Tools for nutrition management in eucalypt plantations

FWPA Project: PNC304-1213

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Steering committee

• **Chair:** Stephen Elms (HVP)
• Tom Baker and Peter Hopmans (UniMelb)
• Ben Bradshaw (ABP)
• John Wiedemann (WAPres)
• Paul Adams (Forestry TAS)
• Mike Powell (Forestry SA)
• Ashley Goldstraw (Midway)
Overall project aim

• To develop tools which identify plantations more likely to show a growth response to fertiliser
  – Tools that rely on relatively easy-to-measure site variables, including:
    • Climate
    • Soil nutrient status
    • Foliar nutrient status
Fertiliser use in eucalypt plantations

• May et al., 2009: Review of fertiliser use in Australian forestry
  – Large discrepancies between growers:
    • Expected magnitude and duration of growth response
    • Methods of managing nutrition/prioritising application of fertiliser
Expectations of growth response to fertiliser application

- Estimations a mix of:
  - Empirical evidence or knowledge
  - Educated guess

May et al., 2009
Site selection methods for fertiliser application

- Establishment
  - Soil
- Young
  - Foliar
- Mid-rotation
  - ‘Site quality’
- Later-age
  - ‘Site quality’

May et al., 2009
Site selection methods for fertiliser application

- Estimations are representative of ‘confidence’
  - No information given on specific method

Estimated confidence in method = 65%

May et al., 2009
Need more input...

• Prediction of growth responses to fertiliser application was identified as a major knowledge gap

  May et al., 2009

• New trial networks take substantial time and financial input
  – Delay in receiving results: 5-10 years
  – Can be grower/region specific
    • Strong collaboration needed
Our approach

- Speed up this process by analysing existing datasets
Criteria for experiments

• Develop tools that rely on relatively easy-to-measure site variables, including:
  – Climate
  – Soil nutrient status
  – Foliar nutrient status

• To be included, experiments had to have:
  – Pre-treatment soil and/or foliar nutrient analysis
    • Major screening tool → removed the bulk of experiments
Criteria for experiments

• To be included, experiments also had to have:
  – A minimum of two treatments
    • A high rate of N (±P) and an unfertilised control
  – A minimum of three replicates
  – Treatments applied in spring
  – Regular growth measures (every 1-3 years)
    • Diameter at 1.3 m of all trees
    • Height of the 100 largest-diameter trees ha⁻¹
  – Minimum 60% survival
  – Similar pre-treatment volumes
## Details of experiments used

<table>
<thead>
<tr>
<th>Application timing</th>
<th>Establishment</th>
<th>Mid-rotation</th>
<th>Establishment and mid-rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Code</strong></td>
<td>EST</td>
<td>MID</td>
<td>EST+MID</td>
</tr>
<tr>
<td>~Age at application (years)</td>
<td>Age 0 and 1</td>
<td>Age 4-5</td>
<td>Age 0, 1 and 4</td>
</tr>
<tr>
<td>Number of experiments</td>
<td>28</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Fertiliser applied at age 0</td>
<td>40-52 kg ha$^{-1}$ N and 27-35 P kg ha$^{-1}$</td>
<td>0</td>
<td>40-52 kg ha$^{-1}$ N and 27-35 P kg ha$^{-1}$</td>
</tr>
<tr>
<td>Fertiliser applied at age 1</td>
<td>200 kg ha$^{-1}$ N and 50-62 kg ha$^{-1}$ P</td>
<td>0</td>
<td>200 kg ha$^{-1}$ N and 50-62 kg ha$^{-1}$ P</td>
</tr>
<tr>
<td>Fertiliser applied at age 4-5</td>
<td>0</td>
<td>250 kg ha$^{-1}$ N</td>
<td>200 kg ha$^{-1}$ N</td>
</tr>
<tr>
<td>~Age at measurement (years)</td>
<td>2-5, 7 and 10</td>
<td>5-8 and 10</td>
<td>2 and 4-10</td>
</tr>
</tbody>
</table>
Sites by climate

ACT SILO MAR (mm yr\(^{-1}\)) vs ACT SILO MAE (mm yr\(^{-1}\))

- EST
- MID
- EST+MID
Sites by baseline productivity

**ESTABLISHMENT**

128 m³ ha⁻¹

**MID-ROTATION**

214 m³ ha⁻¹

**COMBINED**

172 m³ ha⁻¹
Approach to data analysis

• Because sites differed between application timings:
  – We largely described response within each application
  – Tried to avoid comparing between timings

• Our FWPA report describes the data in two ways:
  – First, we described the magnitude and duration of growth response to fertiliser over time
  – Second, we developed models for predicting growth response to fertiliser

• Today, we focus on building predictive models, the core aim of the project
Approach to data analysis

