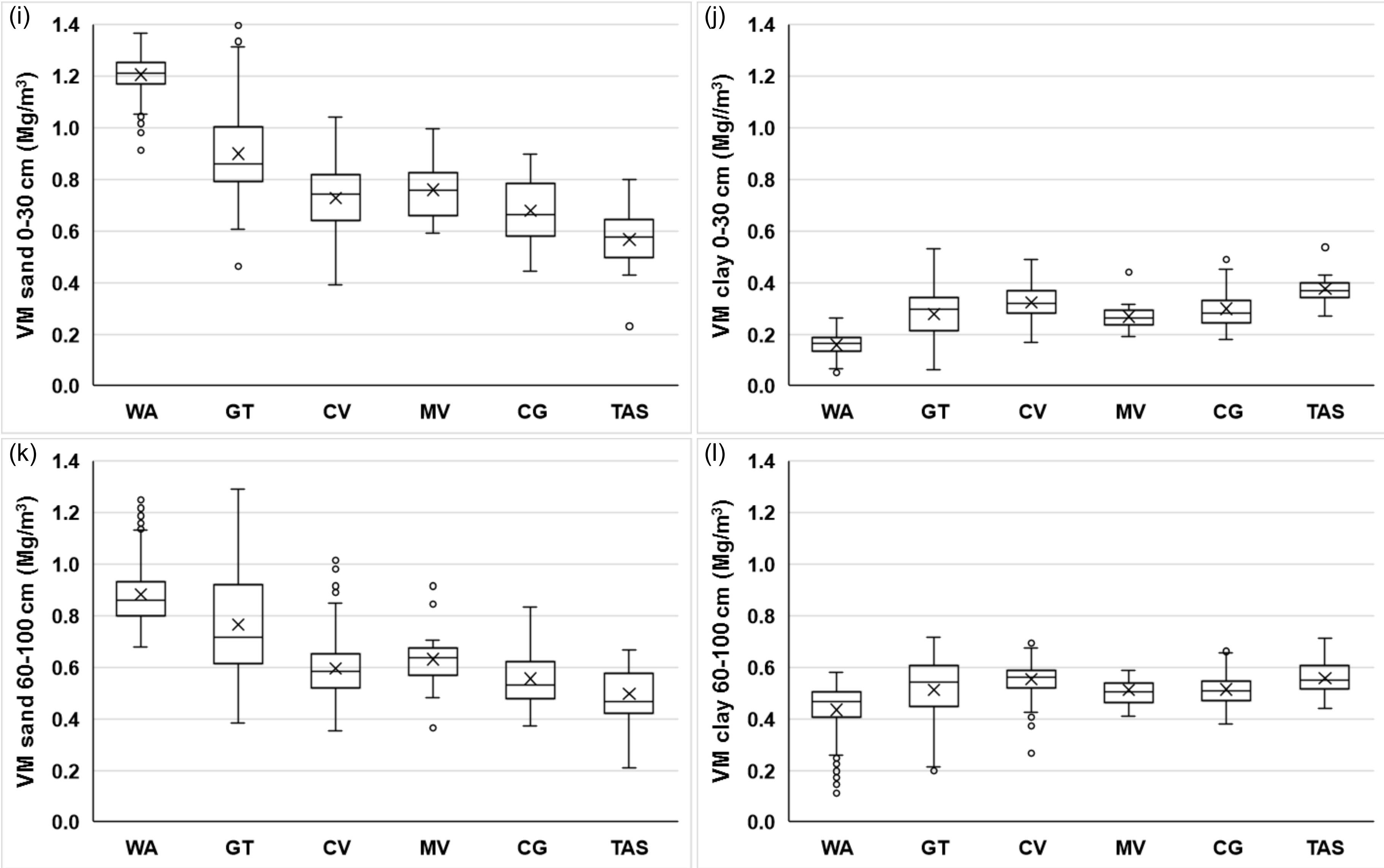

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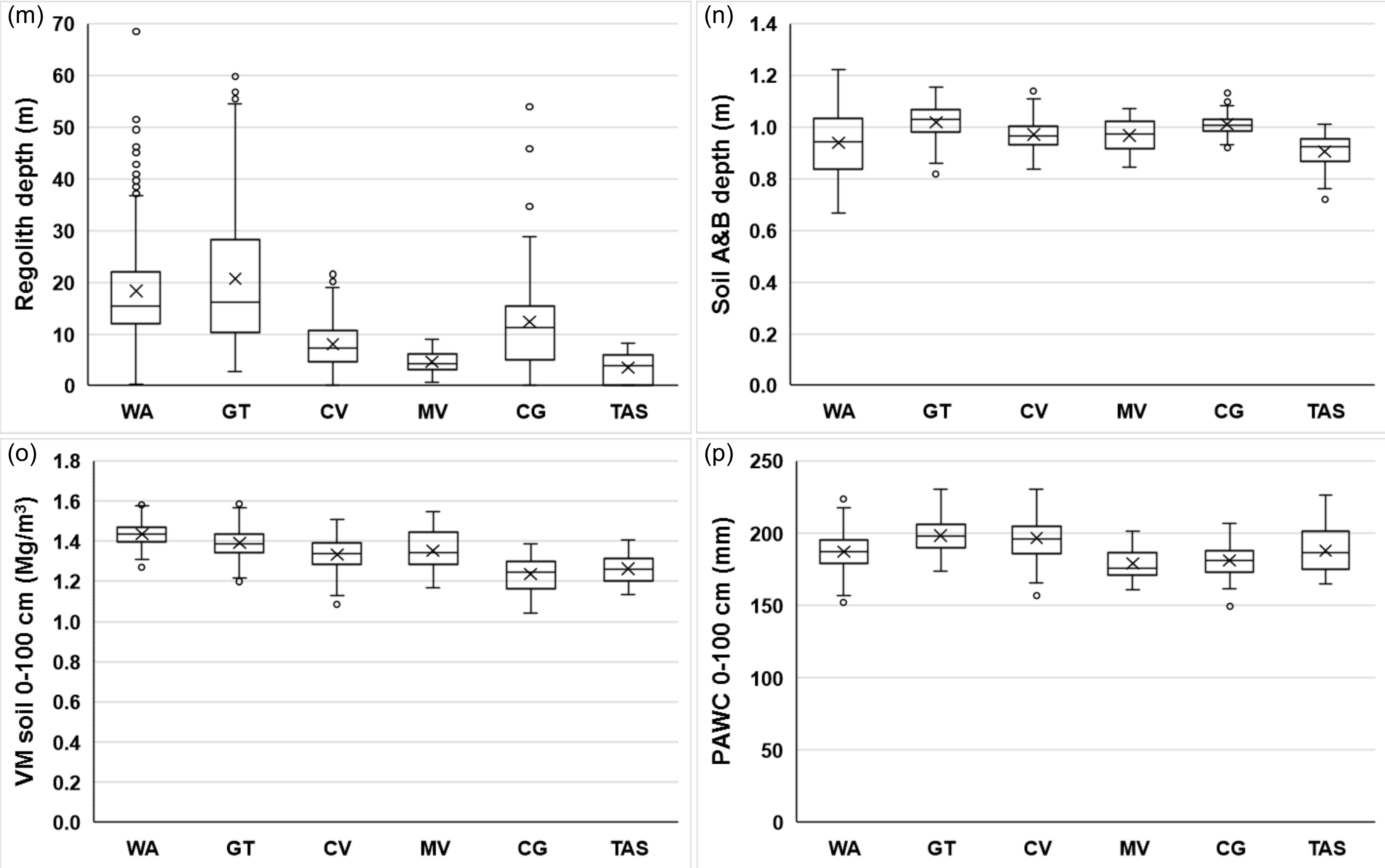

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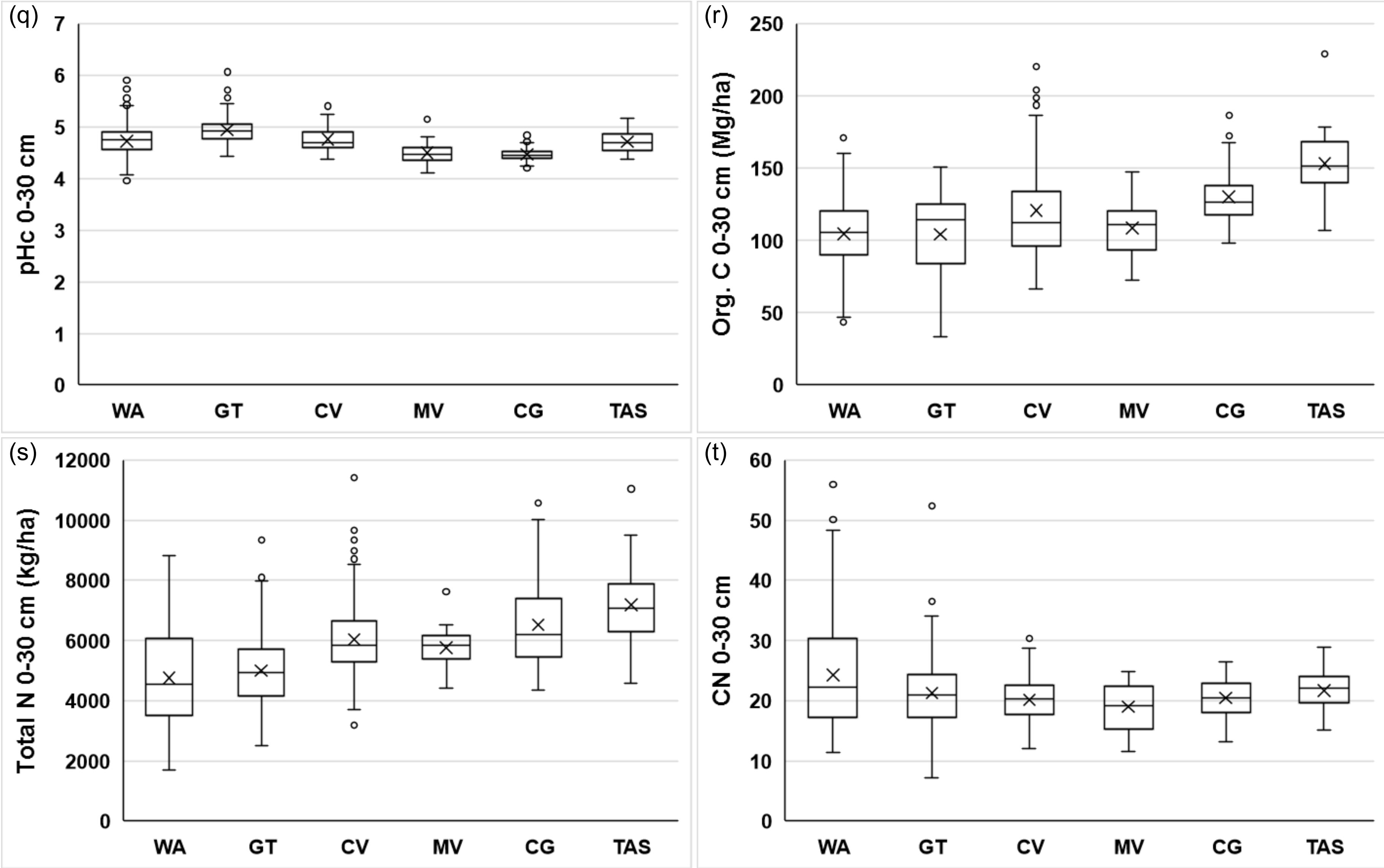


Figure 2.2 continued

Table 2.4. Details of some variables used in text, tables and figures in Section 2

Name / Abbreviation	Description	Units	Source
Vub 10 y	Yield as total stand volume (underbark) at age 10 years	m^3/ha	1
dVub10 y	Absolute difference between posited maximum water-limited yield at age 10 years and Vub 10 y	m^3/ha	-
rVub10 y	Ratio of Vub 10 y and posited maximum water-limited yield at age 10 years	-	-
Longitude	Longitude (WGS84 or GDA94)	°E	1
Latitude	Latitude (WGS84 or GDA94)	°S (–ve)	1
MAT	Mean annual temperature	°C	2
MAR	Mean annual rainfall	mm	2
MAE	Mean annual pan evaporation	mm	2
MAS	Mean annual total solar radiation, adjusted for cloud cover	MJ/m^2	2
MAR/MAE	MAR ÷ MAE (a climate wetness index)	-	2
Elevation	Elevation above sea level	m	3
Relief	Elevation range within 1000 m radius	m	3
Aspect	Direction land surface slope faces, as azimuth from north	°	3
Slope	Inclination of land surface, from horizontal	%	3
TWI	Topographic wetness index	-	3
Regolith depth	Depth to hard rock, inclusive of all regolith	m	4
Soil A&B depth	Depth of soil profile (A & B horizons)	m	4
VM soil	Volumetric mass of soil <2 mm fraction (≈ bulk density)	Mg/m^3	4
VM sand	Volumetric mass of sand in <2 mm soil fraction	Mg/m^3	4
VM silt	Volumetric mass of silt in <2 mm soil fraction	Mg/m^3	4
VM clay	Volumetric mass of clay in <2 mm soil fraction	Mg/m^3	4
VM clay sub/sur	Ratio of VM clay 60-100 cm depth to VM clay 0-30 cm depth (a measure of profile texture uniformity/contrast)	-	4
pHc	pH of 1:5 soil : 0.01 M calcium chloride extract	-	4
Organic C	Organic carbon in <2 mm soil fraction	Mg/ha	4
Total N	Total N content	kg/ha	4
CN	Organic C to Total N ratio	-	4
Total P	Total P content	kg/ha	4
ECEC	Effective cation exchange capacity as cations extracted using barium chloride, plus exchangeable H + Al	kmol/ha	4
PAWC	Plant available water-holding capacity	mm	4
1. Industry-contributed growth/yield plot measurements			
2.ANUCLIM MTHCLIM v.6.1.1 climate attributes (long-term average, LTA, 1976-2005 surfaces)			
3. SLGA 3-arcsecond tile landscape attributes (acquired 2021)			
4. SLGA 3-arcsecond tile soil attributes for 0-5, 5-15, 15-30, 30-60, 60-100, 100-200 cm depths (acquired 2021)			

2.2.2 Silvicultural trial data

The project partners identified 165 *E. globulus* and/or *E. nitens* field trials (i.e. replicated and randomised experiments) with management (silviculture) treatments useful to an exploration of the causes of rotation-length yield gaps (Table 2.5, Figure 2.1b). Most (140) were *E. globulus*; of these most (134) were planted rotations; and 101 had land-use history = FAE or FAEE. About one-third of all trials were t - f and t – wf types for which plot- or treatment-level yield data were not available without significant effort beyond the resources of the present project. Consequently, here we focus on planted *E. globulus* trials with establishment treatments (mostly completed age 0–3 years, but a few continuing to mid- to late-rotation), mostly fertiliser application, and with yield measurements at about age 10 years (usually 9–11 years). There were few e - w type trials with rotation length measurement data, and consequently the long-term effect of weed control applied during early years was not examined here.

Table 2.5. Distribution of trial types between NPI regions. See text in Section 2.2 for explanation.

NPI region	Trial type								
	s	e - cwf	e - f	e - n	e - nf	e / t - f	t - f	t - wf	Total
WA	3		13	5	10	3	9		43
GT	1					7	18		26
CV	4		23						26
MV	2	1	1						4
CG	15		7	1				10	33
EG	4	6	3						13
TAS	2					1	14		17
Total	31	7	47	6	10	11	41	10	163

Climate, and landscape and soil attributes were acquired / derived for the trials similarly to those for PSPs (see earlier). Climate attributes were determined using the geopositioned trial centroid; landscape and soil attributes were determined as means across the 9 (i.e. 3 x 3) 3-arcsecond SLGA tiles (each nominally 90 m x 90 m) centred on the trial centroid. The latter approach was to deal to some degree with spatial variation in these attributes because trials were often several hectares in extent.

2.2.3 WA survey plots

Studies relating *E. globulus* performance to site and climatic condition in southern WA were undertaken by WA government agencies in the late 1990s and early 2000s. The detailed soils data collected in these studies provided the opportunity to assess the role of soil factors in determining productivity using observed soil attributes (cf. modelled attributes from SLGA, see earlier). Three studies were made:

Study 1

To identify the site and climatic factors that influenced the performance of *E. globulus* in south western WA a broad scale survey with 467 plots was undertaken in 113 *E. globulus* plantations located in farmland between Perth, Augusta and Esperance (Harper et al 199). The plantations were established between 1988 and 1992, with a mean stocking of 929 trees/ha. Plots were between 250 and 400 m^2 in area and provided a range of health, productivity, landscape position and soils found within the plantings.

Site index and productivity were estimated from the plot tree measurements using relationships developed by Inions (1992): Site index, defined as the top height at age 5 years, was calculated from measured top heights and measurement age. Tree volume at the time of measurement was derived from measurement top height, stocking and plot basal area. Plot volumes were estimated as basal area x top height/3.

Predicted top height at 10 years was estimated from the site index and predicted plot volumes at age 10 were estimated from models based on predicted top height and stocking and adjusted by taking into account the measured basal area (Inions 1992). Survival was calculated from initial stocking and the number of live trees in the measurement plots.

Study 2

To further understand the effects of soil depth and climate on the performance of *E. globulus* fifty-six plots around 400 m2 (20 m x 20 m) were randomly sited in three *E. globulus* plantations approximately 100 km south of Perth, WA in 1991. The plantations were established in 1989 with initial planting densities of 1250 trees/ha. Plots provided a range of health, productivity, landscape position and soils within the plantations. At each plot tree height and basal area (BA) were measured. Top height (TH) was based on the heights of the 75 tallest trees/ha, and tree basal area (m^2 ha^{-1}) and survival (%) were calculated from the trees alive at the time of measurement. Standing tree volume was estimated from basal area x tree height/3.

Study 3

Following mortality that occurred in a number of WA *E. globulus* plantations after the summer of 2000/01 further studies were undertaken to understand the relationship between site conditions and the occurrence of mortality which averaged approximately 12 % in these plantations. Tree heights and basal areas were measured. A total of 25 pits were dug and soils described and used to assess the cause of mortality

Consistent soil assessments were made in all three studies. Soils were examined at each plot, to depths of up to 4.5 m, either in dug pits or from auger borings. Soil profile and landscape attributes were described using the procedures of McDonald *et al*. (1990). Ferricrete gravel was considered in terms of presence or absence anywhere within the soil profile. Landscape positions ranged from lower slope to crests. Soil depth was described as depth to rock or to saprolite as identified by partially weathered or unweathered feldspars and micas. In Study 2 some of the deep soils were substantially deeper than 2 m (which was used as category for depth in that study), with subsequent drilling revealing the depth of regolith to be >10 m.

Surface samples (0-10 cm) were analysed for physical and chemical properties, with clay content and total nitrogen only reported here. Total nitrogen and available phosphorus were assessed on a surface (0-10 cm) soil sample using standard techniques (Rayment and Higginson 1992). Salinity was estimated by measuring electrical conductivity in a 1:5 soil/water suspension. Values greater than 50 mS/m are likely to affect growth. pH was measured on a 1:5 soil/0.1 M $CaCl_2$ suspension.

2.3 Results – empirical analyses

2.3.1 Estimating plantation yield using operational PSP data

Given the contributed data, cross-regional analysis of plantation productivity in this report focused, but not exclusively, on planted *E. globulus* rotations. In this, to reduce weighting / bias effects that could arise from differences in PSP sampling intensity (see earlier), each plantation was represented by a single PSP (randomly selected where more than 1 was provided). Graphical exploration of the yield data and simple correlations with site climatic and edaphic attributes, and other factors, indicated that MAR explained the greatest proportion of variation in yield (28%, see later), but also that land-use history was a strong categorical determinant of yield.

