Technical Report 162

Options for managing nitrogen fertilisers in temperate eucalypt plantations

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October 2006

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Abstract

Research within the CRC for Sustainable Production Forestry (CRC-SPF) and elsewhere is synthesised to provide a framework for managing nitrogen (N) fertilisers in eucalypt plantations. The system identifies N deficient sites, provides N management options (rate, timing, type and placement), predicts wood yield and quality responses to N fertilisation, considers potential environmental effects, and encourages economic evaluation of the options. The system is best defined for *Eucalyptus nitens* plantations in Tasmania.

Introduction

An aim of research in the CRC-SPF was to develop options for managing nitrogen fertilisers post-canopy-closure in temperate eucalypt plantations. This research addressed three main topics:

1. identifying the sites deficient in N,
2. quantifying their growth response to N fertilisers, and
3. evaluating the potential for adverse effects on wood quality or the environment.

Results of this research are already available in various forms, but this report aims to summarise and link this information with that from other sources, and suggest options for inclusion in management systems.

Identifying N deficient sites

Fertiliser history

Plantation growth on ex-pasture sites is usually better than on ex-forest sites (all other factors being equal), because forest soils are commonly very low in phosphorus (P) and N availability and pasture management includes regular additions of P fertiliser and N inputs via biological N fixation associated with legumes. Hence, investment in pasture for conversion to plantation represents an investment in soil fertility built up by a history of fertiliser use.

It was not surprising then that ex-pasture or ex-forest (second rotation) categorisation was a useful discriminator of N-responsive *E. nitens* or *E. globulus* plantations in Gippsland (Baillie *et al*. 2003). Trees at two ex-pasture sites did not grow more quickly with N fertiliser, but those on five ex-forest sites did. Also amongst *E. nitens* plantations in Tasmania, the only ex-pasture site studied did not respond to N fertiliser (Smethurst *et al*. 2004a)

Farmers generally have been aware of the P and N fertility issues associated with pastures and they responded by routinely applying P fertiliser and using legumes in their species mixes. Limited N fertilisation has also been used. However, potassium (K), which is second only to N in the amounts required by plants for growth, has often been ignored. While most soils had adequate K availability when first sown to pastures (or other crops), decades of removal of animal and plant products containing K depletes these reserves. It was no coincidence then that the first report of suspected K deficiency in *Pinus radiata* in Australia was on ex-pasture sites (Raupach and Hall 1974), which is mirrored by more recent experience in the CRC-SPF (Smethurst *et al*. 2001).

Soil analysis

Reliable diagnostics of N deficiency need to be calibrated against the response to N fertilisation at many sites, and such soil calibrations usually vary according to soil type, climate, and cropping system. An example of such a calibration is that for P deficiency in pastures in New South Wales (NSW) (Figure 1). This type of calibration requires fertiliser experiments at numerous sites conducted over several years, but this requirement has rarely been met for soil analyses in plantation forestry in Australia or elsewhere. Calibrations for N are very rare in agriculture too, because of the complexity of measuring N availability in temporal and spatial scales relevant to plants (Smethurst, 2000).

CRC-SPF nutritional research did not include many ex-pasture sites, but of those we did work with, increased N availability was demonstrated in several types of soil analyses (Smethurst *et al*. 2004a, Wang *et al*. 1996; Fig 2). However, such differences don't necessarily justify the use of these analyses for indicating the need for N fertiliser. Such justification should only come from calibrations such as that indicated in Figure 1. Concentrations of mineral N (ammonium and nitrate) can potentially be calibrated to indicate N deficiency (Smethurst 2000). In exploring N relations in *E. nitens*, we found that ammonium or ammonium+nitrate concentrations in soil solution were potential discriminators of N sufficient and deficient sites and better than the standard potassium chloride (KCl)-extractable concentrations (Smethurst *et al*. 2004a, Figure 3). The concentrations of mineral N in solution associated with N deficiency were similar to those suggested by theoretical analysis (Sands and Smethurst 1995), which provides encouragement for this approach, but we did not have enough data to develop reliable predictive calibrations.

Budgeting demand-supply relations of N in *E. nitens* plantations was tested and found reliable if rates of N mineralisation could be measured on-site (Smethurst *et al*. 2004, Figure 4), but this is a method suited only to research because it is very expensive. These rates also could not be predicted accurately enough from less expensive methods for site-specific predictions (Moroni *et al*. 2004), although such predictions would probably be accurate enough for predictions at a regional or country scale (Paul *et al*. 2002a).