• Site mix allowed us to build separate predictive models for:
  – Establishment fertiliser application (n=28)
  – Mid-rotation fertiliser application (n=21*)

• Highly involved dataset
  – Today, we look at establishment fertiliser models
    • Much more accurate than mid-rotation
Approach to model development

- **Multiple linear regression analysis**
  - Use multiple explanatory (x) variables to predict a suitable response variable (y)

  - Response variable (y):
    - Growth response to fertiliser

  - Explanatory variables (x):
    - Pre-treatment climate, soil and/or foliar-based site factors
Growth response to fertiliser: The response variable

• Generic stand volume equation to convert from plot measures to standing volume:
  – \( \frac{1}{3} \times \sum BA \times MDH \)
    • BA = all trees in plot
    • MDH = mean dominant height of the 100 largest-diameter trees

• Calculated for all control and treatment plots at each measurement
Growth response to fertiliser: The response variable

• Converted to a **relative growth response** for each site
  – to be able to plot all sites together when building predictive models

• **Volume relative to control**

• = [(mean treatment volume – mean control volume) / mean control volume] x 100%
  – % ↑ or ↓ in volume relative to control
  – Very different to **relative volume growth rate** and other relative measures
Growth response to fertiliser: The response variable

• How long after application should we assess growth response?

• Establishment fertiliser models:
  – At age 2    (1 year post-application)
  – At age 4    (at mid-rotation)
  – At age 10   (at end-of-rotation)
Climate-based explanatory variables

- **ESOCLIM**
  - Long-term average 1921-1995

- **SILO data drill**
  - Long-term average 1889-2012
  - ‘Actual-over-rotation’, i.e., during experiment

- **Calculated averages**
  - Daily data condensed into yearly
    - Calculated average for years of interest
Climate-based explanatory variables

- Mean annual rainfall
- Mean annual evaporation
- Mean annual climate wetness index
  - (Rainfall / evaporation)
- Mean annual maximum temperature
- Mean annual minimum temperature
- Mean annual solar radiation
Groundwater: (almost) an explanatory variable

- Groundwater
  - Limited site surveys completed
  - Combined with online tools:
    - Visualising Victoria’s Groundwater
    - WaterConnect

- Resolution not good enough to use as a continuous explanatory variable
  - BUT, sites could be split using presence/absence
    - We initially split our data using this, but there were no differences → pooled
Soil-based explanatory variables

- Composite subsamples (~10 cores per plot)
- From inter-rows (not cultivated)
- From control plots (3-5 per site)

- Kept cool in transit then dried, ground and analysed
Soil-based explanatory variables

• Establishment fertiliser models:
  – Variables available for 0-10 and 10-20 cm depths
  – 1:5 EC, pH
  – Potentially available N (Hot-KCl NH$_4$+NO$_3$)
  – Total N, total C, Bray2 P
Foliar-based explanatory variables

• Establishment fertiliser models:
  – Sampled at age 1; Juvenile leaves

• Sampling:
  – YFEL: 4-6 leaves from 5-6 trees
  – Top 1/3\textsuperscript{rd} of the crown
  – Control plots
  – Kept cool in transit then dried, ground and analysed
Foliar-based explanatory variables

• Foliar variables analysed:
  – N, P, K, S
  – Na, Ca, Mg
  – Cu, Zn, Mn, Fe, B

• Derived ratios:
  – N:P, N:S, N:K
  – FOL N/MAI ratio
    • ‘dilution of N’ → [FOL N] / pre-treatment MAI
Regression approach

• Ran simple regression first on each variable
  – Linear and non-linear regression
  – Looking at individual predictors of growth response to fertiliser at age 2, 4 and 10

• Ran multiple linear regression second
  – Looking at combinations of predictors of growth response to fertiliser at age 2, 4 and 10
Establishment fertiliser models

Response at age 2
(1 year post-fertiliser application)

Simple regression results
Single predictors of growth response
‘Min-N’, also referred to as ‘Potentially mineralisable N’ = Hot KCl extraction of NO$_3$ and NH$_4$. 

$R^2 = 0.62; P < 0.001$ 

Pretty good!
$R^2 = 0.62; P = <0.001$

$R^2 = 0.28; P = 0.016$
$R^2 = 0.62; P = <0.001$

$R^2 = 0.28; P = 0.016$

$R^2 = 0.19; P = 0.041$

$R^2 = 0.34; P = 0.002$
Separate group?
Split by dataset, groundwater, trace elements...everything we had
Couldn’t identify the cause...
$R^2 = 0.15; P = 0.041$

$R^2 = 0.33; P = 0.33$
Volume relative to control (%)

FOL N (g kg\(^{-1}\))

\[ R^2 = 0.15; \ P = 0.041 \]

FOL N:S

\[ R^2 = 0.33; \ P = 0.33 \]