Non-linear quantile regressions (as linear-by-linear rational functions) of Vub 10 y v. LTA MAR were fitted to a subset of the PSP data (n =509) representing planted *E. globulus* rotations with land-use history FAE, FAEE or FAEEE; planting density (where known) 700–1300 trees/ha; and density at measured age 8–12 years 500–1300 stems/ha (Table 2.6):

Vub 10 y = b + a / (1 + d * *MAR*) [Eqn 1]

Table 2.6. Parameters for non-linear regressions of Vub 10 y against LTA MAR (Eqn 1) for planted *E. globulus*

Fit	Parameter			R^2	s.e. obs.
	a	b	d		
10% quantile	463	– 693	0.001189	-	-
50% quantile	1310	– 1421	0.0003080	-	-
90% quantile	1525	– 1561	0.0003020	-	-
95% quantile	6109	– 6081	0.0000608	-	-
Least squares	784	– 943	0.0007000	0.279	68.1

The density restrictions were imposed to exclude PSPs (n =19) planted outside of a nominal operation range, or where low planting density or very high / catastrophic mortality had likely occurred resulting in understocking at age 8-10 years. The 50% quantile fit was similar to the same-model least squares fit. The 90% quantile regression was posited as a working-reference maximum yield for planted *E. globulus* limited only by rainfall as a measure of water availability, (i.e. Yw). The fits (Fig. 2.3, etc.) highlighted:

- Across CV, MV, CG and TAS, markedly lower average yields for planted *E. globulus* (about 50 m^3/ha) for given rainfall were evident where land-use history did not include an Agriculture phase or had both Agriculture and Pine phases (Fig. 2.3b cf. Fig 2.3a).

- In WA and GT regions with respectively wide and narrow ranges of MAR, planted *E. globulus* with markedly greater yield than the estimated Yw for given rainfall were relatively common (Figs 2.3c & 2.3d). These likely result from additional water supply to rainfall: deep soil profile water in WA (White et al., 2009; Mendham et al., 2011), and groundwater in GT.

- Planted *E. globulus* yields on sites with an Agriculture land-use history (but excluding those with a Pine phase) in CV trended around the 50% quantile fit (Fig. 2.3e), whereas those from MV, CG and TAS were somewhat less (Fig. 2.3f–h). While there were relatively few plantations representing the latter regions, collectively they indicate, after rainfall, a marked effect of other site factors on actual yield (e.g. temperature, Fig. 2.2).

- *E. globulus* coppice yields — represented only in WA and GT — were on average 70–90 m^3/ha less than those for planted *E. globulus* for 600–1000 mm MAR in these regions (Fig. 2.3j cf. Fig 2.3i).

- Yields of *E. nitens* plantations — represented only in CV and TAS, MAR >1100 mm, relatively few with a land-use history including Agriculture — were not correlated with MAR and averaged about 240 m^3/ha excluding the plantations in TAS with elevation >600 m (Fig. 2.3k&l).

Variation in yield (Vub 10 y) was explored against stand and site variables for the PSPs representing planted *E. globulus* distributed across the NPI regions (n =509; n =426 with stand density recorded at age 8–10 years) including PSPs where Vub 10 y < estimated Yw (n =458) and Vub 10 y > estimated Yw (n =51).

- Across regions, simple linear regression (SLR) of Vub 10 y on MAR explained 27.8% of variation (n =509, p <0.001; similar to non-linear regression, see earlier). SLR with regional groups explained 38.9% (parallel lines) to 39.6% (separate lines) of the variation (p <0.001), although some intercept / slope parameters for some regions were not significant (p <0.05). That there are regional differences in the relationship between yield and MAR indicates expectedly — albeit that MAR is an imperfect measure of water availability —, that the relative importance of rainfall as a limitation to yield among numerous site factors varies between regions.

- Across regions, Vub 10 y was correlated with stand density at age 8–12 years (stems/ha, n =426, r = 0.170, p <0.001). Planting density (trees/ha) was not available or difficult to determine reliably for most PSPs, but for a subset of WA PSPs where stand density was correlated with planting density (n =148, r =0.729, p <0.001), Vub 10 y was paradoxically not correlated with planting density. In multiple linear regression (MLR) of Vub 10 y on MAR and stand density (p <0.001, R^2 =0.261) the co-efficient for density was 0.078 (s.e. =0.0220). That is, Vub 10 y increased by about 8 m^3/ha per 100 stems/ha, and thus by about 60 m^3/ha between 500 and 1300 stems/ha; consistent with analysis of trial data (see later); and explaining a significant proportion of an apparent yield gap (cf. Yw) for some PSPs. In this, stand density at age 8–10 years was not different between regions, nor correlated with MAR or other climatic (e.g. MAR/MAE) or soil attributes indicating, catastrophic mortality aside (e.g. from severe drought), that management practice to ensure adequate planting density and good early survival is critical to optimising yield, whatever factors might subsequently affect density through to harvest (e.g. competition-induced mortality).

- Across regions Vub 10 y was significantly correlated with 11 of 22 site attributes (Table 2.4 ; longitude, latitude and elevation aside). After MAR (see earlier), most explained only relatively small proportions of the variation in Vub 10 y (3–8%) and the 2 explaining more, MAR/MAE(18%) and Organic C 0-30 cm depth (12%), were highly correlated with MAR. The two site attributes soil A&B depth and PAWC 0-100 cm, expected to have relatively strong correlations with Vub 10 y because of direct relationship to plant water availability, explained only 8% and 3% respectively of the variation and with the latter counter-intuitively having a negative trend. Note that PAWC 0–200 cm, not presented, was effectively 1.95 x PAWC 0–100 cm (r =0.98, p <0.001) and thus provided no improvement.

- From the base SLR between Vub 10 y and MAR across regions (see earlier), the other significantly correlated site variables (Table 2.7; longitude, latitude and elevation aside) were explored using MLR (sequential forward selection) to determine the additional variation potentially explained. From greater to lesser effect the attributes were (trend, cumulative proportion explained): MAR (+, 27.8%) & VM silt 0-100 cm (–, 30.8%) & MAT (–, 32.9%) & MAR/MAE (–, 35.2%) & total N 0-30 cm (+, 36.4%). Soil A&B depth, VM clay 0-100 cm, VM sand 0–100 cm, organic C 0–30 cm, pHc 0–30 cm also entered significantly but each explained <0.6% additionally, and ultimately PAWC 0–100 cm was not significant. Multicollinearity between some attributes (e.g. r = 0.91 between MAR and MAR/MAE) likely affected the order of inclusion and some indicated trends were unexpected and counter-intuitive (e.g. decreasing Vub 10 y with increasing MAT IN MLR cf. increasing with MAT in simple correlation Table 2.4). Consequently, MLR of Vub 10 y against MAR plus 1 site attribute was investigated, but similar multicollinearity problems affected interpretation. From greater to lesser effect the significant additional attributes (n =509, p <0.05) were (slope coefficient, cumulative proportion explained with MAR): VM silt 0–100 (–231.7, 30.8%); pHc 0–30 (43.2, 29.6%); MAR/MAE (–170.5, 29.4%); VM sand 0–100 (48.5, 29.2%); and MAT (5.09, 28.5%).

- Regression trees were used to further explore the effects of site attributes on Vub 10 y, and on the variation of Vub 10 y from the estimated water-limited yield (Yw, as rVub 10 y, Table 2.4). For Vub 10 y, across regions and considering only soil attributes, over-fitting included most attributes with >90 terminal nodes and explained >80% of the variance. A contrasting fit with 15 terminal nodes explained 54% of the variance and incorporated about half the attributes. The initial splits in the regression tree indicated for MAR <890 mm, that MAE and then MAR/MAE were next important attributes, whereas for MAR >890 mm a soil profile texture attribute (as VM clay sub/sur or VM silt 0–100) was next important. For rVub 10 y (i.e. where the effect of MAR on Vub 10 y has been normalised) a fitted regression tree with 15 terminal nodes explained 32% of the variance using 7 attributes, with initial splits on MAE and VM 0–100 similarly to those for Vub 10 y. The effects on both Vub 10 y and rVub 10 y correspond somewhat to regional differences in climate evaporative demand / wetness and soils, largely as WA & GT cf. CV, MV, CG & TAS (Fig 3h–l).

In summary for the site attributes investigated here, variations between regions were problematic to confirming (other than for MAR) expected strong individual or cumulative effects on Vub 10 y of the attributes related to temperature, water availability, evaporative demand, climate wetness and nutrient supply, and on variation from the estimated water-limited yield, Yw across regions. While the relatively high uncertainty in soil attribute values for an individual SLGA tile (i.e. corresponding to a PSP) will have contributed to imprecision in the explored relationships, the analyses made here are not pertinent to their trueness (bias) — an exercise beyond the scope of the present project — and therefore usefulness for site-specific or spatial modelling.

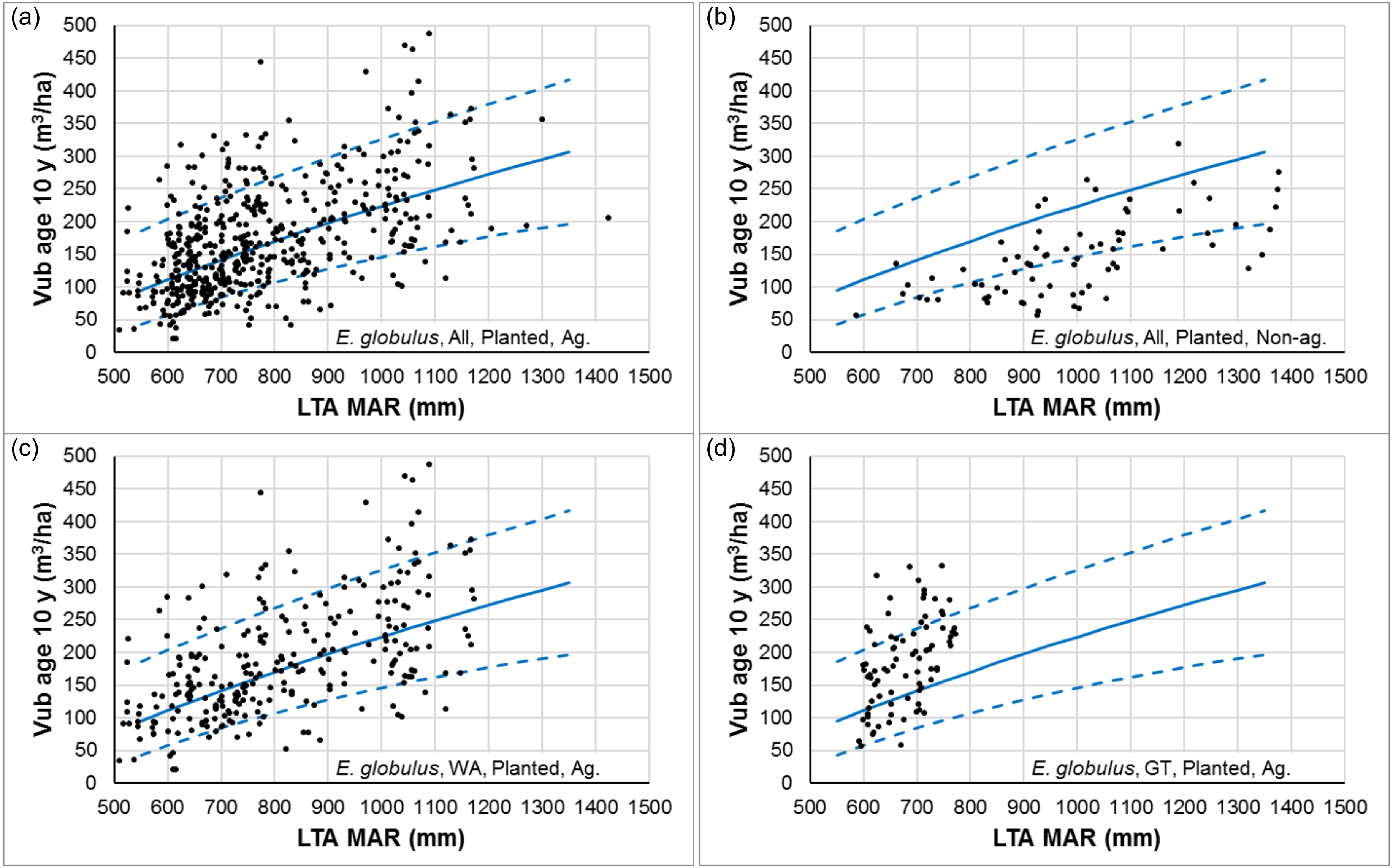


Figure 2.3. Vub age 10 y v. LTA MAR for planted *E. globulus* (a–i), coppice *E. globulus* (j) and planted *E. nitens* (k, l), where density at measurement age 8-12 years 500–1300 stems/ha; land-use history = Agriculture FAE/FAEE/FAEEE (a, c–j), Non-agriculture (b) or both (k, l); across (a, b) or for

WA & GT (i, j), WA (c), GT (d), CV (e, k), MV (f), CG (g), TAS (h, l) NPI regions. Solid blue line is 50% quantile and dotted blue lines 10% and 90% quantile regressions to fit data Fig. 3a. *E. globulus* and *E. nitens* plantations represented by 1 or 2 PSPs respectively.

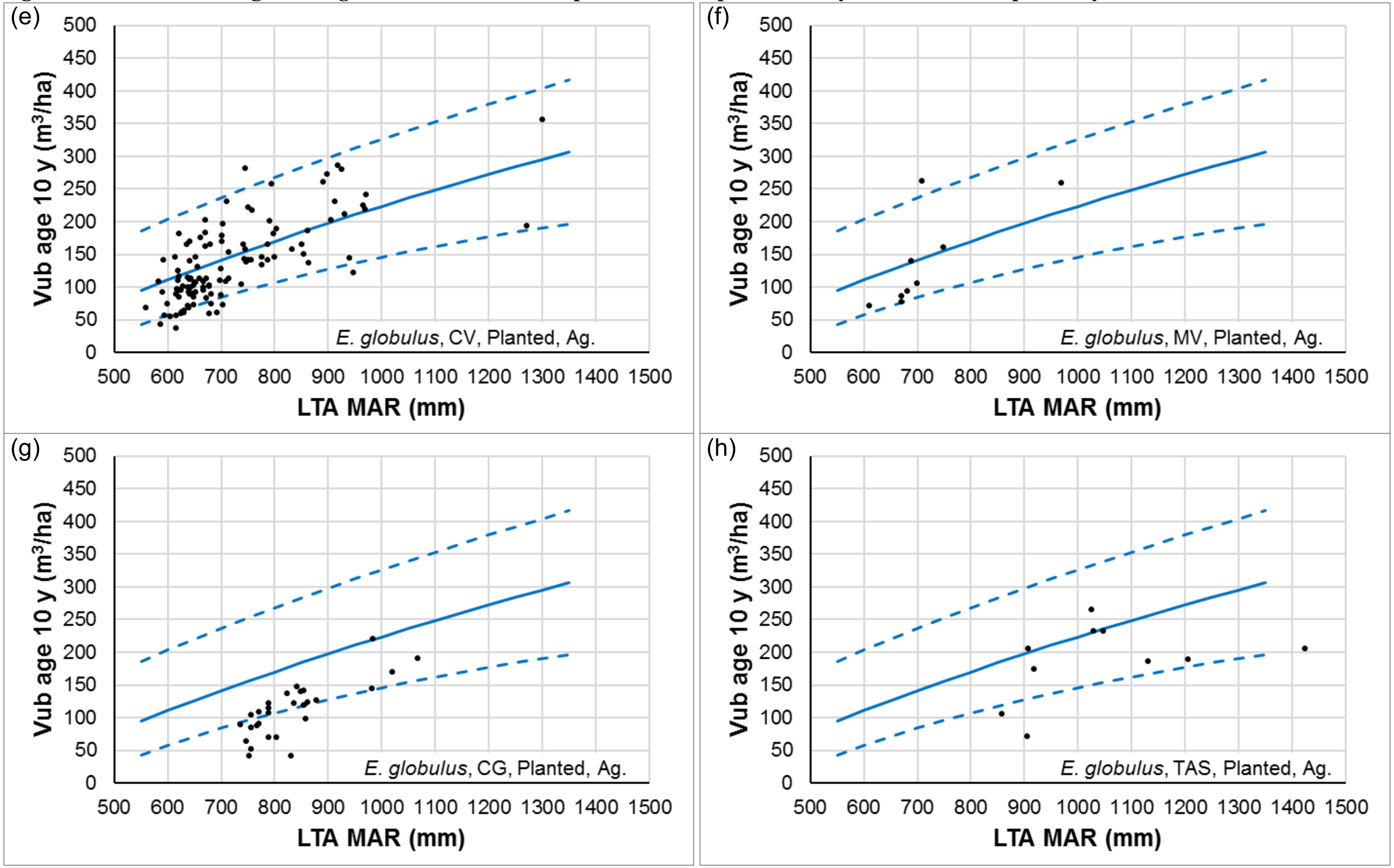


Figure 2.3 continued

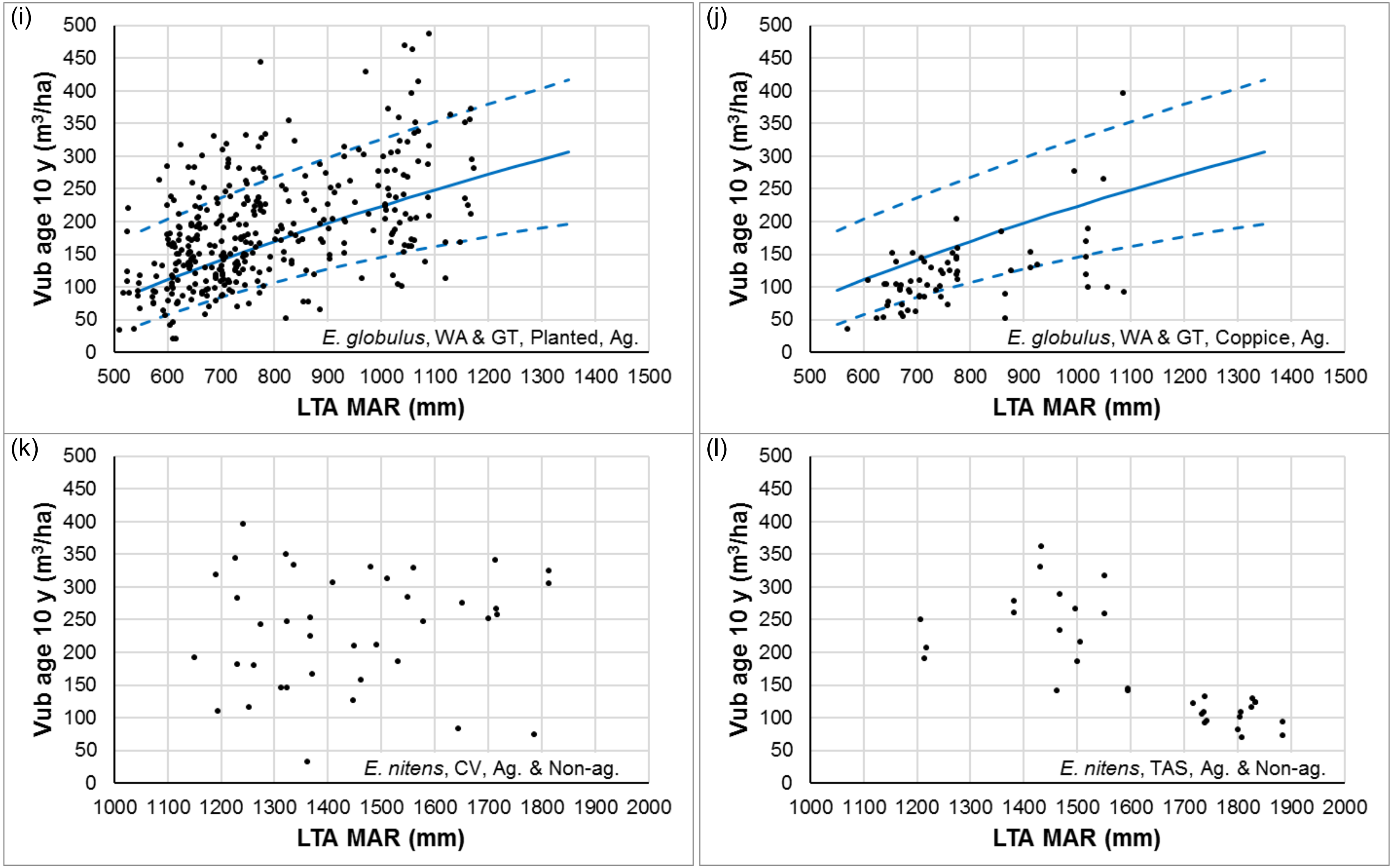


Figure 2.3 continued

Table 2.7. Pearson correlation coefficients (r) between selected yield, location, climatic, topographic and soil variables, directly acquired or derived, for planted *E. globulus* with FAE/FAEE/FAEE land-use histories (n =509). See Table 2.4 for details of variables. Values in grey font are not significant for $r_{critical}$ p <0.01(2) = 0.0115. Values in blue font indicate r^2 >0.05.