One complication with using mineral N concentrations is that they vary considerably with time (Smethurst 2000, Smethurst *et al*. 2001). These concerns led us to testing more stable forms of N, which led to a useful result. Concentrations of total N in surface soil (0-10 cm) less that 6 mg g^{-1} were indicative of N deficiency in *E. nitens* plantations (Figure 5). The lower the concentration the more severe the deficiency, and plantations in the 3-5 year age class seemed most responsive, which coincides with the expected peak in N demand. This calibration is probably the most useful indicator of N deficiency developed for eucalypt plantations in Australia, but it should not be used in other regions, climates or species without further testing, because the N-supplying power for a given concentration of total N is likely to be different, and the pattern of N demand of plantations in other regions could also be different.

Stand vigour

Several characteristics are used to judge vigour of a stand: leaf area index (LAI), leaf colour or form, foliar analysis, timing of 'canopy lift', and comparison of actual and expected stem growth rates. These characteristics can be used reactively by management, but are of limited use predictively because growth has usually been limited by the time that a lack of vigour is evident. In addition, the lack of vigour is also often not a specific indicator of N deficiency. Never-the-less, assessment of stand vigour is an important tool for monitoring the progress of a plantation and can assist in narrowing down the potential causes of a growth limitation.

Under severe nutrient stress, some foliage of some eucalypt species discolours or malforms in characteristic ways (Dell *et al*. 2001), but our experience is that N deficiency usually involves only short-term (a few months) pale greenness of leaves in *E. globulus* and *E. nitens* that is very hard to specifically associate with N deficiency. In the longer term, when N-limited, these eucalypts tend to shed leaves (first from the lower canopy) so that N demand and growth rate are better matched to the prevailing N supply. During this phase of growth, leaf greenness is adequate while growth rates are limited. While visiting numerous N fertiliser experiments in temperate eucalypts since 1992, on only one occasion did I observe a distinct colour difference between N-fertilised and control plots (Figure 6).

The concentration of foliar N broadly, which reflects leaf greenness because of its strong association with chlorophyll, is also of limited value as a predictor of N deficiency in these eucalypt species. For example, while studying concentrations of foliar N in *E. globulus* foliage collected at 3 or 6 monthly intervals, Adams (2004) found a strong correlation with subsequent growth increments on only one occasion during the first few years of growth, despite the experimental conditions producing a wide range of foliar concentrations.

Because LAI is important for indicating N deficiency, we validated tools for assessing LAI. The standard tool, a LICOR LAI-2000, accurately detects diffuse light, and when used under the right conditions it is an accurate indicator of LAI in many types of forest stands. However, this instrument is expensive. Less expensive alternatives have also been tested, i.e. a visual guide developed in the CRC-SPF (Cherry *et al*. 2002), a densiometer and an inexpensive light sensor (Quantum Meter) (Cherry pers. comm.). These methods are useful, but the minimum LAI provided in the visual guide is 2, whereas, many *E. globulus* stands have lower LAI values, and the Quantum Meter and densiometer methods would benefit from additional development and validation. More recently, a useful method of analysing readily obtainable digital photos has shown promise (MacFarlane pers. comm.; http://members.forestry.crc.org.au/cgi-bin/doc.pl?rm=view_doc&doc_id=1559)

Onset of N deficiency is usually accompanied by early canopy lift and can also include a reduction in density of the remaining of the crown (Figure 7).

A method of assessing crown damage by pests has also been developed (Stone *et al*. 2003). Although this method is untested in relation to nutritional management, it is likely to be more useful for characterising canopy vigour of stands with canopies that are not high enough to allow use of the LAI assessment methods.

In Tasmania, commercial plantations are reasonably well-watered and potential P deficiencies are avoided by early P fertilisation. Under these conditions, the main nutritional limitation to growth is low N supply. Hence, we found a strong relationship between LAI and the increment in stem biomass in *E. nitens* plantations with various N fertiliser treatments (Figure 8), and LAI in such stands is therefore a good indicator of N deficiency. Under these conditions, if LAI is less than or equal to c. 4, an application of N fertiliser is likely to increase LAI and growth rate. The situation is more complex on the mainland where both N and water can be expected to limit LAI and growth.

There are a range of tools available for predicting the growth rate of a plantation that can then be compared to actual growth. Each grower has at least some empirical productivity prediction system. The process-based model CABALA (Battaglia *et al*. 2004) is also available, which predicts N availability, uptake and utilisation for growth, and hence the degree of N limitation. Because this model has had some degree of validation in *E. globulus* and *E. nitens* plantations (Battaglia *et al*. 2004, Smethurst *et al*. 2004c), it can be used with some confidence to firstly compare actual and predicted growth, thereby alerting us to potential underperformance of a plantation, and secondly indicate if low N supply is the likely cause of slower than expected growth.