FOL Ca (g kg\(^{-1}\))

\[ R^2 = 0.41; \ P = <0.001 \]
$R^2 = 0.15; P = 0.041$

$R^2 = 0.33; P = 0.33$

$R^2 = 0.41; P = <0.001$

$R^2 = 0.23; P = 0.010$
Establishment fertiliser models

• **Simple regression**

• **Other response ages:**
  – At age 4 (3 years post-application; at mid-rotation)
    • Min-N ($R^2 = 0.28$, $P = 0.004$)
    • Bray 2P ($R^2 = 0.43$, $P=<0.001$)
    • Foliar N ($R^2 = 0.19$, $P = 0.019$)
  
  – At age 10 (end of rotation)
    • No soil variables related to growth response
    • No foliar variables related to growth response
Establishment fertiliser models

• **Simple regression outcomes:**
  – Only one strong individual predictor (soil Min-N)
    • Only effective shortly after application (at age 2)
  – No strong individual predictors of response to establishment fertiliser beyond age 2
Multiple Linear Regression

• **All subsets regression**, restricted by number of sites (n=28)

• Combinations of variables related to N and P

• ‘Batched’ = created 3 different model types:
  – Soil-based, foliar-based, combined
Multiple Linear Regression

• Used Adj-R\(^2\) and Mallow’s \(C_p\) to select ‘best models’
  – Highest Adj-R\(^2\), lowest \(C_p\)
    • Lowest # of explanatory variables for highest Adj-R\(^2\)

• Correlation analysis: models don’t contain related variables
  – ALSO! Allowed substitution of variables in ‘best’ models
  – Practical reasons – create alternative models depending on your available data
Establishment fertiliser models

Response at age 2
(1 year post-fertiliser application)

Multiple linear regression results
Best soil-based model (at age 2)

\[ y = -1.509 \times \text{Min-N} + 0.083 \times \text{ESO MAR} + 20.0 \]

\[ R^2 = 0.70; \; C_p = -2.37 \]

\[ P = <0.001 \]
Best soil-based model (at age 2)

\[ y = -1.509 \times \text{Min-N} + 0.083 \times \text{ESO MAR} + 20.0 \]
\[ R^2 = 0.70; \quad C_p = -2.37 \]
\[ P = <0.001 \]

Long-term average annual rainfall from ESOCLIM

Volume relative to control (%)
Best soil-based model (at age 2)

\[ y = -1.509 \times \text{Min-N} + 0.083 \times \text{ESO MAR} + 20.0 \]

\[ R^2 = 0.70; \quad C_p = -2.37 \]

\[ P = <0.001 \]

Min-N was a strong individual predictor \((R^2 = 0.62)\)

Long-term site MAR only ↑ \(R^2\) by 8%
Best foliar-based model (at age 2)

\[ y = -5.13 \times \text{FOL N:P} - 15.69 \times \text{FOL N:S} + 318.9 \]

\[ R^2 = 0.49; \quad C_p = 5.38 \]

\[ P = <0.001 \]
Best foliar-based model (at age 2)

\[ y = -5.13 \times \text{FOL N:P} - 15.69 \times \text{FOL N:S} + 318.9 \]

- \( R^2 = 0.49; \ C_p = 5.38 \)
- \( P = <0.001 \)

Not as good as soil model
Best foliar-based model (at age 2)

\[ y = -5.13 \times \text{FOL N:P} - 15.69 \times \text{FOL N:S} + 318.9 \]

\[ R^2 = 0.49; \quad C_p = 5.38 \]

\[ P = <0.001 \]

Not correlated
Best combined model (at age 2)

\[ y = -1.388 \times \text{Min-N} + 80 \times \text{ESO CWI} - 3.05 \times \text{FOL N:P} + 66.4 \]

\[ R^2 = 0.74; \quad C_p = 2.12 \]

\[ P = <0.001 \]
Best combined model (at age 2)

\[ y = -1.388 \times \text{Min-N} + 80 \times \text{ESO CWI} - 3.05 \times \text{FOL N:P} + 66.4 \]

\[ R^2 = 0.74; \quad C_p = 2.12 \]

\[ P = <0.001 \]

\[ \uparrow R^2 \text{ by } 4\% \text{ compared with soil-based model} \]
Best combined model (at age 2)

\[ y = -1.388 \times \text{Min-N} + 80 \times \text{ESO CWI} - 3.05 \times \text{FOL N:P} + 66.4 \]

\[ R^2 = 0.74; \quad C_p = 2.12 \]

\[ P = <0.001 \]

Does 4% justify an additional sample?
Best combined model (at age 2)

\[ y = -1.388 \times \text{Min-N} + 80 \times \text{ESO CWI} - 3.05 \times \text{FOL N:P} + 66.4 \]

\[ R^2 = 0.74; \, C_p = 2.12 \]

\[ P = <0.001 \]