Vub 10 y	1	-																											
dVub 10 y	2	-0.80	-																										
rVub 10 y	3	0.90	-0.96	-																									
Longitude	4	-0.26	0.11	-0.16	-																								
Latitude	5	0.15	-0.10	0.11	-0.95	-																							
MAT	6	0.18	-0.09	0.12	-0.87	0.88	-																						
MAR	7	0.53	0.09	0.15	-0.27	0.11	0.18	-																					
MAE	8	-0.03	-0.12	0.06	-0.67	0.76	0.82	-0.21	-																				
MAS	9	0.03	-0.13	0.09	-0.86	0.96	0.83	-0.13	0.80	-																			
MAR/MAE	10	0.43	0.14	0.08	0.06	-0.24	-0.20	0.91	-0.56	-0.46	-																		
Elevation	11	-0.26	0.12	-0.19	0.30	-0.21	-0.63	-0.26	-0.44	-0.16	-0.02	-																	
Aspect	12	-0.07	0.04	-0.05	0.08	-0.05	-0.06	-0.06	-0.01	-0.03	-0.04	0.05	-																
Slope	13	-0.01	0.16	-0.08	0.08	-0.13	-0.19	0.21	-0.26	-0.20	0.31	0.20	0.00	-															
TWI	14	0.06	-0.18	0.13	0.00	0.05	0.10	-0.15	0.17	0.10	-0.20	-0.17	-0.04	-0.60	-														
Regolith depth	15	0.10	-0.08	0.10	-0.23	0.24	0.47	0.05	0.40	0.24	-0.12	-0.60	-0.03	-0.45	0.37	-													
Soil A&B depth	16	0.28	-0.03	0.11	0.09	-0.07	0.01	0.41	-0.22	-0.08	0.39	-0.20	-0.01	-0.10	0.18	0.10	-												
VM soil 0-100 cm	17	-0.04	-0.15	0.08	-0.47	0.52	0.41	-0.29	0.51	0.57	-0.47	-0.04	-0.02	-0.25	0.13	0.22	-0.28	-											
VM sand 0-100 cm	18	0.18	-0.13	0.15	-0.82	0.82	0.84	0.11	0.71	0.78	-0.22	-0.45	-0.06	-0.24	0.14	0.48	-0.09	0.67	-										
VM silt 0-100 cm	19	-0.26	0.19	-0.23	0.81	-0.76	-0.89	-0.16	-0.70	-0.71	0.17	0.65	0.08	0.20	-0.13	-0.54	0.03	-0.39	-0.86	-									
VM clay 0-100 cm	20	-0.23	0.01	-0.09	0.72	-0.70	-0.74	-0.37	-0.52	-0.60	-0.08	0.43	0.05	0.13	-0.08	-0.42	-0.07	-0.25	-0.86	0.74	-								
VM clay sub/sur	21	0.07	-0.13	0.10	-0.61	0.64	0.59	-0.07	0.64	0.61	-0.29	-0.19	-0.01	-0.12	0.04	0.21	-0.23	0.47	0.62	-0.57	-0.46	-							
pHc 0-30 cm	22	-0.17	-0.19	0.06	0.16	-0.08	-0.05	-0.55	0.28	0.08	-0.53	-0.03	-0.01	-0.11	0.15	0.00	-0.07	0.15	-0.11	0.01	0.36	0.17	-						
Organic C 0-30 cm	23	0.34	0.10	0.08	0.02	-0.19	-0.14	0.70	-0.44	-0.39	0.76	-0.08	0.01	0.20	-0.20	-0.12	0.12	-0.46	-0.21	0.12	-0.07	-0.32	-0.64	-					
Total N 0-30 cm	24	0.22	0.03	0.07	0.18	-0.26	-0.33	0.41	-0.51	-0.31	0.54	0.21	0.04	0.37	-0.26	-0.41	0.28	-0.49	-0.46	0.36	0.26	-0.35	-0.11	0.44	-				
CN 0-30 cm	25	0.05	0.06	-0.01	-0.25	0.17	0.27	0.17	0.20	0.06	0.07	-0.27	-0.05	-0.18	0.08	0.29	-0.26	0.16	0.35	-0.31	-0.37	0.12	-0.43	0.38	-0.62	-			
Total P 0-30 cm	26	-0.02	0.07	-0.05	0.40	-0.41	-0.41	0.07	-0.41	-0.42	0.24	0.19	0.07	0.10	-0.14	-0.36	0.02	-0.47	-0.54	0.44	0.39	-0.43	0.00	0.34	0.56	-0.27	-		
ECEC 0-30 cm	27	0.00	0.02	0.01	0.43	-0.53	-0.38	0.03	-0.36	-0.53	0.21	-0.07	0.05	0.21	-0.10	-0.20	0.06	-0.45	-0.54	0.31	0.48	-0.32	0.29	0.20	0.32	-0.19	0.37	-	
PAWC 0-100 cm	28	-0.17	-0.07	-0.02	0.32	-0.26	-0.42	-0.38	-0.25	-0.14	-0.24	0.40	0.06	-0.16	0.10	-0.23	0.01	0.02	-0.34	0.34	0.46	-0.22	0.17	-0.19	0.05	-0.25	0.13	0.10	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
		Vub 10 y	dVub 10 y	rVub 10 y	Longitude	Latitude	MAT	MAR	MAE	MAS	MAR/MAE	Elevation	Aspect	Slope	TWI	Regolith Depth	Soil A&B depth	VM soil 0-100 cm	VM sand 0-100 cm	VM silt 0-100 cm	VM clay 0-100 cm	VM clay sub/sur	pHc 0-30 cm	Organic C 0-30 cm	Total N 0-30 cm	CN 0-30 cm	Total P 0-30 cm	ECEC 0-30 cm	PAWC 0-100 cm

2.3.2 Estimating management effects on productivity using trial data

Treatment-means of Vub 10 y within each trial, plotted against MAR for context, indicated the range and distribution of treatment effects (responses), although all were not necessarily significant. For planted *E. globulus* (Fig. 4a), the scatter of values was consistent with that for PSPs within the estimated water-limited (Yw) envelope (Fig. 3a), but with a greater proportion of lower values representing the reference (control) and lower-input treatments in each trial that were particularly evident where land-use history did not include an Agriculture phase. Vub 10 y for the maximal input treatment (Fig. 4b), usually but not necessarily producing the maximum yield within each trial, trended similarly to that for the 50% quantile fit for PSPs. For trials with fertiliser treatments ($n = 60$), the maximal treatment usually fell somewhat less than the rainfall-limited envelope, indicating that the treatment did not completely address the targeted limitation and/or other limitations were present.

Thirteen species trials compared 4–11 native forest (provenance) seedlots of *E. globulus* (Fig. 4c). The marked range of yield across seedlots, indicates that caution is required in interpreting absolute yield values from some older trials where unimproved seed sources have been used. Regardless of relevance to the current estate using improved seed-orchard genotypes, the best seedlots in most trials had yields greater than the 50% quantile, and despite most of the trials not having an Agriculture land-use history phase.

Twelve e - n and e - nf trials in four sets compared planting densities variously within ranges 300–1200, 500–1500, 570–1000 and 625–2000 trees/ha, and in about half of the trials in some combination with fertiliser application (Fig. 2.4d). Averaged across all trials, Vub 10 y increased by about 8 m^3/ha for each 100 trees/ha increase in planting density between 500 and 1500 trees/ha, consistent with that found for the PSPs (see earlier).

To provide some sense of the relative effect of nutrition (fertiliser application) cf. site and other effects on yield, the maximal treatment (usually N or N & P application at total rates 200–400+ kg/ha N during establishment) was compared with the reference (control treatment) (Fig. 2.5a). Land-use history effects (particularly FE and some FPE sites) were evident as marked outliers likely because of P deficiencies in reference treatments on FE sites (Fig. 2.5a). Six former agriculture sites were also outliers: (i) 2 likely attributable to topographic (water gaining) and/or very infertile soils; (ii) 2 associated with a short agricultural land-use history; and (iii) 2 having annual application of N fertiliser, totalling about 1800 kg/ha over the rotation.

Excluding these outliers, the absolute ($r = 0.498$, $p <0.001$) and relative ($r =0.352$, $p <0.05$) responses to fertiliser increased with LTA MAR (Fig. 2.5b&c). After MAR, soil attributes for the trials determined from SLGA (Table 2.7) were not correlated with fertiliser response (e.g. Fig. 2.5d). Detailed trial by trial examination of observed site factors (e.g. soil analyses) that might be gleaned from records is warranted, particularly for the outliers and the several trials with relatively large apparent negative responses.

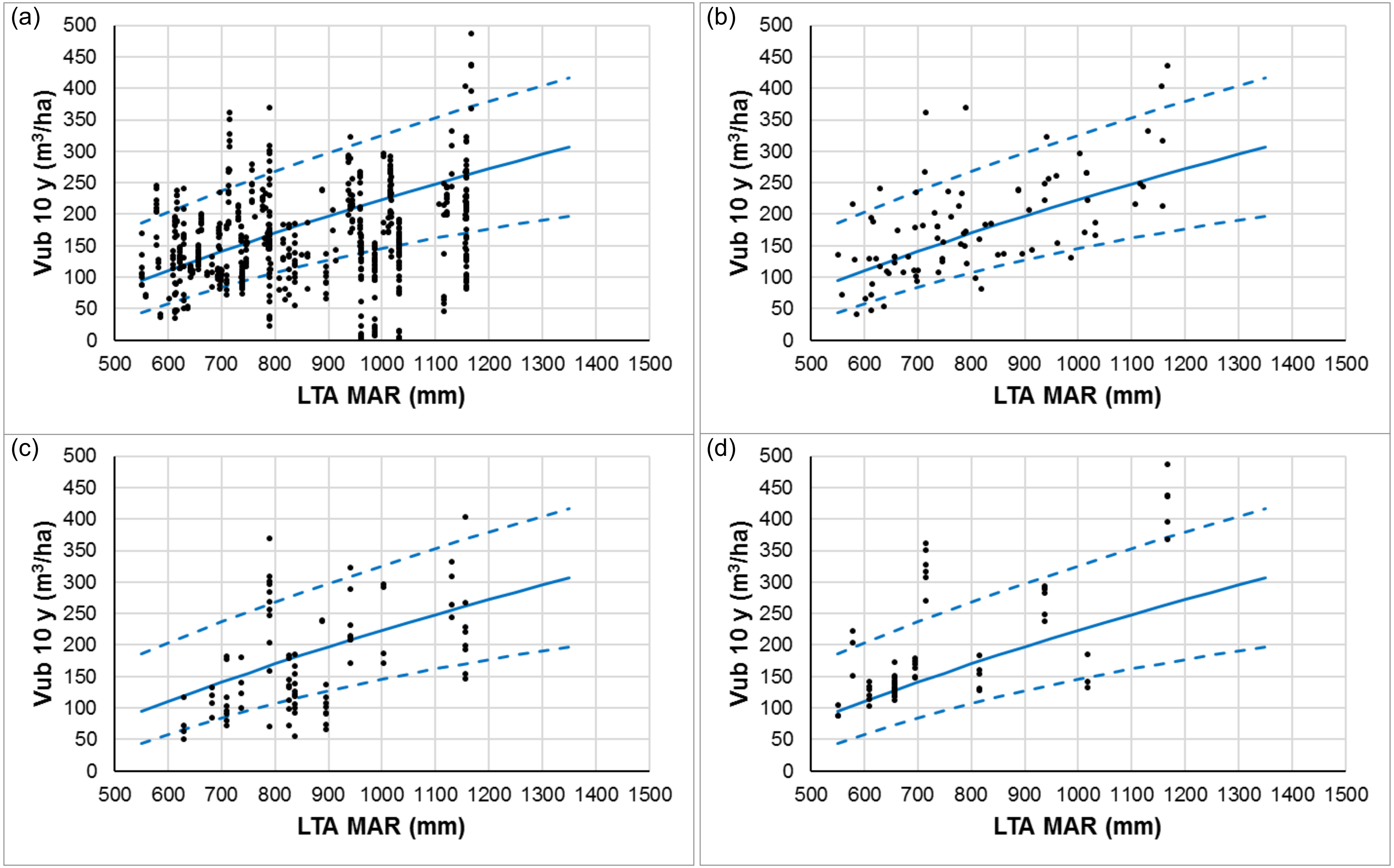


Fig. 2.4. Treatment means for Vub 10 y v. LTA MAR for selected planted *E. globulus* trials: all treatments (84 trials, a); maximal treatment (84 trials, b); seedlot differences (13 trials, c); and planting density differences (12 trials, d). Solid blue line is 50% quantile and dotted blue lines 10% and 90% quantile regressions for PSP yield data (from Fig. 2.3a).

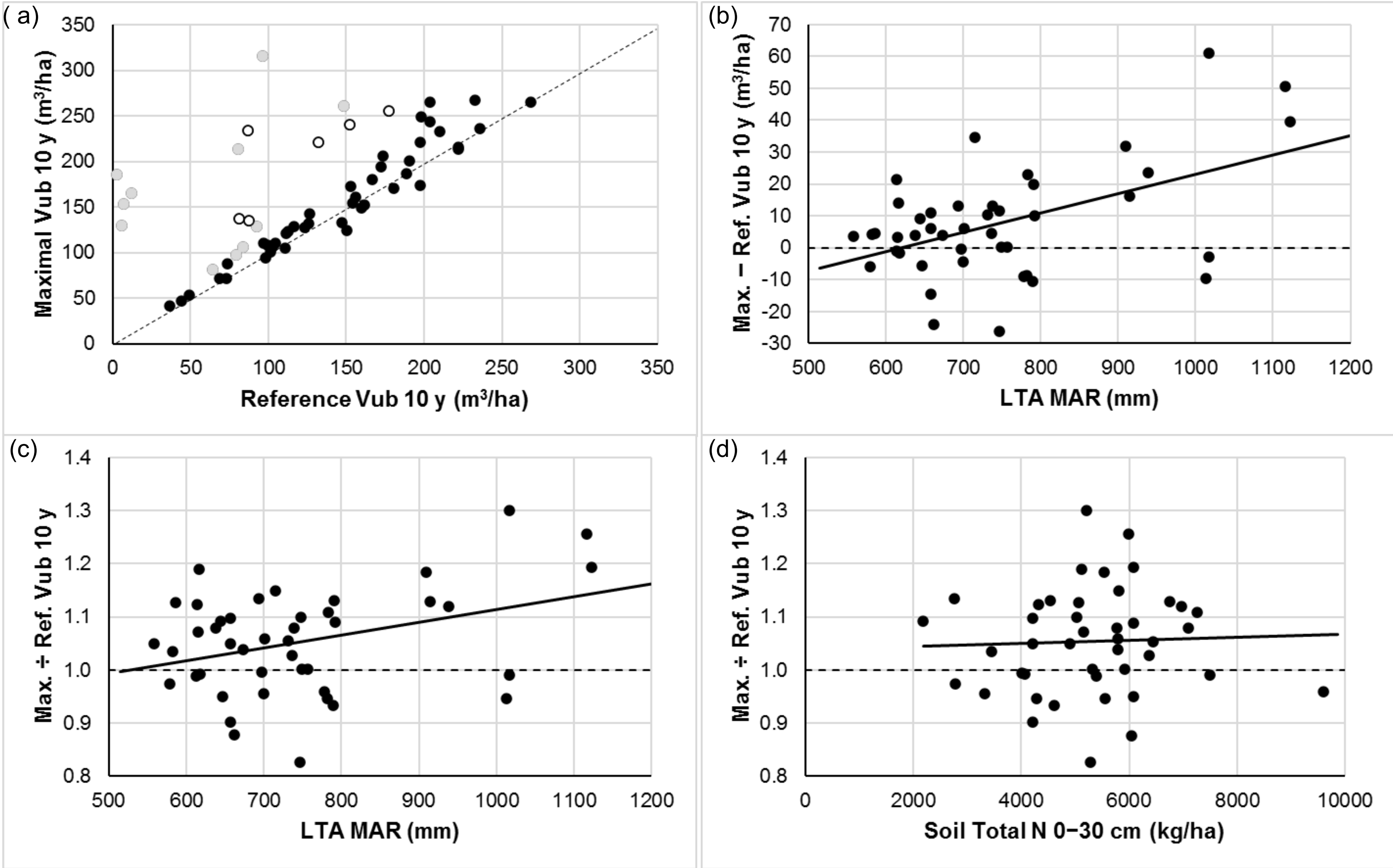


Fig. 2.5. Planted *E. globulus* establishment fertiliser trials Vub 10 y Maximal v. Reference treatment means (60 trials, a); Maximal – Reference v. LTA MAR (b); Maximal ÷ Reference v. LTA MAR (c); and Maximal ÷ Reference v. soil Total N content (d). Values (43 trials) in (b), (c) and (d) exclude non-former agricultural land-use sites (11 trials, grey symbols), and former agricultural site outliers (6 trials, open symbols) in Fig. 5a.

2.3.3 Impact of site characteristics on plantation productivity in WA

At six (6) years of age on deep soils (>2.0 m) with no salinity and with adequate stocking (>800 stems/ha) productivity (as Top Ht, BA, Vol) increased with increasing rainfall and decreased with higher evaporation (Fig 2.6 a,c,d). The impact of evaporation was not apparent at high rainfall (1300 mm). Survival was good and did not increase with rainfall when evaporation was < 1500mm, whereas when evaporation was high (>1500 mm) survival was lower, however there did not appear to be a consistent progressive increase in survival with increasing rainfall (Fig 2.6 b)

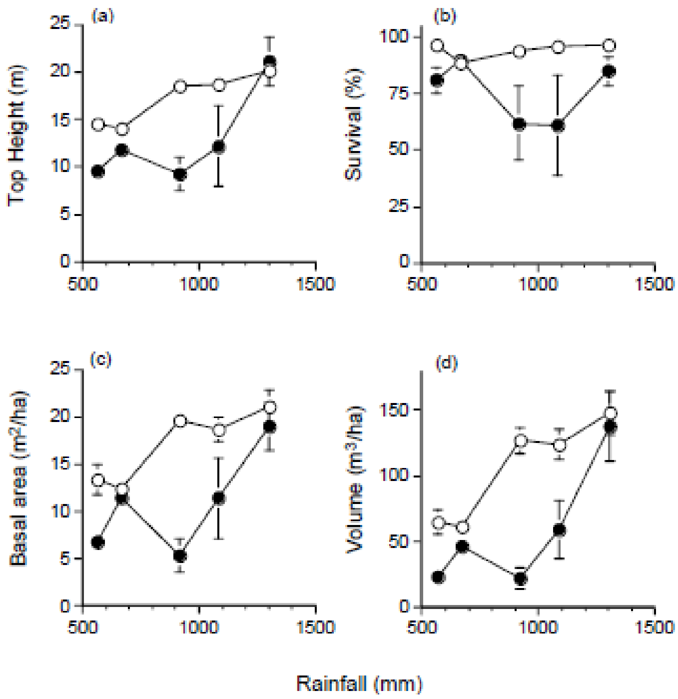


Figure 2.6. Performance of 6-year-old *E. globulus* planted on farmland across south-western Australia, in relation to major climatic attributed Plots >2m soil, EC < 50mS/m and > 800 stems/ha at establishment ○ < 1500 mm, ● > 1500 mm total evaporation (From Harper et al. 1999).