Predicting growth and wood quality responses to N fertilisation

As already indicated, soil total N is a useful indicator of N limitation in *E. nitens* plantations in Tasmania (Figure 5). These data show that growth responses to a single application of 200 kg N ha^{-1} can led to a maximum response of 43 m^3 ha^{-1} of extra wood when applied at 3-6 years of age, but lower responses were more common and depended on age of application and concentration of total N. In our experience with unthinned pulpwood crops, no or little growth response is expected to N fertiliser applied later than c. 6 years of age. Responses at this stage of crop development might be more significant and profitable in combination with thinning, but this was not tested.

However, on many sites, this rate of application will not completely alleviate N deficiency, because responses at some sites were not maximised at 500 kg N ha^{-1} applied during the first 3 years of growth (Figure 9), and additional responses to later applications can be expected on some sites. However, our data suggest there is no clear benefit in exceeding 200 kg N ha^{-1} in any single application. Hence, on severely N deficient sites, periodic applications of N fertiliser will be needed to maximise growth (Cromer *et al*. 2002, Smethurst *et al*. 2004, Ringrose and Neilsen 2005).

Few data are available on the effects of N fertilisation on wood quality (e.g. wood density) in temperate eucalypts, but these data suggest that few detrimental effects can be expected (Raymond 1998, Smethurst *et al*. 2004a, Gonçalves *et al*. 2004). Some positive and negative effects have been observed, but we currently lack a reliable basis for predicting N fertiliser effects on the quality of wood produced in these species while suspecting that seasonal interactions with water availability could be important (Gonçalves *et al*. 2004).

Potential environmental effects

Nitrogen fertilisation has several potential negative environmental effects on- and off-site that need to be recognised and either avoided or managed within acceptable limits. Soil-based effects all arise from N fertilisation leading to an increase in nitrate leaching that concurrently reduces the availability of base cations (K, Mg and Ca), increases soil acidity (i.e. decreases pH) and the concentrations of aluminium (Al), and increases the delivery of nitrate and accompanying cations to groundwater and streams. These effects are well known and confirmed in our own eucalypt plantation systems (Mitchell *et al*. 2004, Ringrose and Neilsen 2005), but we don't yet have reliable criteria for critical values of base cation availability or Al toxicity.

These effects are minimised if non-nitrate, ammonium-based fertilisers (e.g. urea or ammonium sulphate) are used as the N source, but in nearly all soils some of the applied N will be transformed to nitrate by soil microbes anyway. The effects are also minimised if N fertilisers are applied only if they are needed to promote tree growth and at rates less than 200 kg ha^{-1} in each application. Because the effects of N fertilisation on soil N availability are ephemeral (lasting only 6-12 months, usually), it is important that applications coincide with periods of N deficiency. In addition, direct applications to free water in streams or drainage ways should be avoided, but this is unlikely to be a problem if operations are consistent with the codes of forest practice. If such practices are followed, international experience indicates that concentrations of nitrate in drinking water would not be expected to exceed levels of concern, but there still might be some positive or negative impacts on stream biota (Binkley *et al*. 1999).

Even if such guidelines are followed, cumulative rates of N fertilisation greater than 1000 kg N ha^{-1} should be considered with caution, because such practices in CRC-SPF experiments led to decreased pH and concentrations of base cations in surface soils (Ringrose and Neilsen 2005, Mitchell *et al*. 2004), and base cation deficiencies are already suspected or have been demonstrated in some plantations.

Biological N fixation, e.g. use of legumes or acacias, is an alternative source of N that should be considered, especially if N fertiliser costs increase substantially (Turvey and Smethurst 1980, 1983). These technologies have already been developed and used in pine plantations in temperate Australia and New Zealand (Smethurst *et al*. 1986), and could probably be adapted to eucalypt plantations if required. Currently, N fertilisation is favoured over legumes because it is cheap, effective and convenient.

Nitrogen fertilisation can also have a potential positive environmental effect. If N fertilisation stimulates growth, additional carbon is sequestered which positively affects the balance of greenhouse gases and can potentially be recognised in C accounting schemes (Paul *et al*. 2002b). Sequestration of C is also an application for CABALA.

Little information is available on the effects of N fertilisation on beneficial or harmful insects and microbes in eucalypt plantations, but, in general, N fertilisation can potentially promote or hinder growth of these organisms and potentially assist the tree to avoid damage or recover from it. A research project on this topic is nearing completion (Pinkard pers. comm.).

Decision framework

Current knowledge in relation to N-fertilisation of temperate eucalypt plantations is summarised in a schematic framework to support fertilisation decisions (Figure 10). The knowledge base for implementing this system is incomplete for any of our plantations, but this system is an improvement on that previously available and it could assist in identifying priorities for further research. The system is most complete for *E. nitens* in Tasmania, because of the reasonably extensive network of N fertiliser experiments under these conditions, the calibration of soil total N, and knowledge that LAI in these plantations under current growing conditions is primarily limited by N.