CWI, rather than MAR
Best combined model (at age 2)

\[ y = -1.388 \times \text{Min}-N + 80 \times \text{ESO CWI} - 3.05 \times \text{FOL N:P} + 66.4 \]

\[ R^2 = 0.74; \ C_p = 2.12 \]

\[ P = <0.001 \]

One of the main reasons we explored alternative models
Best models (at age 4 or 10)

- Multiple models could still predict volume growth response to establishment fertiliser by age 4
  - $R^2$ decreased for best soil–based model
    - 70% $\rightarrow$ 60%
  - $R^2$ increased for best foliar-based model
    - 49% $\rightarrow$ 60%
  - Variables changed slightly; but still relied on Min-N (soil-based) and foliar N and P (foliar-based)

- No models could predict volume growth response by age 10
Alternative models: substitution of model variables

• What if you don’t have the variables required by the best models?

• Best soil-based model (age 2):
  – Min-N and ESO MAR; \( R^2 = 70\% \)
    • Swap ESO MAR with SILO MAR or CWI; \( R^2 = 65-68\% \)
    • Swap Min-N with total N; \( R^2 = 47\% \)

  – If you don’t have ESO MAR, other MAR-related variables can be substituted

  – Need Min-N
Alternative models: substitution of model variables

- Best foliar-based model (age 2):
  - Foliar N:P and N:S; $R^2 = 49$
    - Model already poor predictor
    - Second-best foliar model only uses Ca; $R^2 = 41$

- With only 49% of variance explained by this model, you most likely wouldn’t use it anyway...
Alternative models: substitution of model variables

• Best combined model (age 2):
  – Min-N, Foliar N:P and ESO CWI; $R^2 = 74\%$
    • Swapping climate variable; $R^2 = 70-72\%$
    • Swapping Min-N; $R^2 = 53-57\%$
    • Swapping Foliar N:P; $R^2 = 64\%$

  – Again, climate variables easily substituted
  – Model still relies heavily on Min-N = needed
Alternative models: substitution of model variables

- Same exercise for growth response to establishment fertiliser at age four
  - Similar effects
  - $R^2$ decreased from 60% to 50%
    - Model fit not strong in the first place
    - Substitution of variables not ideal
Synthesis

• **0-10 cm Min-N** = a strong predictor of growth response to establishment fertiliser
  – Especially 1-year post application
  – Marginally effective predictor by mid-rotation

• Performance as a predictor improves when combined with a measure of long-term site rainfall
  – Proxy for available water....?

• Other measures of soil or foliar N-status **could not** be effectively substituted for Min-N
Why is Min-N a good predictor?

• **Min-N = potentially mineralisable N**
  
  – Represents potential release of mineral N (NO$_3^-$ and NH$_4^+$) from soil
    
    • Extracted with KCl and **heat**
    
    • Release of microbial N and labile organic matter

  – Has been well correlated with aerobic and anaerobic biological incubation methods (Ros *et al.*, 2011)
    
    • Other extractions even better (potassium dichromate)
How to apply this information?

• Not going to solve all problems and can’t be used in isolation

• **BUT** – each model will estimate a % change in volume growth in response to fertiliser application
  – Our best models do this 1 year post-application
  – Of any use...?

• We think so --- use it to rank sites in terms of responsiveness
How to apply this information?

• Select model (equation!)
• Capture required pre-treatment inputs
  – Follow recommendations in report re: sample handling and analysis
• Calculate volume growth response to fertiliser
• Set minimum threshold for growth response
  – Based on your own economics – 10%, 20%?
• Apply fertiliser to those sites show a growth response > your threshold
How to apply this information?

• What’s the point if you can’t predict growth response to end of rotation?
  – It doesn’t mean there isn’t a growth response
  – Would you expect to be able to?

• At the very least, following this process will stop you from applying fertiliser at sites which definitely don’t need it
Validation: Old Experiments

• Do you have experiments with the required model inputs?
  – Or have legacy samples that could be re-tested?

• GREAT!
  – Calculate relative growth response to fertiliser for your experiments
  – Run the models you are interested in/have explanatory variables for
Validation: New Experiments

• Collaborative trials
  – Experimental design is relatively simple
  – Analytical and growth measurement costs
  – Management of experiment integrity
  – Paired-plot networks
    • Stape et al. 2006; Watt et al., 2008

• Check model requirements to make sure you get all the pre-treatment site information required
  – Develop strong empirical models
  – Properly validate process-based models
Final thoughts

• Most commonly said around the table:
  – “It’s not perfect, but it’s our best crack at it yet…”

• Palletise the pegs, roll up the flagging tape…?

• These models provide a system – something you can test and use
  – Much easier to test something when it’s there
    • best outcome is for people to show whether it does or doesn’t work