When volume estimates were projected to age 10 using a local growth model (Inions 1992) there was a strong impact of increasing rainfall on sites with low evaporation (<1500 mm/year) with an additional ~80 m^3/ha of wood being produced over 10 years (Table 2.8). At the lower rainfall sites (600-800 mm) higher evaporation reduced productivity by 50 m^3/ha over 10 years (Table 2.8).

Table 2.8 Estimated volume of trees at 10years old from measurements taken at age 6, using the Inions 1992 growth models. Plots with >1000stems at 6 years old and non-saline soils, >2m deep (From Harper et al.1999).

Evaporation (mm)	Rainfall (mm)					
	600-800			>800		
	n	Volume[A] (m³/ha)	Volume[B] (m³/ha)	n	Volume[A] (m³/ha)	Volume[B] (m³/ha)
<1500 (South)	18	158±12	163±13	47	238±12	257±17
>1500 (North)	37	102±4	129±10	C		

[a]A: Predicted volume – TH and stocking model of Inions (1992) from age 6 data
[b]B: Corrected volume – corrected using basal area from age 6 data
C: no plots with >1000 stems/ha

There was a strong interaction between stocking and climate (water availability). Where evaporation was low (<1500 mm) volume production increased with increasing stocking and increasing rainfall (Figure 2.7). Volume production was higher in the higher rainfall zone, with between ~50 m^3/ha higher productivity in the high rainfall zone. Where evaporation was high (>1500 mm) and rainfall was >800 mm there was an increase in volume production with increasing stocking, however, with lower rainfall (<800 mm) and high evaporation (>1500 mm) there was no increase in volume production with increasing stocking. It appears that where water availability is favourable then volume production increased with increasing stocking, and where water supply was more limited there was no increase in volume production with increasing stocking.

The previously observed influence of evaporation on volume production was evident across the stocking range.

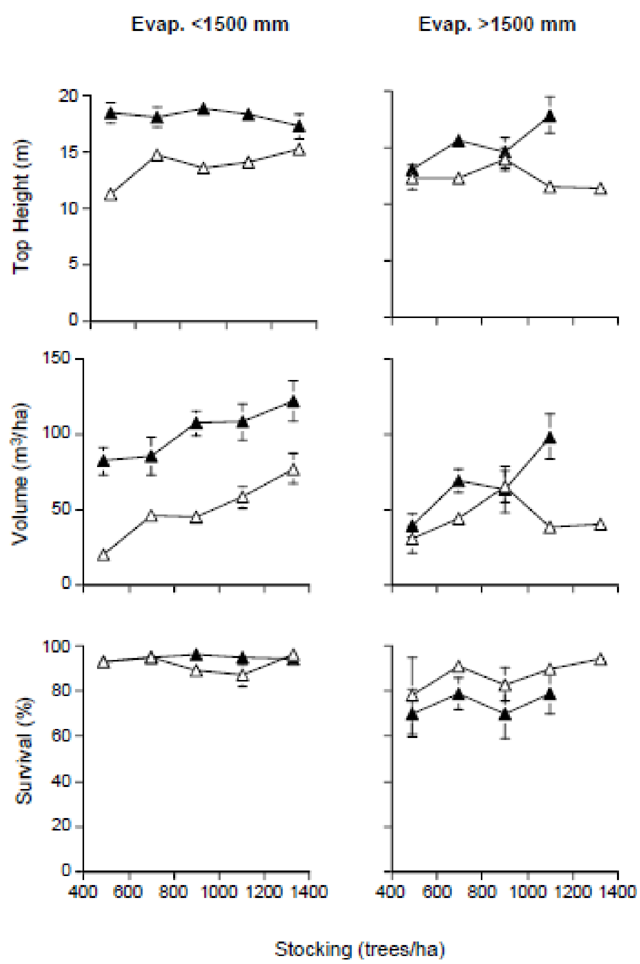


Figure 2.7 The effect of initial stocking and climate on *E. globulus* growth at age 6 years. Plots with >2 m soil, EC, 50mS/m 600-800 mm (△r) and > 800 mm (▲) rainfall zones. (From Harper et al. 1999).

Fertility or specifically soil nitrogen influenced productivity with a strong increase in productivity being evident with increasing soil N (Figure 2.8). This trend was strongest in the high rainfall low evaporation zone (Figure 2.8). Below soil N of ~0.2% there did not appear to be a significant response to soil N suggesting that below 0.2% soil N growth was limited by nitrogen supply.

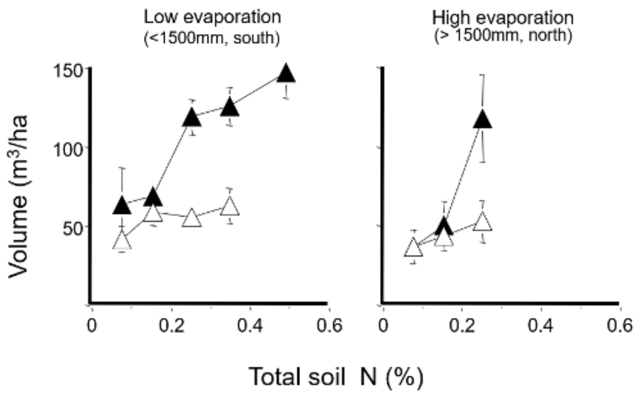


Figure 2.8 - Relationships between volume production, soil nitrogen concentration and climate. ▲ >800 mm rainfall, △ <800 mm rainfall (Harper and Edwards unpublished)

The impact of drought on young (3-year-old) *E. globulus* was based on an analysis of mortality in three high rainfall zone plantations. The mean rainfall range was 980-1100, matched with pan evaporation 1555-1599 mm (CWI of 0.63-0.64) so the three sites had virtually identical climate conditions and for WA this was a well-watered site.

The study examined the drought impacts during a very dry period (between Nov-April 19 mm rain, 872 evaporation, deficit during summer of 852 mm.

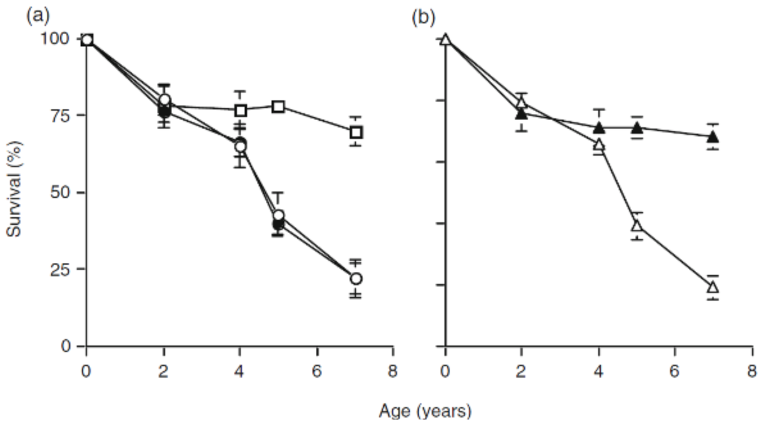


Figure 2.9 Variation in tree survival with (○) soil depth 0-1, (●), 1-2 m (l) and >2m (□) and (b) absence (△) or presence (▲) of ferricrete gravel within the soils. (from Harper et al. 2009)

Soil depth was an important constraint on performance (Figure 2.9 a) with > 2 m of soil required to minimise mortality, with the presence of ferricrete gravel (lateritic soils) providing a large advantage (Figure 2.9 b). In WA the presence of ferricrete gravel indicates deep lateritic soils.

While this study provided insights into the drivers for mortality it did not provide a broader picture of the factors that influence productivity across southern WA as it was focussed on the high rainfall areas. Importantly it demonstrated that even on high rainfall sites drought related mortality and low productivity and can occur due to the limitations imposed by soil water storage capacity.

This aligns with the concept that soil water storage capacity is an important factor in determining productivity when rainfall is high, however as rainfall declines (cf. Collie 2001 study) then soil water storage capacity becomes less influential on plantation productivity and survival.

The study of the performance of *E. globulus* in the 600-800 mm rainfall zone east of Collie, prompted by dry conditions in the 2000/01 year that resulted in drought related mortality confirmed the findings of the earlier broader regional study described above (Harper et al.1999):

Under drought conditions in this relatively low rainfall zone (<800 mm) mortality occurred on soils as deep as 3-4 m. This indicated that climate exerted the overall influence on plantation performance, particularly as rainfall declined. Deep soils did not provide protection from severe water stress under low rainfall conditions.

Table 2.9. Influence of rainfall and evaporation on volume production by *E. globulus* plantation in the Collie area (2001) (from Harper and McGrath 2001).

Rainfall (mm/year)	Evaporation (mm/year)	
	<1500	**>1500**
<600	88 (2)	50 (5)
600-800	126 (20)	88 (2)
800-1000	245 (19)	
1000-1200	230 (16)	197 (3)
>1200	296 (14)	267 (2)

Plotting these data against the midpoint of the rainfall ranges confirms the strong relationships between rainfall and evaporation and the productivity of the plantations (Figure 2.10). The productivity in the higher evaporation zone was ~50m^3/ha lower than in the lower evaporation zone.

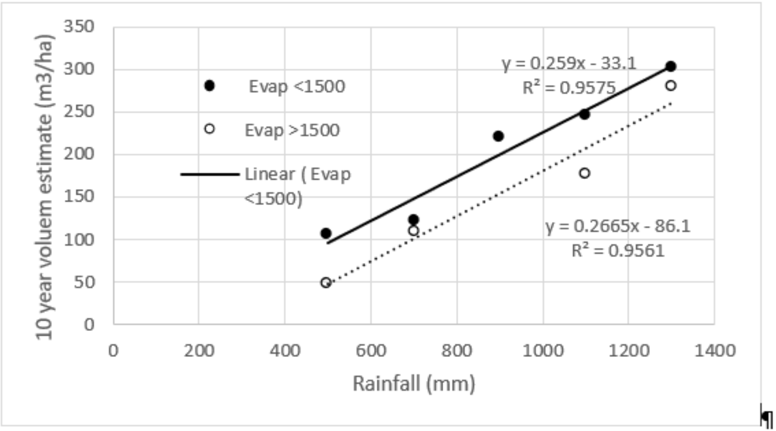


Figure 2.10. Influence of increasing rainfall and evaporation on the 10-year productivity of *E. globulus* in WA.

2.4 Discussion – empirical analyses

Trends and magnitude of some effects of climate, soils and management on plantation yield and yield gap were evident in the analyses of the three empirical data sets (PSPs, trials, WA survey plots) and are summarized in Table 2.10. About two-thirds of the data were from WA and GT, somewhat reflecting the distribution of the national estate, but therefore possibly biasing some estimated relationships in the cross-regional analyses and their interpretations, particularly for MV, CG and TAS plantations which are most different from WA and GT in general growing conditions. Moreover, while there were indications that the relative importance of individual site attributes affecting yield varied between regions, such differences were difficult to confirm statistically or to develop regional-specific relationships where there were few data.

The usual caveat affecting all empirical-based estimates and their applicability and accuracy outside of the range of conditions on which they are based applies to the present study. For example, the estimates of potential yield (absolute values), and the parameterisation of the fitted relationships, may not be applicable to the future given continual improvement in deployed genotypes, and silvicultural practices, and particular given climate change (which will vary regionally) and increased atmospheric CO_2 (affecting for example NPP water-use efficiency). However, the relative importance of the factors identified as contributing to yield gaps is likely to be more robust. The impacts of climate change are likely to be incremental as CO_2 rises progressively.

2.4.1 Climate effects

Increases in actual and/or potential yield with increasing rainfall were consistent across the three data sets (Figs 2.3a, 2.4a, 2.6 and 2.10). The productivity trend (as yield per unit rainfall) of MAI 2.6 m^3/ha per 100 mm MAR was similar to those reported for *E. globulus* in WA (calculated from White et al. 2009) and for P. radiata (Fig. 1.2, from Nambiar 1995) over a similar rainfall range (MAI increasing about 2 m^3/ha per 100 mm MAR).

After the effect of rainfall, yield declined with increasing evaporation, but particularly so in WA with markedly reduced yield where MAE >1500 mm/year. CWI (here as MAR ÷ MAE; cf. MAR ÷ Potential Evapotranspiration used in some analyses, e.g. White et al. 2009) was across regions strongly correlated with MAR but had a poorer relationship with yield than MAR (Table 2.7). However, for fits with (regional) groups, MAR and CWI both explained about 40% of variation in Vub 10 y.

After rainfall, yield increased with temperature despite the countervailing effect of temperature increasing evaporation and decreasing yield. The effect across regions was to increase yield from TAS to WA by about 30 m^3/ha for a given MAR. Relationships between yield and MAR (Table 2.6) were subtly non-linear over the full range of MAR, likely capturing to some extent that MAT was negatively correlated with MAR (except in WA where there was no relationship).

The maximum yield for planted *E. globulus* on former Agriculture sites (Yw, Fig. 2.3a etc., Table 2.6) is estimated to be elevated by about 5–25 m^3/ha between 600–800 mm MAR because of inclusion of a relatively large number of plantations likely receiving additional water (groundwater; deep profile-stored water, at least for first rotation). Objective exclusion of these from fits was not feasible without additional (observed) site information.

Most of the relatively few represented MV, CG and TAS plantations (Fig 2.3f–h) had yields less than the 50% quantile and combined trended 50–60 m^3/ha less for MAR increasing 600–1400 mm. Relatively low MAT (Fig. 2.2e) and MAS might explain some of this difference for TAS, but there is no clear cause among the available site attributes. Among the represented CV plantations, a cluster in the range MAR 600–700 with yields less than the 50% quantile was evident (Fig. 2.3e). About two-thirds of these plantations had igneous surficial geologies (either Devonian granite or Quaternary basalt) and likely soils with relatively low PAWC to rooting depth exacerbating the effect of low rainfall on yield.

2.4.2 Soil effects

In CV, MV, CG and TAS, average yields were greater on sites with an Agriculture land-use history phase. The 'pasture effect' ('old-field') of increasing plantation growth is well known (e.g. Skinner and Attiwill 1981a&b) and for Australia's generally low P-status soils can be attributed largely to application of substantial amounts of fertiliser P and associated development of legume-based pastures. A marked effect of fertiliser P in trials on FE land-use history sites was also observed (see later). While the pasture effect can diminish over successive rotation(s), and there was evidence in the PSP data for this on FAPE sites, this not to say that tree crops or species per se reduce soil fertility; and in the present study a similarity of FE and FAPE land-use history sites may have also resulted from historical differences in agricultural P fertiliser application rates.

The distributions of some SLGA acquired / derived values seemed useful for general descriptive purposes across regions (Fig. 2.2) and were usually consistent with well-known or expected differences. However, SLGA soil attribute values have relatively high uncertainty ranges at any specific location (tile) and consequently must be used with caution to describe soils, or to interpret the effects of soil properties on yield, at specific locations. Across regions, some soil attribute and derived values were correlated with plantation yield, but usually relatively weakly even for attributes expected to have a strong influence on yield through effects on water and nutrient supply (Table 2.7, e.g. soil texture attributes, Total N 0–30 cm). Moreover, soil A&B (horizon) depth and PAWC 0–100 cm are poorly indicative of the depth of regolith that can be exploited by *E. globulus* roots, for example up to 18 m in WA (Mendham et al.2011).

The observed soil profile attributes in the WA survey data indicated that in higher rainfall areas (>800 mm) increasing soil depth reduced the susceptibility to drought mortality. In lower rainfall areas mortality occurred on both shallow and deep soils, indicating the supply of water (rainfall) becomes the dominant driver of productivity and the susceptibility to drought.

2.4.3 Management effects

Stand density

For *E. globulus* pulpwood production, where thinning is unlikely in planted short rotations (c. 10 years), planting density is a primary silvicultural decision aiming to optimize yield and/or stumpage (as affected by diameter distribution at harvest) and avoid drought mortality (e.g. Baker et al. 2009, White et al. 2009, Pinkard et al. 2014).
An increase in yield with increasing stand density was consistently evident in the PSP, trial and WA survey data sets. There was no evidence of a maximum yield within in the range 500–1300 stems/ha howsoever the density at rotation age arose (i.e. from planting density and/or competition-induced mortality). Any effects of catastrophic mortality (e.g. arising from drought) were avoided in the analysis.

Coppicing

A comparison between planted and coppice rotation yields was only available using limited PSP data from WA and GT. Coppice yield (selected for 500–1300 stems/ha at c. age 10 years; usually achieved by thinning) was on average 70-90 m^3 less than for same-density, (mostly) first-rotation planted rotations. The difference might be attributed variously to (i) stand density at coppicing and stool survival, (ii) thinning practice (e.g. singling or other), fertiliser application, and (iii) depletion of deep soil profile water during the preceding planted rotation and change in soil fertility (White et al. 2009; McGrath and Mendham 2018; McGrath et al. 2023) but could not be explored further because of metadata limitations. Similarly, a study of 1R vs 2R harvest yield east of Bunbury indicated that productivity was 4 to 6 m^3/ha.year lower in the second rotation for both coppice and seedling reestablishment suggesting that the depletion of stored water during the first rotation was at least partly responsible for the observed decline in productivity in 2R coppice (McGrath and Harper pers comm).

Nutrition

There was a strong increase in yield with increasing soil N concentration in the WA Survey data, with a much stronger response observed at high rainfall sites (Fig. 2.8). Similar responses have been observed in other WA studies (e.g. White et al. 2009, McGrath and Mendham 2018).

In the PSP data across regions, yield was positively but weakly correlated with SLGA-estimated soil N content (as Total N 0–30 cm). However, soil N was correlated with MAR, and after allowing for MAR in regression, yield was not significantly related to soil N. In the trial data across regions, yield response was also not related to SLGA-estimated soil N content (Fig. 2.5d). In current nutrition trial work (McGrath et al., 2023) early growth responses to N fertiliser seem not related to measured soil N concentration (0-10 cm depth) across regions, but segregated by region relationships are more apparent, particularly for WA. The response to N fertiliser was also related to soil N concentration in a series of *E. nitens* trials in Tasmania (Smethurst et al. 2004).