Figures

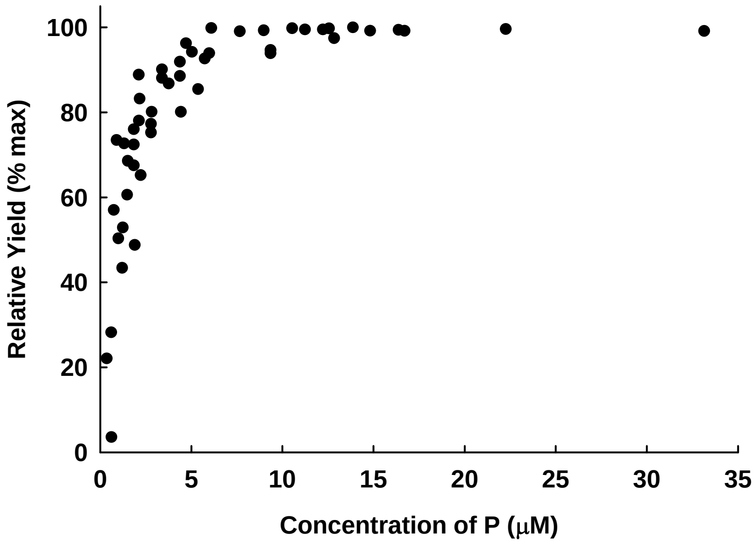

Figure 1. Calibration data for the concentration of P in a dilute $CaCl_2$-extract in relation to yield response of clover pasture at 10 sites in NSW (redrawn from Dear *et al*. 1992). Relative yield is growth of the unfertilised treatment relative to the maximum response to P fertiliser obtained at the corresponding site. This calibration shows that there is a high likelihood of response if the P concentration is less than 5 M and little likelihood at higher concentrations.

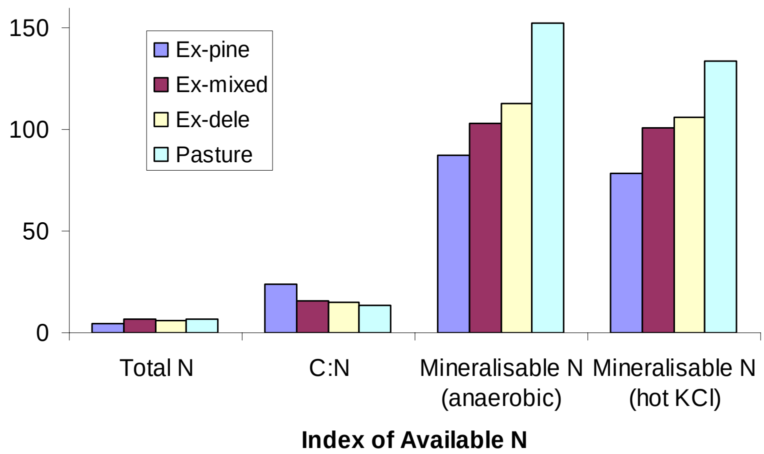

Figure 2. In a survey of 28 sites in Tasmania, pasture sites were generally more N-fertile than other site types (6 or 7 sites of each type measured), because they had higher concentrations of total and mineralisable N and lower C:N ratios (Wang *et al*. 1996).

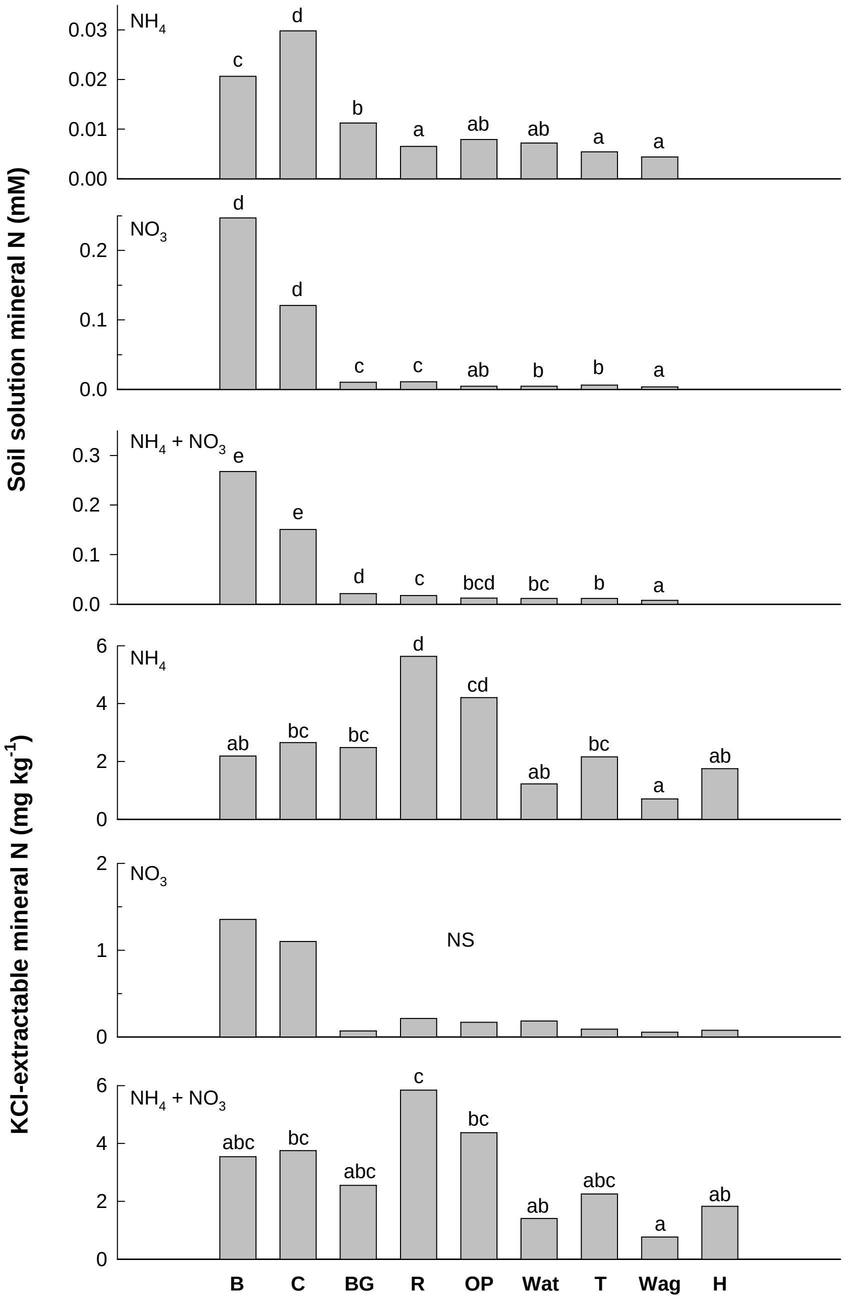

Figure 3. Concentrations of NH4 and NO3 in soil solution and KCl extracts at 9 sites, including 2 sites where trees did not respond to N fertilisation (B and C) and 7 sites where trees did (BG, R, OP, Wat, T, Wag, and H) (Smethurst et al. 2004a). Soil solution data were not available for site H. Bars with common letters within a graph are not significantly different (P = 0.05), based on an LSD for transformed data. NS indicates no significant site effect.

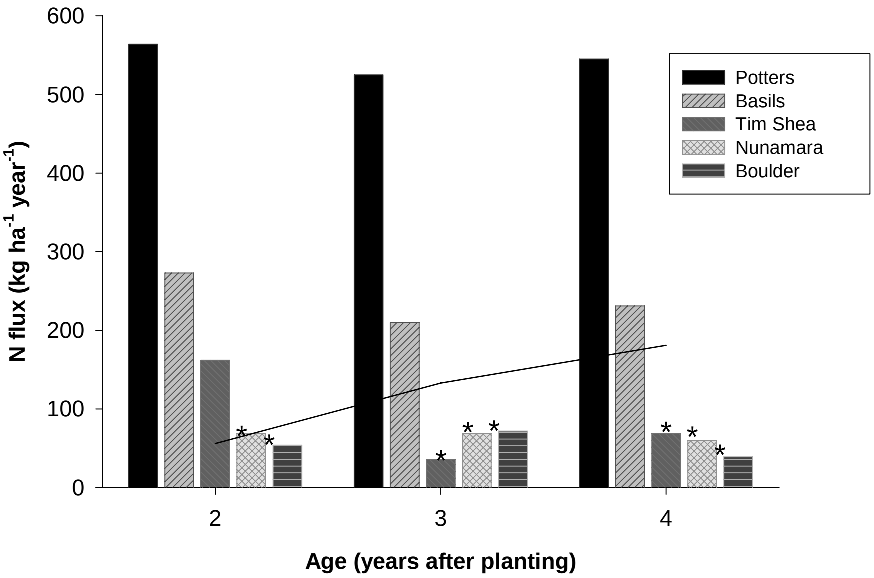

Figure 4. Comparison of estimated rates of N mineralisation (bars) and uptake (line) for five sites where soil N fluxes were measured in the surface soil (0-10 cm) of unfertilized plots of N fertiliser experiments (Smethurst *et al*. 2004). This analysis assumes N mineralisation for the whole profile is three times that measured in the surface 10 cm (Moroni 2001), and that potential uptake of a high-productivity *E. nitens* plantation is consistent with the N contained in above-ground components for high-productivity *E. nitens* (Moroni 2001) and *E. globulus*, and that below-ground N is 0.4 of that above-ground (Misra *et al*. 1998). Mineralisation in year 4 at Potters was estimated as the average of that measured in the two previous years. Asterisks indicate that N deficiency was indicated by a significant, positive growth response to N fertiliser.