Table 2.10 Summary of climate, soil and management effects on yield and yield gaps for *E. globulus* determined from empirical analyses ([1]PSPs, [2]trials, [3]WA Survey)

Factor	Approx. range of effect on Vub 10 y	Description / Note
Rainfall[1,3]	About 100 m^3/ha increase for MAR increasing 650 to 1050 mm; and 150 m^3/ha increase for MAR increasing 600 to 1200 mm	Vub 10 y increased ~26 m^3/ha per 100 mm increase in MAR
Evaporation[1,3]	About 20 m^3/ha decrease for MAE increasing 1000 to 1450 mm	Vub 10 y decreased ~5 m^3/ha per 100 mm increase in MAE (after effect of MAR)
	Up to 50 m^3/ha less for high evaporation sites	WA high evaporation sites (>1500 mm) cf. low evaporation sites (<1500 mm)
Temperature[1]	About 30 m^3/ha increase for MAT increasing 10.5 to 16.0 °C	Vub 10 y increased ~5.1 m^3/ha per 1 °C increase in MAT (after effect of MAR)
Land-use history[1,2]	About 50 m^3/ha less if land-use history does not include an Agriculture phase	CV, MV, CG and TAS MAR 600–1400 mm
Soil depth[3]	Up to 75% mortality on shallow soils (<2 m)	In WA >2 m soil depth required to reduce drought mortality risk
Stand density[1,2,3]	About 30 m^3/ha increase for 750–1100 stems/ha	Vub 10 y increased ~8 m^3/ha per 100 stems/ha increase in stand density at age 8–12 years
Coppicing[1]	70–90 m^3/ha less for 2R coppice than 1R planted	WA and GT MAR 600 to 1200 mm
Nutrition[2]	Fertiliser response 20–200 m^3/ha	Where land-use history does not include Agriculture, or includes Pine phase
	For most sites a fertiliser response trend 0 to 35 m^3/ha (range –30 to 60) for MAR increasing 600–1200 mm.	Where land-use history includes Agriculture phase and
	On some sites 60–150 m^3/ha	Including sites where annual application has maintained a high level of nutrient availability

3. Process-based modelling of plantation yield and yield gaps

3.1 Summary – process-based modelling

- Selection of the model: The process-based model APSIM was selected to provide the modelling capacity for the project as it provided similar or better capability to either CABALA or 3-PG and was assessed as easy to use, accessible, and it has good support via the APSIM Initiative and developer network.
- Model parameterisation: APSIM was successfully parameterised for *E. globulus* and *E. nitens* based on research trials and data available from the current empirical modelling work (Section 2)
  The parameterised APSIM Eucalyptus model was used to provide examples of four diverse scenarios:
  Aquifer water and nitrate uptake
  Climate change scenarios
  Assimilation of remote-sensed data
  Modelling Representative WA Plantations
- Model assessment: In each case the model provided a useful estimate of productivity and these simulations aligned with the estimates available from empirical studies.
- The model was used to estimate rain-fed yield gaps due to management factors at 13 sites covering the range of states and productivities. Sub-optimum nitrogen availability was the largest or equal largest gap at all sites, followed by stocking, weed control and other factors.

3.2 Choosing a process-based model

A common question on entry to the field of process-based modelling for plantations is: What are the strengths and limitations of different modelling options, and which one should be used for a particular application? Here we address this question by comparing the attributes of three models: 3-PG, CABALA, and APSIM. These three models were chosen for comparison because they have been used relatively recently in the industry and they remain in active consideration for various applications. A tabulated comparison of many attributes is provided in Table 3.1, with an emphasis on distinguishing between the models. At a very general level, a potential user has to trade-off technical simplicity (3-PG) versus complexity (APSIM and CABALA), and dedicated forestry models with an unclear pathway for support (3-PG and CABALA) versus one that includes agricultural options and on-going support that is well-established (APSIM). With simplicity also comes a higher need for observations, because simpler models have more reliance on empirical calibration of parameters that define processes and that are summarised in fewer parameters. For example, 3-PG includes a fertility factor, in contrast to the other two models that specifically include nitrogen, and the latter two also have an aspiration to include phosphorus.

The level of empiricism in a model, and data availability for calibration, affects its usefulness for predicting outcomes in future conditions that haven't yet been experienced. Because future climates are trending to be significantly different to the past, it has been argued that process-based models are better placed to predict future forest growth (Korzukhin et al. 1996, Bosela et al. 2022), and there is heavy reliance on process-based modelling for the successful prediction of future climates (https://skepticalscience.com/climate-models.htm). However, where detailed processes like those leading to tree mortality are not well-understood, process-based models can be less reliable than empirical models (Adams et al. 2013).

The project steering committee took several months to evaluate these three modelling options (and others) for a process-based approach to yield gap analysis for Australian eucalypt plantations, and they chose the APSIM model. Industry partners and researchers were particularly drawn to the ability in APSIM to include (i) complex soils (deep, with water, C and N), (ii) silvicultural flexibility (particularly the inclusion of N fertilisation, weeds, and slash management), (iii) science and software engineering credentials, and (iv) links to agricultural models and software support. At that stage, June-October 2020, the available framework included only eucalypt genotypes suitable for tropical and subtropical climates. After the decision to use APSIM was taken, the inclusion of temperate eucalypts was completed, as well as temperate-to-tropical pines, and these models have so far met expectations of the project for analysing yield gaps down to the level of plot-scale management. Another attraction to using APSIM is that it is maintained by the APSIM Initiative (https://www.apsim.info/) on almost a daily basis by a team of about four full-time-equivalent staff and 50 other contributors when needed (https://github.com/APSIMInitiative/ApsimX).

Future use of process-based modelling for eucalypt plantations in Australia will need to take better account of the increasing need for fertiliser as nutrient availability decreases from the higher levels inherited from previously fertilised agricultural and forestry sites. This increasing need for fertiliser is well-established in this report. The CABALA and APSIM models specifically cater for N using many functions and parameters that define soil N availability, uptake, and use. In contrast, N fertiliser responses in 3-PG are catered for in a single fertility factor. Both approaches can be used, but the heavy empiricism of 3-PG for soil fertility necessitates a greater reliance on calibration with observations, which might also be expected to lead to less transportability of predictions, less confidence in virtual experiments, and a greater need for fertiliser experiments in the field.

All three models have credibility in catering for the main factors involved in plantation yield responses to stocking and climate change (i.e. changes in CO_2, temperature, rainfall, and radiation). The simpler approach of 3-PG is quite attractive in this context, i.e. using monthly climate data. The 3-PG model can also be run successfully daily at a catchment scale to predict stream flow (Almeida et al.2016). Developers have a similar catchment scale hydrology aspiration for CABALA, and although this capability has also been demonstrated in earlier versions of APSIM, it is not yet available in the current version of APSIM that includes the plantation models of interest. Where models have commonality in predicted variables, predictions can sometimes be strengthened by using more than one model in an ensemble approach (Elli et al. 2019).

Predictions of individual tree sizes as well as total volume or biomass yield are important for some uses of forest yield modelling. This capability is available in 3-PG and demonstrated in an earlier version of CABALA, and there are aspirations to include it in APSIM.

Management of weeds is important for plantation forestry. This can be handled generically in 3-PG and CABALA. Weeds as specific herbs, shrubs or trees can be modelled in APSIM plantation simulations. APSIM also includes agroforestry options for the simulation of tree effects on adjacent pasture or crop production. The CABALA and APSIM models simulate C and N cycling through litter and soil, but this option is not available in 3-PG.

Increasing CO_2 concentrations can be handled by all three models mentioned here, but using alternative methods that are well-established in the literature. In the CABALA model, atmospheric CO_2 concentrations affect the rates of photosynthesis at the sub-stomatal level in an asymptotic relationship with the concentration. This model operates at a deeper physiological level than the other two models. Almeida et al. (2009) calibrated a CO_2 factor that provided less limitation to canopy fixation and water use as atmospheric concentrations increased above 350 ppm CO_2, using a calibration dataset derived from CABALA (Aleida et al. 2009). The APSIM model, also uses a base concentration of atmospheric concentrations of 350 ppm, but it uses the method of Reyenga et al. (1999) to adjust light resource use efficiency, transpiration rates and critical nitrogen concentrations.

As seen here, these three models have several common technical capabilities, but, for projects in the near-term, the technical differences will probably feature highly in determining the choice of one model over another. A diversity of models at the research level is highly desirable, as it does not constrain model features to the thinking of a small group of researchers, and it therefore allows the testing of new approaches. However, in the long-term, for reasons including (a) efficiency in the use of industry research funds in providing one or more operationally useful process-based models, and (b) importance for auditing and accounting processes of providing a consistent, repeatable and reliable version control system for resource modelling, it might be worthwhile industry considering which of these three models it wishes to support the most for developing a full range of features. The APSIM model was also used successfully in Smethurst et al. (2022) to explore its use for resource assessment and forecasting, including model-data fusion to update wood inventory forecasts using LiDAR data. This section is repeated with minor variations, but the following table remains unchanged.

Table 3.1 Comparison table of three process-based models currently under active consideration for use in productivity predictions in Australian plantation forestry[1]

Aspect for Comparison	3-PG	CABALA	APSIM
Model strengths	Relatively easy to learn and use Simple canopy processes, soils (grow with the root development up to maximum soil depth), and climate (monthly) Many publicly available free versions without legal constraints. Private versions can be created and used, e.g. within a plantation company. Validated for the main planted species in Australia and overseas Climate change effects on plantation growth including increasing CO_2 Plot, spatial, and catchment scales Widely used around the world and operationally used in several large forestry companies Multiscale Identifies and quantifies growth limiting factors Decision support tool Yield forecasting	Canopy is represented as an array of eclipses LAI response is dynamic and not time dependent Multiple soil horizons for water and N Root system grows to occupy soil Allocation to maximise NPP by balancing supply and demand for the most limiting resource (energy, water, or N) Alternate forest structures are realistically represented Capacity to represent thinned stand as array of eclipses rather than a paler big leaf Co-limitations of climate and nitrogen on productivity Climate change effects on plantation growth including CO_2 Allows modelling of responses to N fertiliser and pruning Individual tree model gives size class distributions Plans for water balance to include perched water tables Calibrated and parameterised for a few planted species in Australia Applied in several research cases in Australia Decision support tool Yield forecasting	Intermediate complexity for learning and use Simple canopy processes Adequate complexity above- and below-ground Silviculture – weeds, N fertiliser, stocking, coppice Easy-to-use interface Peer science and software review processes Open access with version control Modular Calibrated and parameterised for the main planted species in Australia Climate change effects on plantation growth including CO_2 Direct links to national soils and climate databases Integrated with Australia's system for agricultural modelling Improvements to agricultural models are easily included in plantation simulations Widely used around the world Decision support tool Yield forecasting
Design philosophy	Freely available and let developers define and build the level of complexity required Simplify complex processes that are not feasible to be intensively measured using generalised relationships (e.g. ratio of NPP/GPP)	Services researcher needs by including the complexity required Capture physiological response to changes in the forest - natural and imposed by management Based on a philosophy of representing physiological research on the responses of photosynthesis,	Services researcher and operational needs Includes the minimum level of complexity required to satisfactorily predict yield and other important variables

Aspect for Comparison	3-PG	CABALA	APSIM
	Provide a practical tool for decision making at a broad scale No version control required, but well documented	respiration, transpiration, and allocation to environment and management	Includes all improvements in the current version, but earlier versions remain available Auto-documentation APSIM is widely used around the world in agriculture, with recent international use for eucalypt plantations
Key publications and development path	Landsberg and Waring (1997) – original model description Coops et al.(1998) – spatial, including satellite data Sands and Landsberg (2002) *E. globulus* Almeida et al.(2009) – climate change analysis Almeida and Sands (2016) – improved water balance Almeida et al.(2016) - catchment scale Forrester and Tang, 2016 – mixed species There are 127 publications listed on the website	Battaglia et al.(2004) – original model description Drew et al.(2009) – wood properties modelling Pinkard et al. (2010), Kriticos et al. (2007) – forest health module for weeds and insects Battaglia et al. (2015) - individual tree model Battaglia and Bruce (2017) – climate change impacts on Australian plantations	Keating et al. (2003) – original model description for agricultural crops Paydar et al. (2005) – Eucalyptus model Holzworth et al.(2018) – new platform Elli et al.(2019)– eucalypts in Brazil Smethurst et al.(2020) – further description of the Eucalyptus model Smethurst et al.(2022) – pines and temperate eucalypts added, deep aquifer nitrate, satellite evapotranspiration
Comparative reviews: Luedeling et al. (2016) Elli et al.(2019) Miehle (2009)	Compared Compared Compared	Compared Compared Compared	Compared Compared -
Website for access	https://3pgforestryubcca/software/ contains model overview, publications, software download, manual, course and developers	None yet, but planning to be available as python/C ++ version later in 2022	https://www.apsiminfo/
Dimensionality	Typically 1D Spatial version allows link to 2D and 3D water flow at catchment scale	Typically 1D Plan to be linked directly with 2D and 3D distributed flow models	Typically 1D Agroforestry zones (2D) An early case study was spatially interactive for hydrology (3D)
Time-step	Typically monthly	Daily for main model loop Hourly in advanced conductance model	Daily

Aspect for Comparison	3-PG	CABALA	APSIM
	Daily for detailed water balance and catchment scale	Monthly for individual tree module	
Scales	Plot (single or multi sites), spatial, catchment, regional, country	Plot (single or multi sites), spatial, catchment, regional, country	Plot (single or multi sites), spatial, catchment, regional, country
Platforms supported	Windows	Windows	Windows, LINUX, OSX and clusters
Biophysical Modelling			
Forest systems suitability	Even-age, single species plantations Mixed forests	Even-age, single species plantations, agroforestry designs, can model two species in a mixed stand, can model two canopy layers	Even-age, single species plantations Mixed forests Agroforestry
Silviculture possible:			
Stocking	Y	Y	Y
Mortality	Y	Y	Y
Thinning	Y	Y	Y
Pruning	Y	Y	Y
N fertilisation	Single fertility factor	N cycle	N cycle
Irrigation	Y	Y	Y
Weeds	Generic water use	Generic resource use and biomass production	Species or generic full models
Slash and litter management	N	Y	Y
Defoliation	User-specified LAI reduction'	Y (Health Module)	User-specified LAI reduction'
Modelled Australian plantation species	*P radiata, P elliottii, E globulus,* and *E nitens, E saligna, E grandis, E dunnii, P pinaster, E camaldulensis, Corymbia maculata, E cladocalyx, E pellita, E cloeziana, E pilularis E longirostrata, E tereticornis, Khaya*	*P radiata, P elliottii, E globulus, E nitens, E grandis, E kochii, C maculata*	*P radiata, P elliottii, E globulus, E. grandis,* and *E nitens*

Aspect for Comparison	3-PG	CABALA	APSIM
	tectona, Khaya senegalensis, sandalwood, oil mallees		
Can new genotypes be included	Y	Y	Y
Can observed data be imported and graphed for comparison	Y		Y
Observed vs predicted graphs internally generated	Y		Y
Model skill statistics reported [3]	R^2, RSR, ME, MAE, RMSD		R^2, NSE, RSR, ME, MAE, RMSD
Photosynthesis representation[2]	Net - using a resource use efficiency factor	Gross- using Farquhar-von Caemmerer-Berry biochemical model Net - accounts for respiration	Net - using a resource use efficiency factor
C allocation	Semi-fixed patterns; monthly stresses and growth limiting factors	Dynamic with daily stresses, to maximise NPP	Dynamic - daily limited by highest stress
Number of soil horizons	2	3, but planned to be many in new version	1 to many - user-defined
Soil water balance method	Tipping bucket	Tipping bucket, plan for Richards method	Tipping bucket or Richards method (SWIM model)
Methane and NO-gases	N		Some capability
Climate effects	Y	Y	Y
Soil C	N	Y	Y
Nitrogen	Simple fertility limitation factor	Detailed in soil and plant	Detailed in soil and plant
Phosphorus	N	N, but planned	N - under development
Weeds	Generic calibrations demonstrated	Generic calibrations demonstrated	Multiple species already calibrated can be added
Tree size classes	Y	Y	N
Mixed forests	Y – several examples	Y	Possible, but not well tested
Agricultural crops and pastures	Water use is quantified	N	Y

Aspect for Comparison	3-PG	CABALA	APSIM
Agroforestry zones for crops (2D)	N	N	Y
1D spatial hydrology (catchment scale)	Y	Y	Past applications
Livestock	N	N	Y
Software Engineering			
Version availability	Versions available in VBA (Excel), C++, Python, and R 3-PG (1D) - free 3-$PG_{spatial}$ (1D spatially) – free or licensed 3-PG hydrology, licensed 3-PG_R - free 3-PG_Python – free 3-PG_{mix} (mixed species) - free	Scion are considering making available a new version that is being developed (D White pers comm)	Current and past versions are available via website
Version control	Y – website releases	Plan - via GitHub	Y - GitHub
Software and infrastructure maintenance and upgrades	Y – infrequent, voluntary	After June annual update on GitHub	Y- frequent via the APSIM Initiative involving four partners in Australia, one in NZ, and one in USA
Support for ongoing maintenance and interface upgrades	Plantation companies for internal versions or via research projects, or by researchers voluntarily	Some support from CSIRO via projects	Provided by the APSIM Initiative
Coding in a net language	Y	Y (being recoded in python, C++ for all operating systems (LINUS, UNIX, PC)	Y
Open source	Y	Plan is to be made publicly available late in 2022 via a GitHub	Y
Development community	Y	Not yet, but encouraged once new version released	Y
Highly modular and can benefit from developments for agriculture	N	N	Y

Aspect for Comparison	3-PG	CABALA	APSIM
Convenient ingestion of gridded soils and climate data, including future climate scenarios	Y	N	Y
Convenient batch processing of large numbers of gridded simulations	Y	Y	Y
Convenient setup of experiments in the user interface	N	N	Y
Convenient set up of sensitivity analyses	Y - sensitivity analysis, NonlinXL optimiser	N	Y - factorial experiment, Sobol, and Morris methods
Can non-coders rapidly develop new tree species or cultivars in the model?	Y	N	Y

[1]Table developed with assistance from Auro Almeida and Don White. Current at time of preparation, i.e. May 2022.
[2]Photosynthesis approach as defined by Medlyn et al.(2003): radiation use efficiency (RUE), big leaf (BL)
[3] R^2= coefficient of determination, NSE = Nash-Sutcliffe efficiency, RSR = mean square error to standard deviation ratio, ME = mean error, MAE = mean absolute error, RMSD = root-mean-square deviation

3.3 Yield gap estimation using APSIM Eucalyptus

3.3.1 The model

Here we provide an overview of the Eucalyptus model in APSIM as it was at the time of reporting.

Within the genus of Eucalyptus, genotypes can be specified in the model to represent any level required, e.g. species, provenances, hybrids, or clones. Currently there are genotypes for *Eucalyptus globulus*, *E. nitens*, *E. grandis*, *E. urophylla*, *E. saligna*, and *hybrids*. During this project, the temperate genotypes required for plantation forestry in Australia (*E. globulus* and *E. nitens*) were added. 'Genotype' as referred to here is a specific combination of physiological parameters that define a plant model's behaviour in the in APSIM framework, where they are also called 'cultivars'. This is similar to use of the 'genotype' term by tree breeders (G. Dutkowski pers. comm.), i.e. a very specific combination of genes, but the specific set of parameters in APSIM can be arrived at by calibration using observations at any level of taxa such as genus, species, provenance, family, and clone. The model can be accessed at www.apsim.info.

Observed datasets on which calibrations of the temperate eucalypts were based came from research and operational plantations in Western Australia, South Australia, Victoria, Tasmania, and Portugal. These datasets are explained and cited in the validation simulations for Eucalyptus and Pinus that can be downloaded from GitHub, and in the pdfs available at https://apsimnextgeneration.netlify.app/modeldocumentation/.

Smethurst et al. (2020) described the development and use of APSIM for tropical and sub-tropical plantations in Australia and Brazil. Elli et al. (2020a, 2020b) earlier used this model to study various aspects of eucalypt plantation forestry in Brazil, with a modification to calculating stem volume where wood density was assumed and therefore volume calculated directly from biomass. The current implementation, though, calculates stem diameter, height and volume as a function of individual tree biomass, and then wood density.

Provided in Fig. 3.1 are examples of graphs of observed versus predicted (OvP) values for several outputs of the Eucalyptus model after calibration: aboveground weight, root:shoot ratio, LAI, height, DBH and leaf weight. Statistics for model skill are provided for each graph. The aim during model development is to have each set of OvP points follow the 1:1 line, but this is very rarely achieved due to model imperfections (structure and parameterisation) and errors in observed data due to measurement error. The model statistics shown indicate good model skill and are comparable to those for most other plant models in APSIM and with other forest process-based models.