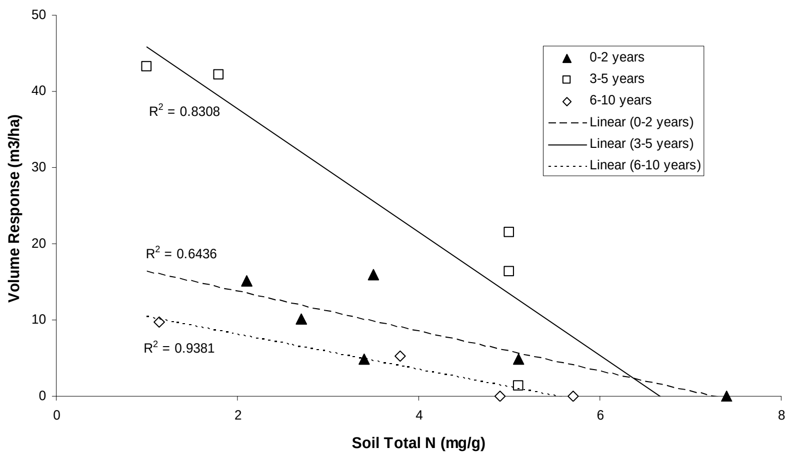

Figure 5. The relationship between stem volume response to 200 kg N ha^{-1} fertilisation and soil total N (Smethurst *et al*. 2004b).

Figure 6. Note the colour difference between unfertilised 2-year-old *E. nitens* in the foreground and N-fertilised trees in the background. Peter Naughton is standing at the plot boundary, in an N fertiliser experiment at Nunamara, Tasmania. Also note that canopy lift had not commenced when this photo was taken.

Figure 7. This is a photo of the same plantation as that shown in Figure 6, but taken one later. Note that canopy lift has occurred and remaining foliage appears a satisfactory green colour. This plantation had been experiencing N deficiency for about the previous 1.5 years.

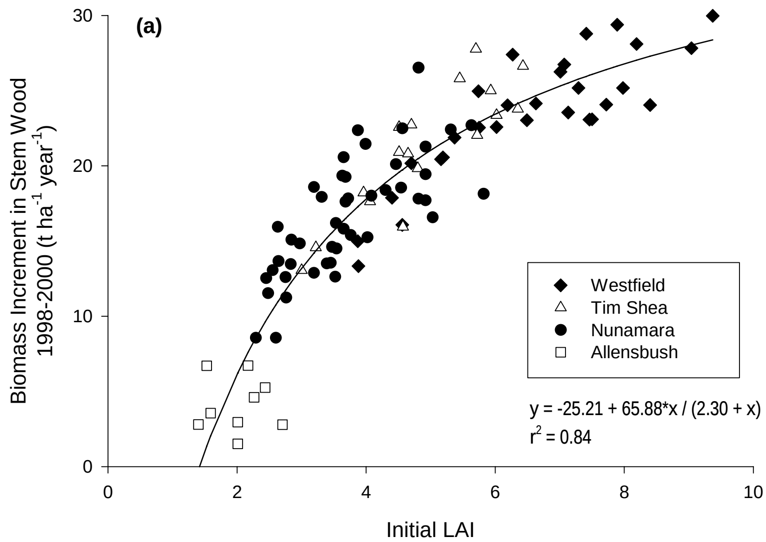

Figure 8. Annual increment in the biomass of stem wood of individual plots of *E. nitens* in relation to initial LAI in N fertiliser experiments at four sites (Smethurst *et al*. 2003).