Four examples of applying the APSIM Eucalyptus model are provided:

1. Aquifer water and nitrate uptake
2. Climate change scenarios
3. Assimilation of remote-sensed data
4. Modelling Representative WA Plantations

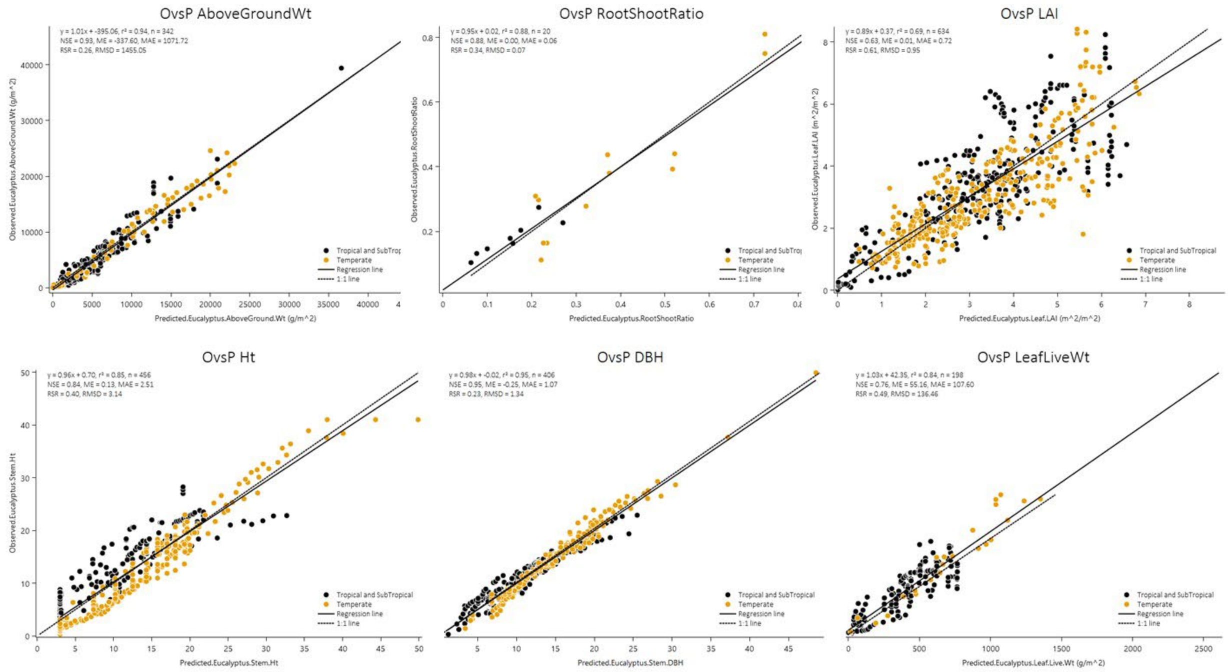


Fig. 3.1. Model skill graphs and statistics for several outputs of the calibrated Eucalyptus model. Black points are for tropical and sub-tropical genotypes and the yellow points are for temperate genotypes. Multiple points per site were included where available.

Although this development phase of the Eucalyptus plantation model in APSIM was completed, several desirable improvements were identified for future projects:

1. Improve specific leaf area and bark thickness specifications
2. Expand the set of weeds models
3. Add a mortality tool that includes the self-thinning rule and or process-based mortality
4. Improve effects of stocking on C and N biomass allocation patterns
5. Include waterlogging effects
6. Add soil P and K effects
7. Expand wood quality options
8. Geo-locate and interact adjacent plots for run-on, stream flow and groundwater
9. Add tree and log size class distributions
10. Better summarise outputs for environmental accounts (water use, C sequestration, greenhouse gases, biodiversity indexes)

3.3.2 Simulation setting up

To estimate yield gaps using the APSIM Eucalyptus model, simulations were constructed with the following components for a selection of plots in the database that covered the range of productivities and regions. Apart from having a location, year of establishment, and an estimate of stem volume under-bark at age 10 years, there were no other preconditions for plot selection.

1. Weather data were accessed from SILO without further adjustment.

2. Soil data were accessed from the SLGA, but values were changed to measured values where available; typically these were slope, aspect, 0-10 cm depth concentrations of C, C:N, pH, PAWC, total depth, and suspected maximum rooting depth. Soil values were later used for calibration, if required.

3. The genotype for simulation was chosen from those available in the model, but in a few very high productivity cases, available genotypes needed to be modified during the calibration phase to enable more efficient wood production by altering values of, for example, RUE, leaf longevity, and C allocation to coarse roots and stems.

4. Management data were updated by consultation with industry collaborators responsible for the plots chosen. These data were slope, aspect, initial stocking, mortality, N fertiliser applied at or soon after planting and later, and weed cover. Herbaceous weeds were simulated by sowing barley annually, and woody weeds by including *Pinus radiata* as small transplants one month after transplanting small Eucalyptus. Fertilised as urea. Mortality was specified in the model as a thinning on selected dates to achieve final stocking, which was usually known, and intermediate stocking if also known.

5. An experimental structure for each simulation enabled an estimation of rain-limited yield (Yr) by removing in factorial combinations the limiting factors of incomplete survival (mortality), weeds, N fertiliser, and limitations that could not be quantified like pests and diseases, non-uniformity of the plantation, non-N nutrient limitations, and unknown genetics. The extent of these unknown (other) limitations was set by assuming attained yield (Ya) was 90% of what could have been attained if these other factors were not limiting (10% limitation). Absolute potential yield (Yp) if all water and N limitations were removed was simulated by hypothetically using automatic irrigation and ample N-fertiliser to alleviate the water and N stress indexes estimated by the model.

6. Yield gaps were summarised as their contribution to MAI_{10} in bar charts. Management gaps were quantified by calculating the average effect of each management variable (survival, weed control, and N fertiliser) from the factorial set of treatments that contributed to Yr.

3.4 Results and discussion – process-based modelling

3.4.1 Aquifer water and nitrate uptake

During the project, the Eucalyptus and Pinus models were used to explore the hypothesis that nitrate in the unconfined aquifer in the Green Triangle (Mount Gambier) region of South Australia could be taken up and be contributing to high growth rates observed in some locations. A thinned pine plantation over an aquifer at 23 m depth was simulated for 37 years, and an unthinned eucalypt plantation over an aquifer at 4 m depth was simulated for 14 years. This work was published as Smethurst et al. (2022); it demonstrated that the model could perform well under these complex conditions, i.e. with very deep profiles that contained an aquifer with nitrate to which the roots could grow in or in the capillary fringe and take up water and N. Modelling supported the hypothesis that both water and N uptake could be important for plantation productivity in the region where plantations were growing over water tables that were less than or equal to 6 m depth. Simulated rates of evapotranspiration, an emergent property of the model, were consistent with satellite estimates at the location where both sources of data were available. Other simulated processes or properties were also generally consistent with measurements in the region, i.e. rates of net N-mineralization and N-leaching, concentrations of nitrate-N in the aquifer, and rates of water uptake from the aquifer. Cautions were also provided about using soil values from the Soil and Landscape Grid of Australia. Results were used to identify research priorities needed to prove or disprove the hypothesis. Please refer to the publication for details.

3.4.2 Climate change scenarios

A capability is being built for APISM that will enable relatively easy inclusion in simulations of climate change scenarios consistent with IPCC climate datasets. There is a plan to provide daily climate data by the end of the project for numerous predicted climates at nominated global locations and dates into the future. A user will be able to nominate one or more global circulation models (GCMs), and climate variability will be provided by 30 different yearly sequences of climate based on past variability.

To illustrate this type of capability, an example is presented for an *E. globulus* plantation in WA (Figure 3.2). Apart from increasing CO_2 concentrations, climate change increased temperatures, and more so for the high emission scenario (HE; CO_2 = 541 ppm). Rainfall decreased for the HE scenario, but it was little affected by the low emission scenario (LE; CO_2 = 443 ppm). Radiation at the WA site decreased for both scenarios and slightly more so for the LE scenario. The processes simulated in APSIM integrate the effects of these climate changes.

Effects on simulated wood production will depend on the specific LE and HE scenarios chosen, and the relative potential effects of various climatic and other limitations. For the two HE and LE scenarios chosen as examples, both were simulated to increase wood yield by 17-19%, compared to historic climate. That this increase in wood production occurred despite a decrease in radiation and small contrary effects on rain, suggest that increases in CO_2 and temperature were the driving influences. These two scenarios assumed no weed, mortality, or N-limitation, i.e. water-limited yield potential (Yw). Results depend on the choice of location, silviculture, genetics, GCM, and particular year sequence. For this type of climate change analysis, location has a resolution of 5 km, because this is the spatial resolution of the climate data. A more detailed analysis would take these factors into account, and it would involve a large number of simulations for even one location and choice of establishment year. Large numbers of such simulations are often conducted by APSIM users using scripts in R or Python for batch processing of APSIM simulations, and example batch scripts are available if required (contact P. Smethurst).

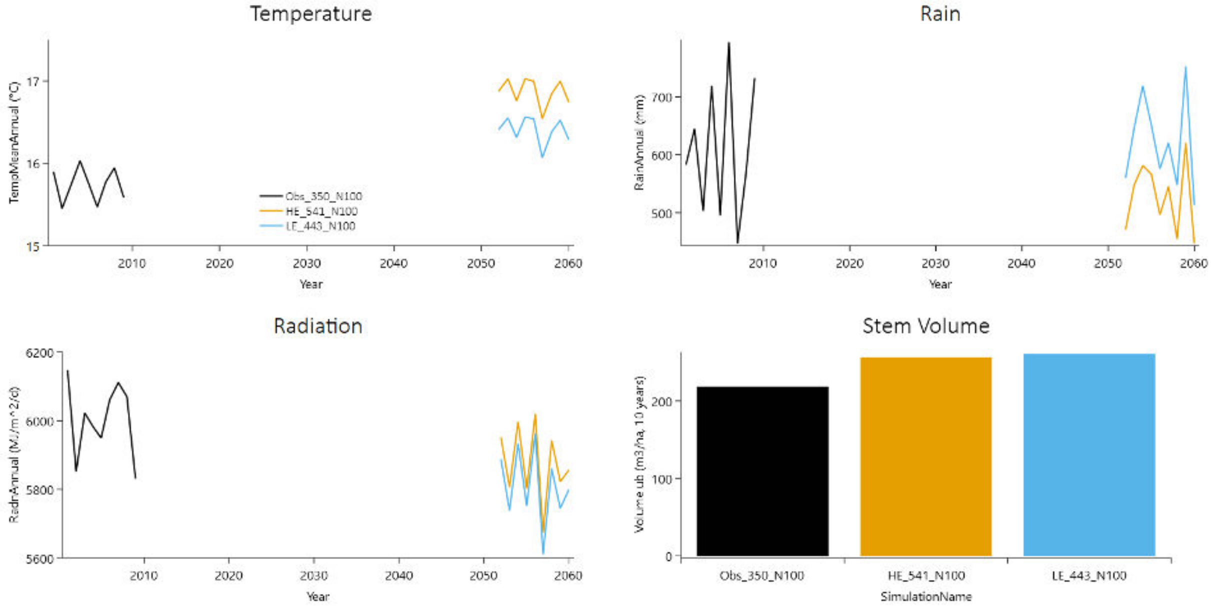


Figure 3.2. Simulated results of a 10-year rotation of *E. globulus* at the Springwell site in WA established in 1999 with climates observed (black, 350 ppm CO_2) or established in 2050 with one possible climate scenario each resulting from either a high emissions scenario (yellow, 541 ppm CO_2) or low emissions scenario (blue, 443 ppm CO_2). Shown are annual average of daily mean temperature (top left), mean annual rainfall (top right), annual sum of daily radiation (bottom left), and wood yield (stem volume under bark, bottom right).

3.4.3 Modelling representative WA plantations

The objective of this modelling was to test whether APSIM simulations using the same variables identified in the WA survey data resulted in similar trends to the observed data.

Six locations were chosen in south-west WA that represented the range of rainfall and evaporation experienced. The sites were Albany, Bannister, Esperance, Manjimup, Pemberton, and Scott River. Climate data were sourced from SILO for the 10-year period of the simulation (June 1996 to June 2006). At each site, a rotation of *E. globulus* was simulated using the WABlueGum genotype in APSIM. Factors investigated were:

- Soil Depth – typical depth or extended to 10 m
- Initial soil water content – 35% or 95% full
- Soil C concentration (%, 0-15 cm) – 4 levels 1.4% to 5.6%, with proportional changes at other depths and C:N ratio of 14
- Survival - 50% or 95%
- N fertiliser rate – 0, 200 or 400 kg N ha^{-1} during the first 4 years

Within this dataset, as average annual rainfall increased from c. 600 to 1200 mm, average annual pan evaporation decreased from c. 1700 to 1200 mm (Fig. 3.3). A similar relationship occurred between average annual potential evapotranspiration and rainfall (Fig. 3.4), but potential evapotranspiration rates were c. 600-800 mm higher than pan evaporation rates.

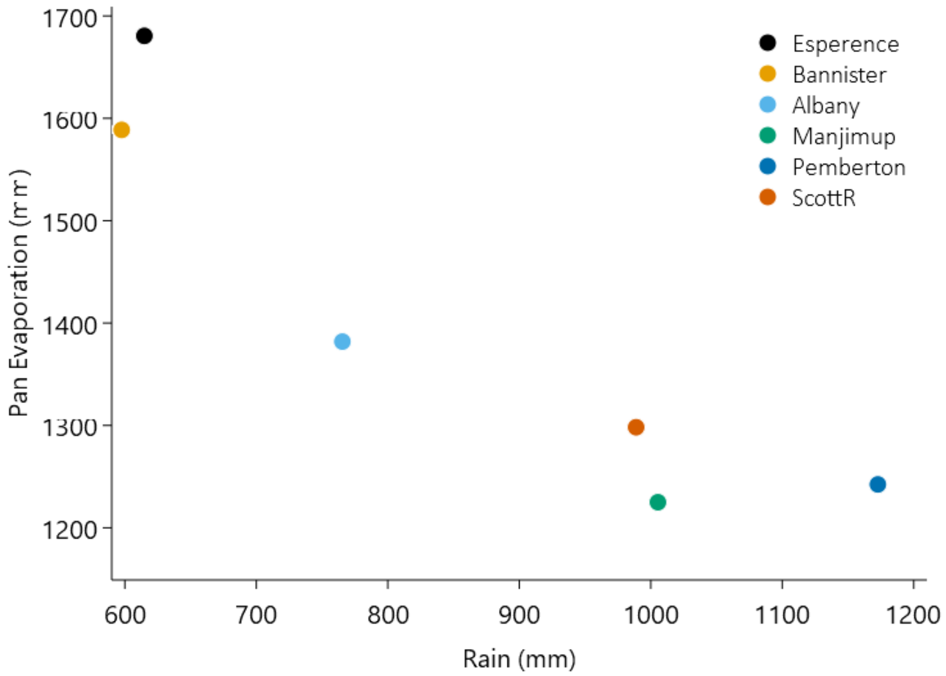


Fig. 3.3. Relationship between average annual pan evaporation (mm) and rainfall (mm) during the rotation (1996-2006) for the six sites.

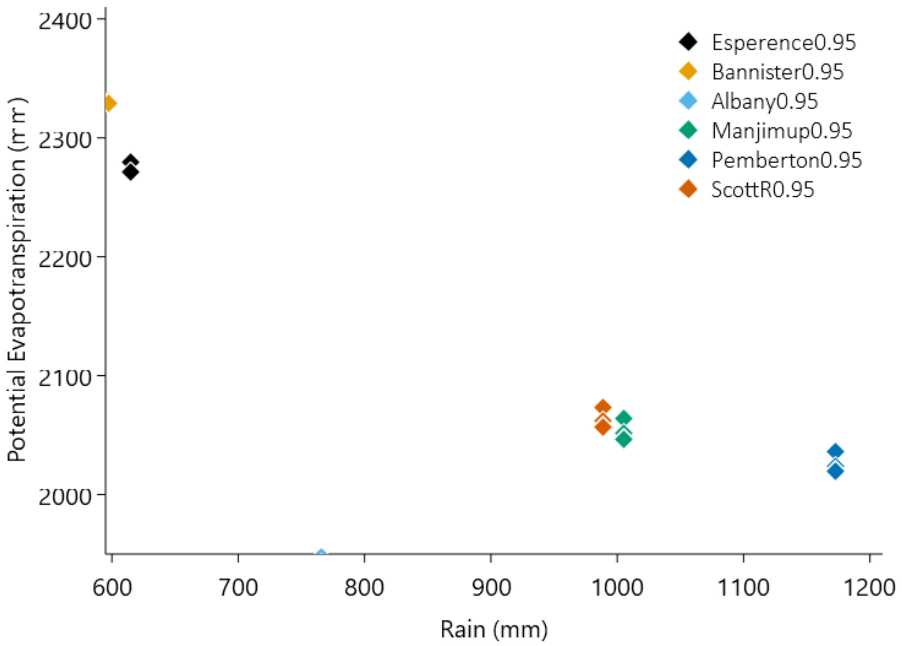


Fig. 3.4. Relationship between average annual potential evapotranspiration (Eo, mm) and rainfall (mm) during the rotation (1996-2006) for the six sites. Differences in Eo within a site are due to differences simulated in evaporation and transpiration due to four levels of surface soil C concentration.

Stem volume production increased from c. 160 to 270 m^3/ha across the range of rainfall (Fig. 3.5). There is an overall increase in stem volume of c. 25 m^3 with increasing rates of N fertiliser at both high and low stocking, and low stocking led to a penalty of about 50 m^3

(Fig. 3.6). Surface soil fertility also improved stem volume, but potential evapotranspiration had little effect (Fig. 3.7)

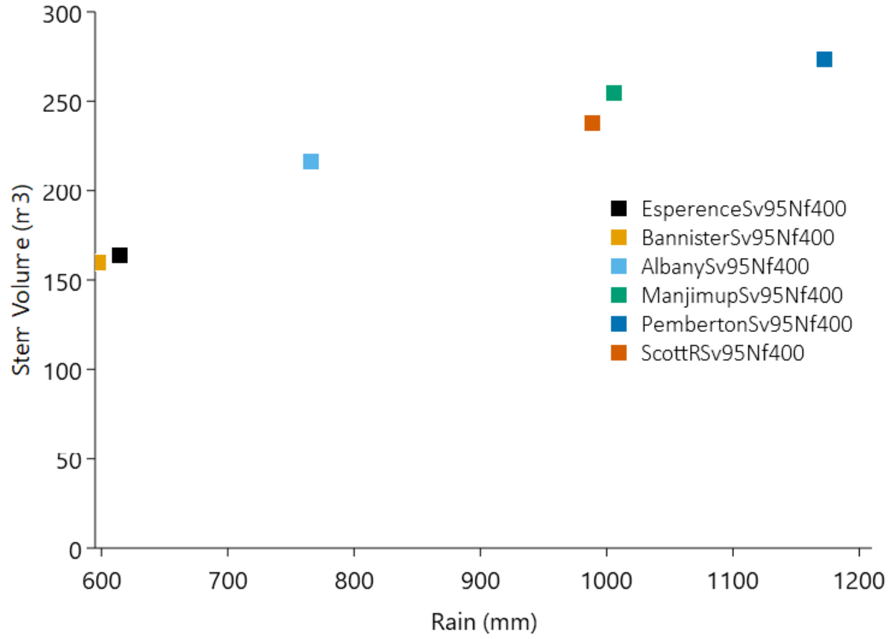


Fig. 3.5. Stem volume in relation to rainfall for all site with high initial water content (95%), a high rate of N fertiliser (400 kg ha^{-1}), 95% initial water, 5.6% C in surface soil, and typical soil depth.

Fig 3.6. Stem volume in relation to survival and N fertiliser levels for all sites with high initial water content (95%), high surface soil C (5.6%), and typical soil depth.

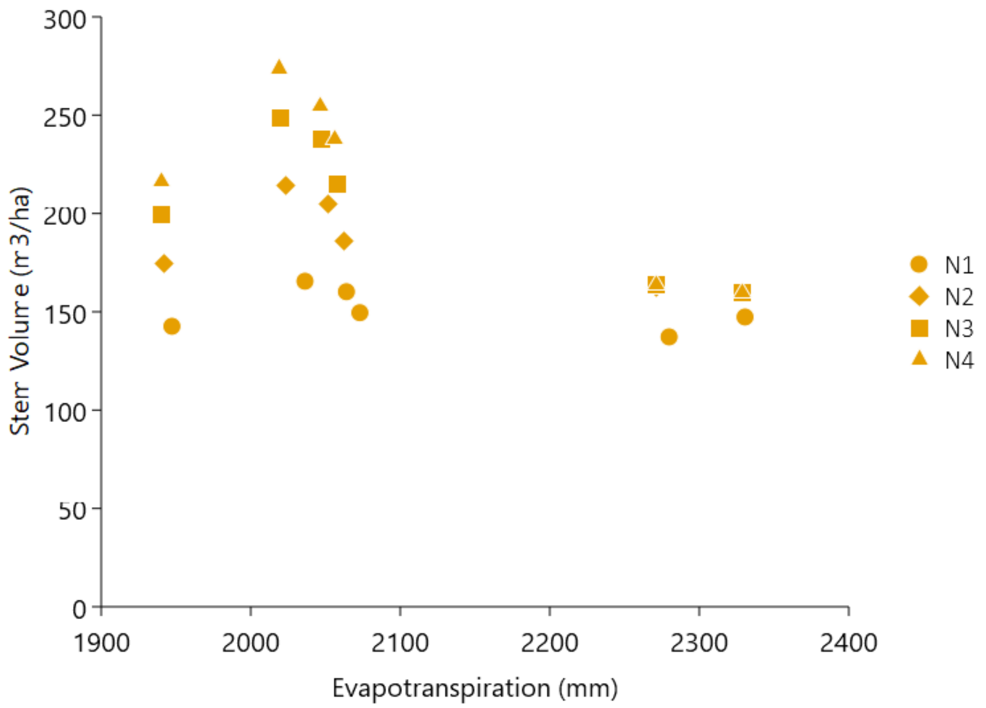


Fig. 3.7. Stem volume in relation to Eo for all sites and at 4 levels of surface soil fertility with high initial water content (95%), high survival (95%), and a high rate of N fertiliser (400 kg ha^{-1})

Increasing the initial soil water fraction from 0.35 to 0.95 increased stem volume slightly at Esperance and Scott River, which had shallow soils (4 m and 3 m, respectively), but had little or no effect at the other sites where roots could reach 8 m depth (Fig. 3.8). Therefore, in this analysis, initial water content had only a minimal effect on productivity compared to rainfall received during the rotation, but the deeper the soil the more this effect is likely to be, and some sites are known to be 17 m deep.

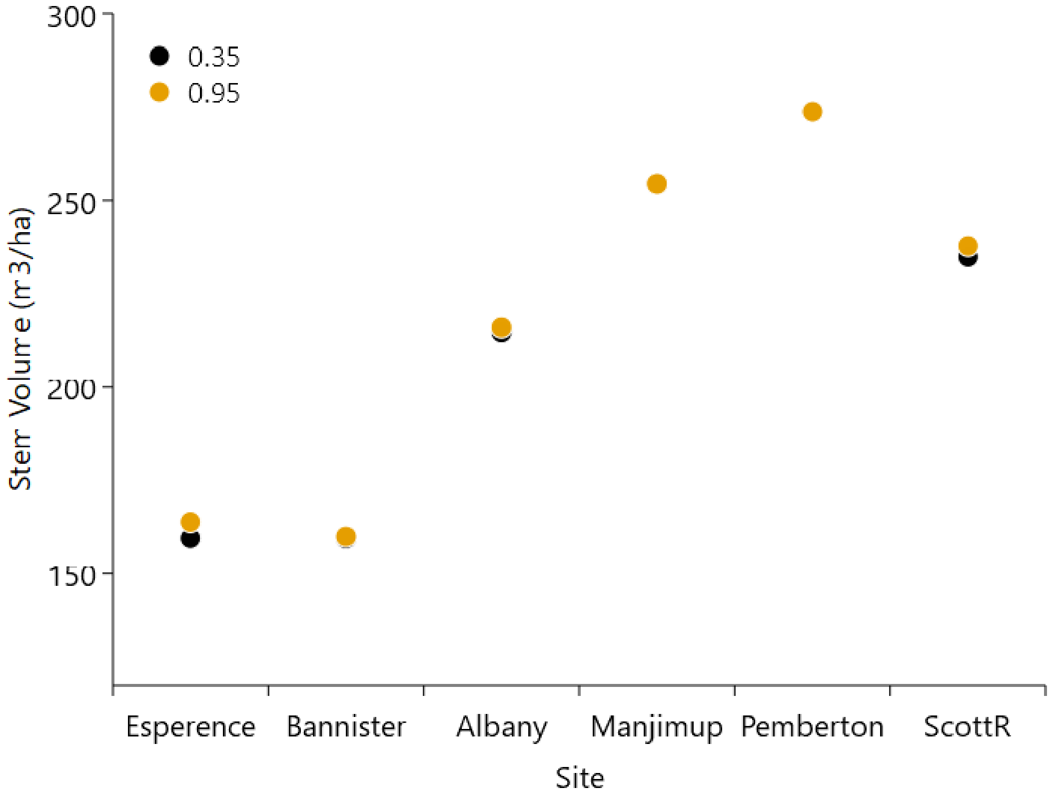


Fig. 3.8. Effect of site and initial soil water content fraction on stem volume with high survival (95%), high rate of N fertiliser (400 kg ha^{-1}), high surface soil C (5.6%), and typical soil depth.

For the two sites with typically shallower soils (3-4 m), increasing rooting depth to 10 m led to increased stem volume (Fig. 3.9). Increasing rooting depth to 10 m at Esperance increased stem volume by 21 m^3/ha and at Scott River by 11 m^3/ha. In contrast, the differences in rainfall led to a difference of 70-80 m^3/ha in stem volume. So, similar to initial soil water content, rainfall was more influential on growth than soil depth.

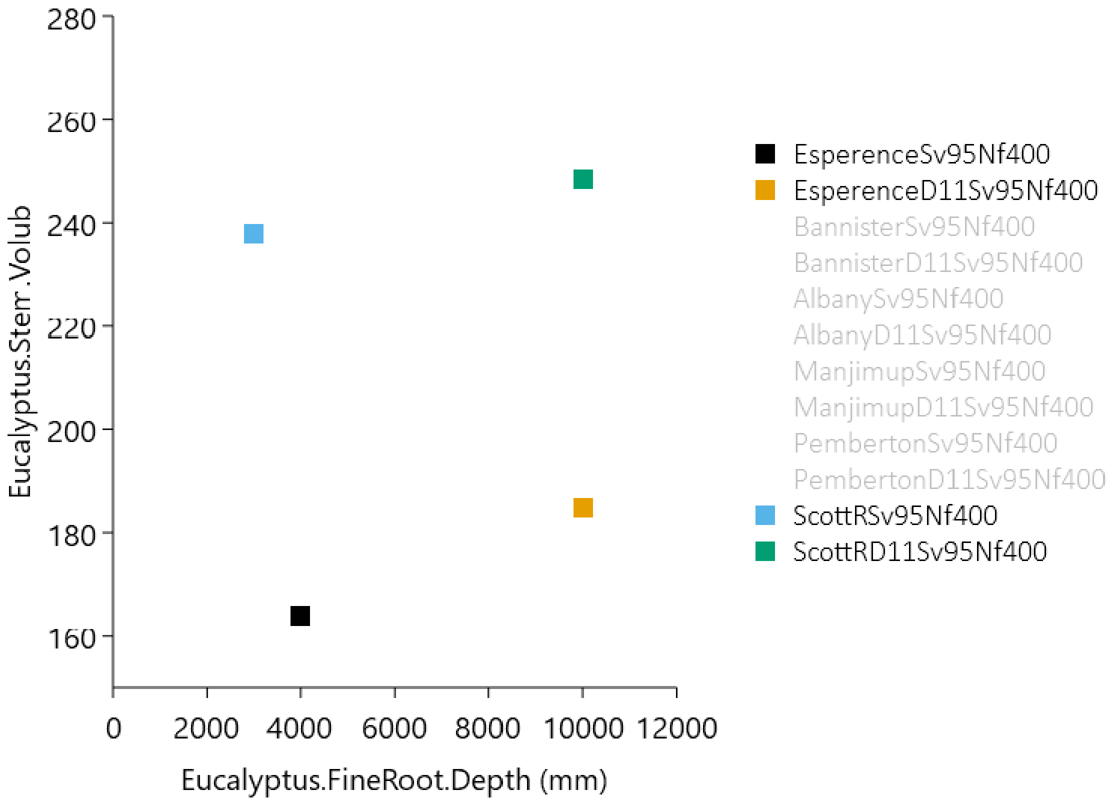


Fig. 3.9. Stem volume in relation to rooting depth for two sites, with high initial water content (95%), high survival (95%), high surface soil C (5.6%) and a high rate of N fertiliser (400 kg ha^{-1}). The two sites shown have comparable depths with the WA survey data.

Overall, the simulations proved to be a useful way to examine the role of individual factors effecting growth without the confounding effects of un-controlled factors. The resulting trends were similar to those found in the empirical datasets, but the variability around those trends was less for simulations. Less variability with simulations can be explained by (a) the simulations not covering the full range of conditions encountered in the field, and (b) the APSIM plantation models being calibrated mainly on treatment mean data rather than individual plot data.

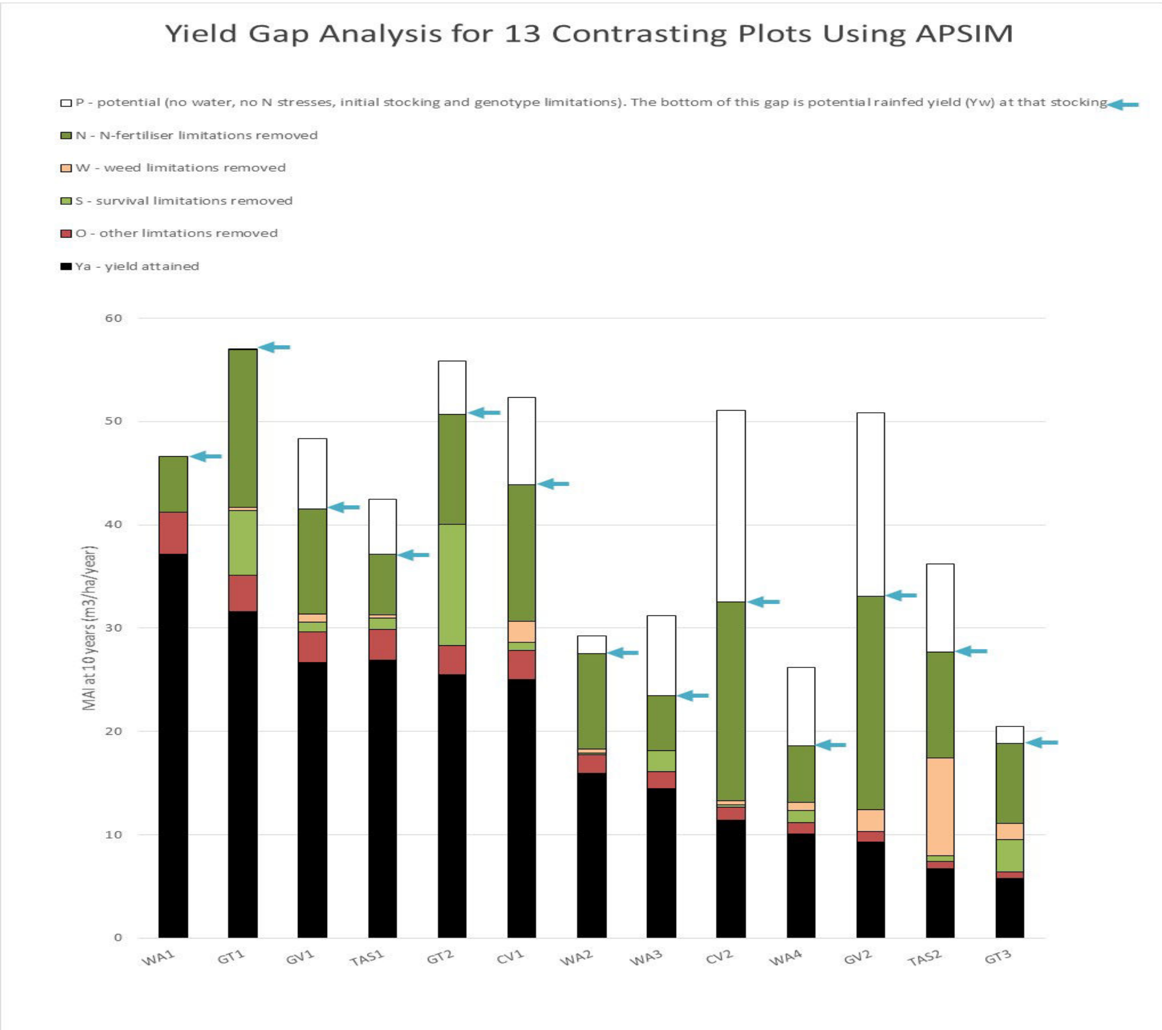
3.4.5 Assimilation of remote-sensed data

A parallel project (FWPA project VNC519-1920 'Next Generation Resource Assessment and Forecasting for Australian Plantation Forestry') demonstrated how data from remote sensing, inventory and empirical modelling could be assimilated with APSIM modelling to forecast future wood production. Two approaches were demonstrated. The first approach demonstrated how recalibration of individual simulations to better match observations of height and stocking from a LiDAR virtual plot. In the second approach, employing an Ensemble Kalman Filter method, a multitude of simulations based on the possible ranges of important input variables for a plot were filtered for remaining possible scenarios to those that were within uncertainty limits of observations. These remaining scenarios provided mean and uncertainty statistics for wood yield and other model outputs at a future date. Refer to the final report for that project for further details.

3.5 Yield gap estimates

3.5.1 APSIM-simulated yield gaps

Simulations that estimated yield gaps and summarised in Fig. 3.10 suggest that, of management factors analysed, all the plantations were limited by N, and some were also limited by poor survival and competition from weeds.
Several attributes of the simulations were significantly correlated (Table 3.2) and the most interesting relationships plotted (Figs. 3.11). We examined the results for expected relationships within and between soil and climate variables. It was reassuring that long-term mean annual rainfall (MAR) from the database, which was calculated from 1976-2005, was highly correlated with both long-term MAR in the APSIM dataset (1985-2021) and MAR during the period of simulation (Fig. 3.11a). This result means that the period of plantation growth did not deviate substantially from long-term averages. It also suggests that simulated rainfall was not a major source of error, but we recognise that simulated rainfall was up to c. 200 mm different to long-term averages at a couple plots. However, in this series of simulations Ya was not significantly correlated with MAR (Fig. 3.11b).
It is generally known that soil C concentrations and C:N ratios are higher at higher latitudes north and south of the equator, i.e. negative values in the south. Likewise in our simulations, cooler temperatures (at more negative latitude) with more rainfall lead to slower rates of decomposition of soil organic matter, less N available from nitrogen fixation, higher C concentrations (Fig. 3.11c), but no relationship with C:N ratio (Fig 3.11h).



Attribute	Plot:												
	WA1	GT1	GV1	TAS1	GT2	CV1	WA2	WA3	CV2	WA4	GV2	TAS2	GT3
Latitude	-34.64	-37.36	-38.02	-42.74	-37.92	-38.29	-34.93	-34.72	-37.67	-34.65	-38.22	-41.60	-37.48
Rotation	1	1	1	2	3	1	2	1	1	2	3	3	1
LU History	FAE	FAE	FAE	FEE	FPPE	FAE	FAEE	FAE	FAE	FAEE	FPPE	FEEE	FAE
MAR-LT (mm)	1176	625	961	834	761	794	1018	648	749	697	623	1005	672
StockingInitial (stems/ha)	1131	1164	990	1131	1158	1010	873	1127	1010	827	985	1131	1222
PAWC (mm)	1316	895	98	587	1723	833	805	2049	275	929	78	90	272
Initial water (mm)	620	661	157	253	1248	474	644	876	218	186	37	905	207
APSIM Genotype[1]	WABG*	gS	gS	g	gS*	gS	WABG	WABG	gS	WABG	gS	g	WABG

Fig. 3.10. Simulated yield gaps using the APSIM Eucalyptus model for 13 plots across the plantation regions of temperate Australia chosen to cover a wide range of productivities. The top of the dark green bar for N represents water-limited (rainfed) potential yield (Yw). The top of the white bar represents potential yield if all water and N limitations were removed.

A table of plot attributes is included below the x-axis. This analysis suggest that all plantations would have responded markedly to additional N fertiliser, and some suffered from either or both poor survival and competition from weeds. There seemed to be a trend for percentage responses relative to Ya to be highest at the lower values of Ya (Fig. 3.11g), but there was no obvious trend for absolute differences. APSIM Genotype abbreviations are g = 'globulus', gS = 'globulusShepparton', WABG = 'WABlueGum', * = modified, where text within quotation marks are genotypes in the released version of APSIM.

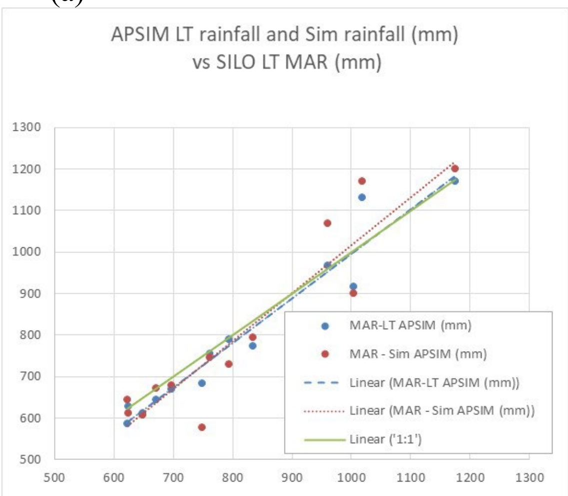
Table. 3.2. Matrix of correlation coefficients (r) for various attributes of the yield gap simulations. Yellow-highlighted are those where the r value exceeded the critical value (P = 0.05).