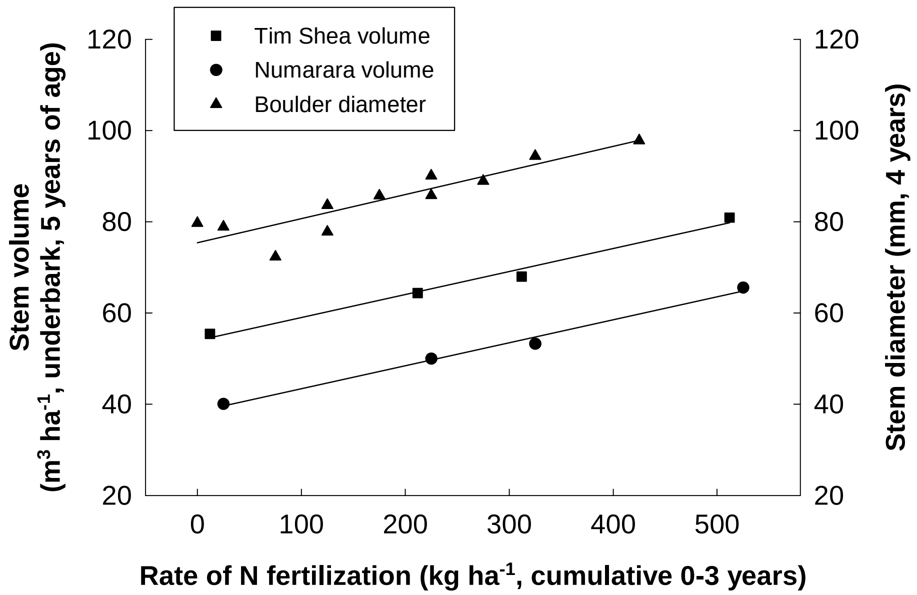

Figure 9. Stem volume at age 5 years or diameter at age 4 years of three *E. nitens* plantations in relation to the cumulative rate of N fertilisation between planting and 3 years of age (Smethurst *et al*. 2004a).