	Ya	S	W	N	P	Yp	Yr-Ya	Management Gap (% of Ya)	W (% of Yr-Ya)	W (% of Yr-Ya)	S (% of Yr-Ya)	Latitude	Rotation	MAR-LT (mm)	MAR-LT APSIM (mm)	MAR - Sim APSIM (mm)	StockingInitial (stems/ha)	PAWC (mm)	Initial water (mm)	C (%, surface)	C:N (surface)
O	1.000																				
S	0.258	1.000																			
W	-0.454	-0.233	1.000																		
N	-0.170	0.005	0.100	1.000																	
P	-0.504	-0.311	0.188	0.654	1.000																
Yp	0.605	0.323	-0.153	0.604	0.237	1.000															
Yr-Ya	-0.004	0.476	0.272	0.810	0.346	0.697	1.000														
ManagementGap (% of Ya)	-0.756	-0.117	0.734	0.478	0.492	-0.153	0.476	1.000													
N (% of Yr-Ya)	-0.291	-0.570	-0.212	0.630	0.608	0.086	0.072	0.144	1.000												
W (% of Yr-Ya)	-0.504	-0.251	0.987	0.017	0.142	-0.264	0.183	0.719	-0.230	1.000											
S (% of Yr-Ya)	0.110	0.930	-0.291	-0.212	-0.345	0.044	0.217	-0.155	-0.620	-0.276	1.000										
Latitude	0.043	-0.017	-0.521	-0.200	-0.214	-0.261	-0.366	-0.377	0.200	-0.497	0.069	1.000									
Rotation	-0.329	0.218	0.461	0.148	0.259	0.033	0.354	0.468	-0.187	0.434	0.101	-0.378	1.000								
MAR-LT (mm)	0.370	-0.344	0.228	-0.362	-0.343	-0.019	-0.312	-0.205	-0.159	0.213	-0.477	-0.008	0.008	1.000							
MAR-LT APSIM (mm)	0.410	-0.291	0.094	-0.352	-0.431	-0.032	-0.322	-0.306	-0.093	0.083	-0.430	0.129	-0.030	0.970	1.000						
MAR - Sim APSIM (mm)	0.396	-0.289	0.062	-0.393	-0.467	-0.085	-0.369	-0.312	-0.108	0.059	-0.401	0.137	0.011	0.932	0.974	1.000					
StockingInitial (stems/ha)	0.230	0.454	0.117	-0.122	-0.335	0.152	0.224	0.141	-0.609	0.074	0.479	-0.360	-0.120	-0.083	-0.175	-0.183	1.000				
PAWC (mm)	0.377	0.478	-0.471	-0.464	-0.369	0.011	-0.242	-0.591	-0.453	-0.494	0.569	0.516	-0.121	-0.073	-0.010	-0.047	0.183	1.000			
Initial water (mm)	0.467	0.710	-0.453	-0.238	-0.433	0.231	0.082	-0.509	-0.441	-0.502	0.677	0.381	-0.032	-0.016	0.088	0.041	0.286	0.880	1.000		
C (%, surface)	-0.230	-0.445	0.621	-0.235	-0.083	-0.351	-0.214	0.301	-0.064	0.650	-0.500	-0.414	0.383	0.687	0.636	0.647	-0.170	-0.506	-0.431	1.000	
C:N (surface)	-0.570	-0.008	0.801	-0.086	0.195	-0.316	0.142	0.644	-0.343	0.848	0.032	-0.596	0.439	-0.003	-0.154	-0.185	0.132	-0.416	-0.430	0.502	1.000

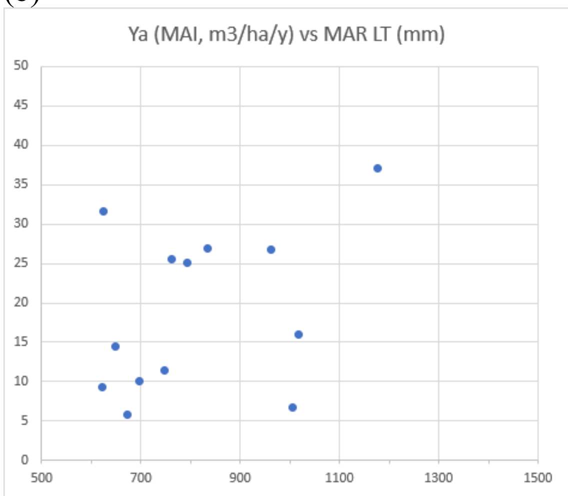
We also examined the results for relations with various yield gaps and noted:

- The absolute value of the yield gap due to N in m^3/ha was a major component (50-60%) of the total management yield gap (Fig. 3.11e).
- The management gap (Yr-Ya) as a percentage of Ya increased exponentially with a decrease in PAWC and Ya (Figs. 3.11f and 3.11g) and increased with surface soil C:N ratio (Fig. 3.11h) and decreased exponentially with the maximum possible plant available water content (Fig. yd) and Ya (Fig. 3.11e), because Ya was slightly positively correlated with PAWC. These results can be interpreted to indicate that management can have the greatest effects on closing yield gaps in absolute terms where the climate and soil is most favourable, but percentage increases can be greatest at low productivity sites.

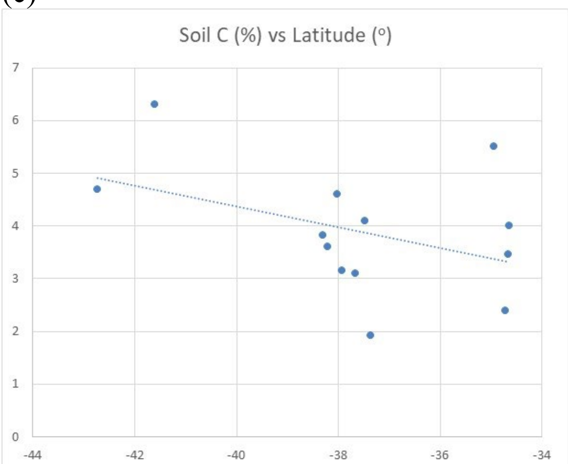
(a)



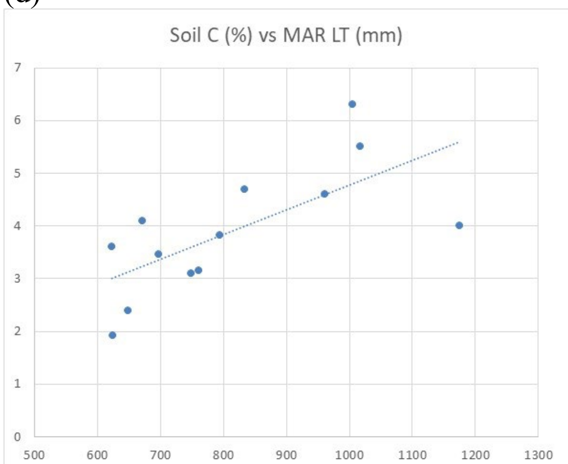
(b)



(c)



(d)



(e)

(f)

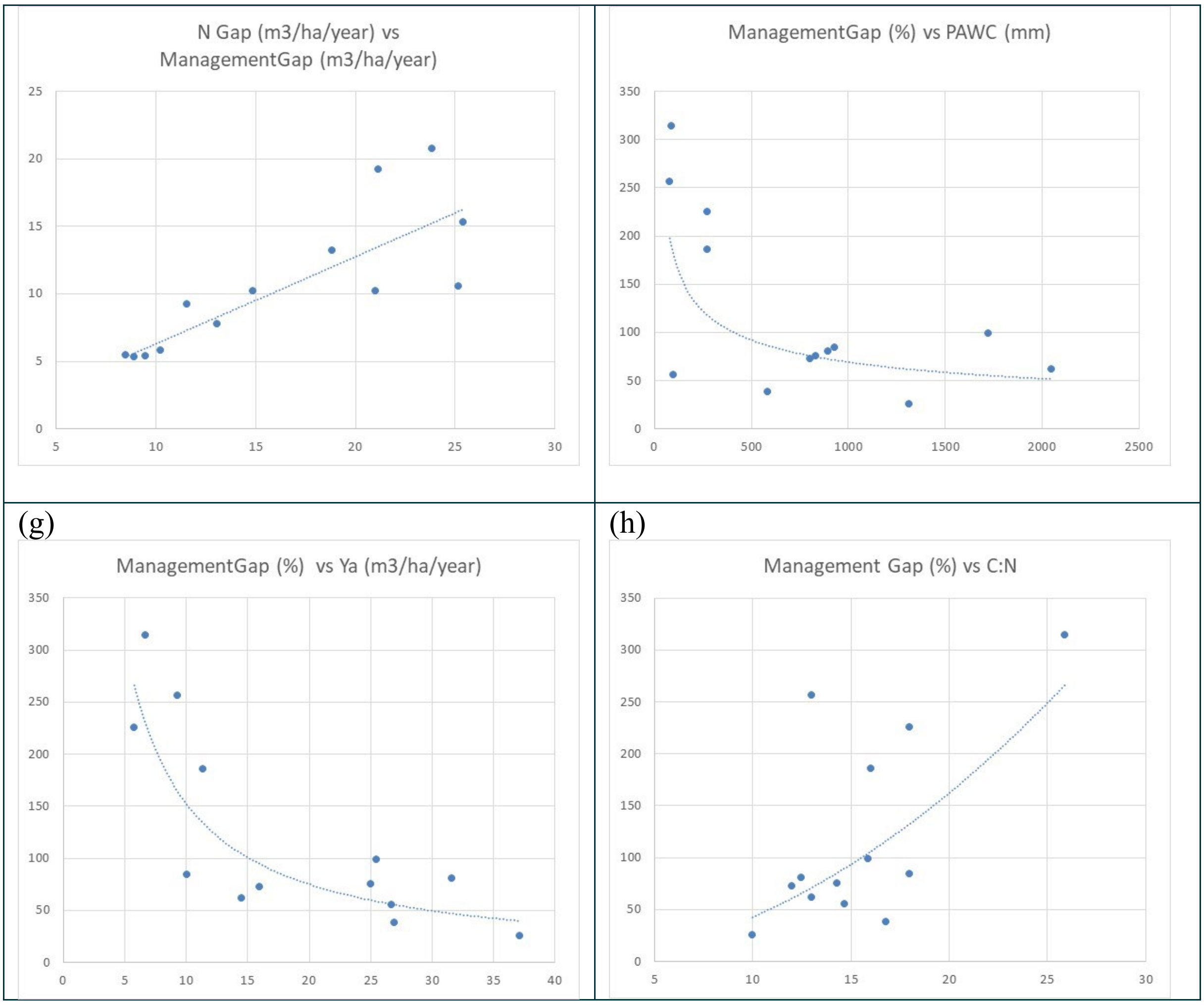


Fig. 3.11. Selected relationships within the simulated dataset. Relationships between mean annual rainfall across various periods and data sources were highly correlated (a), which was expected as they had a common primary data source (interpolated values in SILO). The relationship of Ya to MAR LT within the 13 plots simulated for yield gap analysis was positively correlated (b), but the extremes of values were deliberately chosen for simulation, which invalidates any attempt to fit a relationship. Other relationships emerged from the simulations (c-h).

3.5.2 Sources of error

Sources of error in the analysis include:

1. High productivity calibration data: Lack of calibration for very high values of MAI. Maximum MAI simulated for Yp was c. 57 m^3/ha, which seems high, but it might not be unreasonable as CAI's > 50 m^3/ha.year have been observed for a few plots across the country (McGrath pers. comm.). However, model error is probably high at such levels of productivity because no such data were available during the calibration phase of the model.

2. Incomplete plantation records: Setup of the simulations was prone to error, as silvicultural records were incomplete for all plantations due to a range of legacy factors: soil attributes for each plot had a high level of uncertainty, e.g. total soil depth, pH and concentrations of C and N for depths greater than 10 cm; level of weed

competition; timing of mortality. Although record-keeping in relation to each PSP has probably improved markedly since the plots used in this analysis were established, it still might not completely fulfill the needs of future analyses of this type.

3. Stocking: Stocking was not optimised in the analysis of Yr or Yp. Initial stocking was assumed to be optimum, but this might have been incorrect.

4. Genotype: Although the range of genotypes used in the simulations can be expected to generally cover those actually planted at the chosen plots, there might have been marked deviations in attributes like resource use efficiency, biomass allocation to plant components, sensitivity to stresses, leaf longevity, and specific leaf area. Some of the attributes in these model genotypes limited the P gap (white bar) resulting in uncertainty about the upper extent of that bar, and in some cases genotype specifications were modified to reach the very high productivities attained (Ya) at a few sites.

   In addition, the upper limits of productivity (Yp or Yw) identified in this report by modelling or empirical analyses do not take account of improvements in productivity that might have result from tree breeding. In the future, it is plausible that those improvements might even have some degree of regional difference. Some of the past improvements in stem growth rates due to tree breeding have probably resulted from improvements in resource capture and resource use efficiency. However, the extent to which an increase in stem volume has resulted from a relative increase in carbon allocation to stems compared to other plant components (e.g. course roots or branches) is unknown, but understanding its role in tree improvement of Australian eucalypt plantations would assist in more accurate process-based modelling.

5. Climate: We suspect only small errors can be attributed to the daily weather data obtained from SILO for each location, which were interpolated (modelled) data with a spatial resolution of 5 km, and that rainfall was the main concern. There was a significant correlation between long-term mean annual rainfall as available in the database and mean annual rainfall during the simulations.

6. Parameter sensitivity: There are a large number of parameters in processed-based models that are subject error, which leads to uncertainties in outputs. Uncertainty analysis is well documented in the literature in relation to process-based models, and for APSIM in particular. For example, Elli et al. (2020c) provided a sensitivity analysis for an earlier version of the APSIM Eucalyptus model.

7. Ecosystem Interactions: Although process-based modelling provides a framework for integrating the known effects of climate change on plantation growth, including soil processes, there is actually very limited knowledge of all the potential changes and their interactions on resource availability (light, water and nutrients), uptake and use efficiencies, and damage agents such as pest, diseases and fire. Mortality induced by weed competition might also be important. Knowledge of the temporal and spatial dimensions of these effects is also very limited. For example, the effects of climate change on nutrient availability in soils and the interactions with plant residues, particularly organic matter amounts and quality. Phosphorus availability is also likely to change with temperature, rainfall and evapotranspiration changes. Stomatal control, photosynthetic processes, and many other physiological processes will probably also be more complex than currently represented in these models. These uncertainties therefore in turn provide uncertainty about potential yields and yield gaps estimated

using models. Thorough examination and prioritisation of research to address these knowledge gaps, however, is beyond the scope of this report.

3.6 APSIM workshops and training

Training in APSIM modelling for plantation forestry was provided on the 15th of October 2022 in Launceston, Tasmania, and hosted by Forico. There was a total of 14 participants (8 in-person, 6 on-line). Participants individually worked through training materials, which were augmented by presentations to the group by P. Smethurst and group discussions. Positive feedback was received about the APSIM framework, its user interface, and the plantation-specific training materials. As one-on-one tuition was easiest in-person, this cohort received most attention by the instructor.
Participants provided feedback on these training materials, which were slightly upgraded, and are now available publicly on-line at https://www.apsim.info/support/apsim-training-manuals/. Philip has been letting colleagues know nationally and internationally about these options. Industry researchers and resource managers in Australia, USA, Brazil, Chile, Finland and NZ have so far expressed interest. As noted in the training materials, Philip remains available for help with training and advice on use of these models.

4. Synthesis

The environmental and management factors that influence productivity (yield) of hardwood plantations in southern Australia was determined from analysis of empirical data from several sources and using process-based growth modelling.

4.1 Environmental factors that influenced productivity

Climate sets the upper limit to potential yield, with rainfall, evaporation and temperature all influencing productivity. The dependence of potential yield on climate means that as climate varies or changes that potential yield will change. Similarly changes in genotype and management inputs will likely lead to changes in potential yield. There were differences in potential yield between the regions reflecting the different growing conditions, but these could not be determined precisely where data were limited. Sites where water supply was enhanced by groundwater or local site conditions didn't conform to the productivity limits provided by climate alone.

Of the climate variables investigated rainfall had the strongest influence on productivity explaining 29% of the variation in yield across regions and 40% of the variation allowing for regional differences. Temperature and evaporation were highly correlated across regions with countervailing effects on yield after allowing for rainfall, and consequently it was difficult to determine their individual effects.

Soil depth (as the depth that roots can grow in the regolith) is a strong surrogate for PAWC to that depth (because unit PAWC is relatively less variable with texture), and it had a strong impact on survival. However, soil depth alone did not provide a general indicator of the susceptibility to drought mortality, because of the interplay of water input (rainfall) and storage capacity (PAWC to potential rooting depth). In higher rainfall situations 2 m of soil depth was sufficient to minimise drought mortality, but under low rainfall situations even deeper depths did not prevent mortality, likely as the supply of water (rainfall) rather than water storage was more influential.

The nationally consistent soil attribute values acquired / derived from the Soil and Landscape Grid Australia (SLGA) were in the absence of observed values useful for descriptive purposes empirical analyses, and (at least) starting values for APSIM modelling. Critically however, potential rooting depth could not be determined from these.

4.2 Management factors that influenced productivity:

On average, coppice rotation yields (2R) were less than 1R planted rotation yields in WA and GT. However, interpretation of this difference is confounded because deep soil profile water will have been reduced by the previous 1R planted rotation. There were no data to compare yields for 2R coppice and 2R planted yields. However, a subset of the WA PSP data enabled comparison of 1R and 2R planted yields and indicated that reduction in 2R yield was relatively greater at lower rainfalls than higher rainfalls. There was a clear though modest increase in productivity by replanting rather than coppicing.

There was strong agreement between the overall trial data and the WA survey data that productivity increased with increasing stand density.
The large difference in productivity between plantations on previous agricultural land and previous forested land was attributable to a difference in fertility, and to a small extent stored

water. This is particularly likely in subsequent rotations where any influence of the stored water under agricultural systems would have dissipated, if rates of fertilization are high enough to meet nutrient demand. In WA, productivity increased as total soil N increased. Earlier WA trials indicated that yield responses of between 20 and 100% were possible, which could translate to responses of 50 to 150 m^3/ha across a rotation. Similar responses to mid rotation nitrogen applications of between 20 and 130 % have been measured in a recent series of trials across southern Australia (McGrath et al., 2023). This appears consistent with the different productivity on ex forest and ex agricultural sites.

4.3 Model effectiveness

A key issue was whether the modelling was able to capture the observed responses.

A series of simulations were undertaken using APSIM to evaluate whether the model provided realistic estimates of productivity and estimates of the yield gaps attributable to management interventions.

When stocking, fertility and soil depth were optimised APSIM predicted an increase in stem volume production from c. 160 to 270 m^3/ha as rainfall increased from 600 -1200 mm. This increase was similar to the observed mean response in the overall data. However, the band of productivity estimates were well within the 10th and 90th quantile estimates of production in the empirical data due to model calibrations being based on averages of several plots compared to single plots in the PSP dataset, which reduced the influence of outliers.

The modelling supported the hypothesis that plantations growing on shallow groundwater (< 6 m depth) were able to access both water and nitrate from the aquifer. Similarly, the modelling demonstrated increased productivity following the application of nitrogen fertiliser that generally agreed with the trend observed with increasing soil total N and the fertiliser in previous studies, i.e. c. 10% response predicted to 400 kg N ha^{-1} during the first four years.

Productivity was predicted to increase as stocking increased by a similar amount to the observed responses of ~50 m^3/ha with a doubling of stocking from 600-1200 stems/ha.

It appears that APSIM provided useful predictions of the responses to environmental and management factors, and it was particularly useful for evaluating yield gaps at the individual plot level.

4.4 Prediction of yield gaps

The analysis of yield gaps with APSIM suggested that all of the plantations modelled would have responded markedly to additional N fertiliser, and some suffered from both poor survival and/or competition from weeds.

There appeared to be a trend for percentage responses relative to measured yield to be highest at the lower values of yield as there was no obvious trend in absolute differences in yield. The similar response at low and high yield means that the percentage increases are higher at low yields.

Most observed adequately-stocked coppice-rotation yields were less than the 50% quantile yield for planted rotations. Greater second-rotation yields should be attained with replanting and ensuring high stocking is achieved and maintained, and that fertility is maintained across the rotation with multiple fertiliser applications.

4.5 Conclusions and recommendations

The study has estimated rainfall-limited maximum *E. globulus* yield in southern Australia for deployed genotypes (1990s – 2000s) and identified and provided some quantification of the management factors that can affect yield. However, there are differences between regions in both potential productivity and the extent to which environmental and management factors affect yield.

The major drivers of productivity are water availability nutrient supply and stocking, and thus following recommendations to minimise yield gaps:

- Avoid planting shallow rooting-depth soils
- Plant rather than coppice
- Achieve full stocking and early canopy closure through weed/competition control
- Ensure adequate tree nutrition throughout the rotation

Nitrogen appeared to be the main nutrient limiting productivity on ex agricultural sites. A key issue in optimising fertiliser responses remains the identification of responsive sites. Productivity will be optimised on responsive sites by multiple applications of nitrogen across the rotation.

Priorities for further development of modelling capacity and data analysis include:

- There is a need to improve the modelling capacity available for the plantation sector. This includes both the capacity for model development and importantly the human and technical capacity to deliver the modelling systems in an effective manner for the industry.

- Improved nationally consistent soil data layers that provide attributes that can be functionally linked to plantation productivity are required. The first step towards this could be to collate and harmonise the several regional forest productivity/soil studies.

- The analysis of the extensive trial data available from the efforts of industry and research institutions over the past three decades has only received a preliminary analysis in the present study. We strongly recommend that the value imbedded in this existing work be fully explored and synthesised before additional research is undertaken.

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