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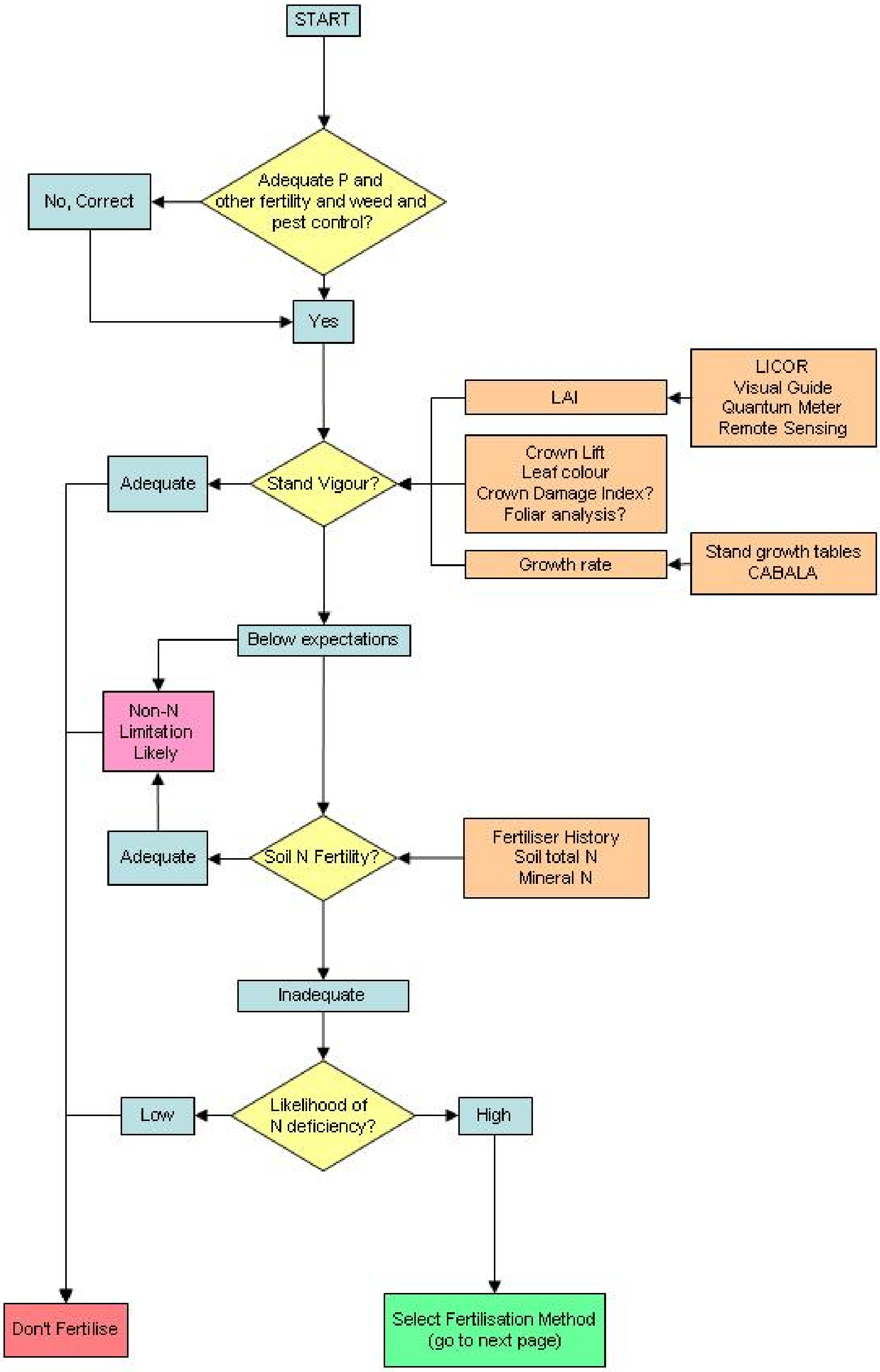
START
Adequate P and other fertility and weed and pest control?
No, Correct
Yes
LAI
LICOR
Visual Guide
Quantum Meter
Remote Sensing
Crown Lift
Leaf colour
Crown Damage Index?
Foliar analysis?
Growth rate
Stand growth tables
CABALA
Adequate
Stand Vigour?
Below expectations
Non-N Limitation Likely
Adequate
Soil N Fertility?
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Inadequate
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Don't Fertilise
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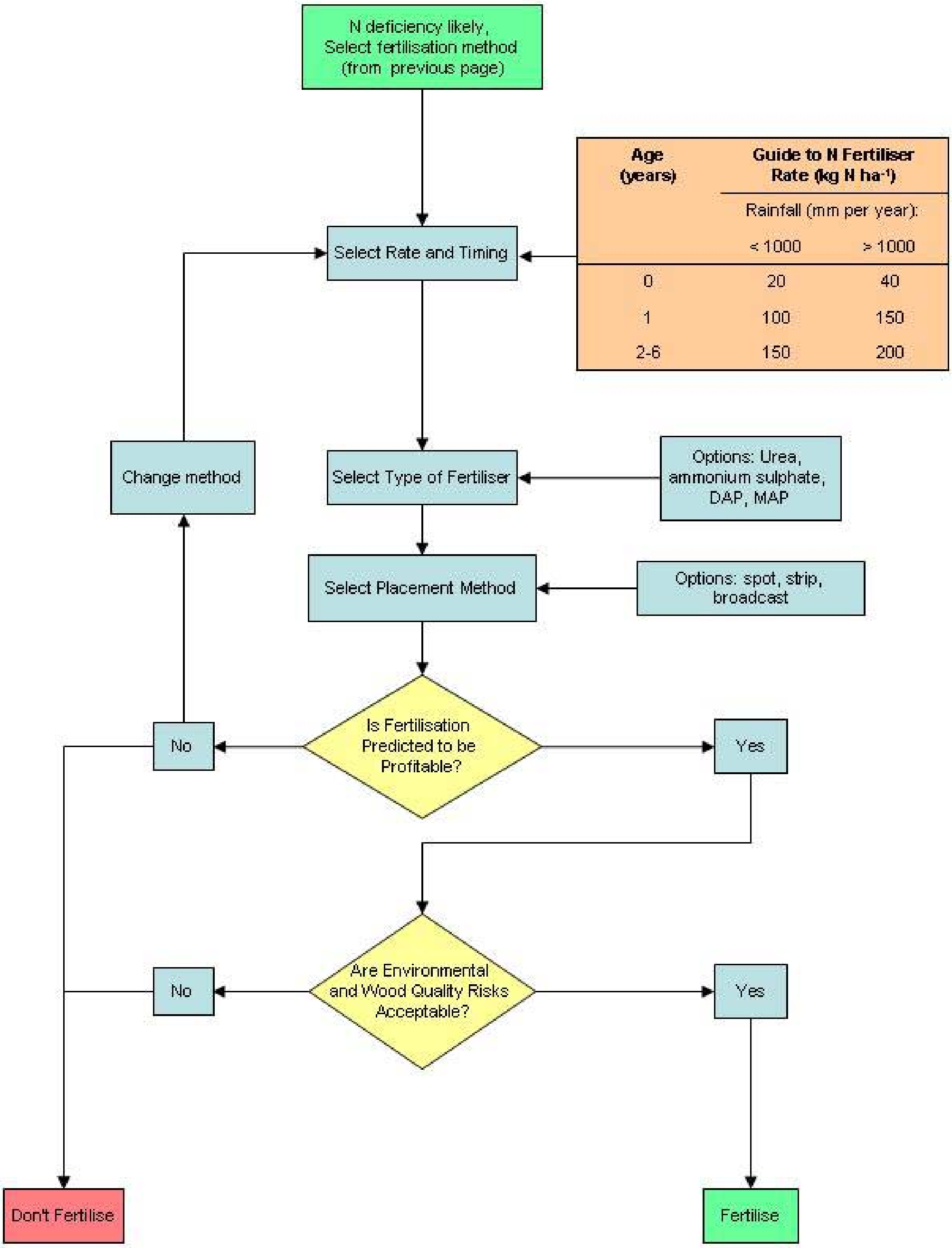

Figure 10. Schematic framework for managing N fertilisers in temperate eucalypt plantations (including previous page).

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Glossary

Al	Aluminium
Ca	Calcium
E. globulus	*Eucalyptus globulus* (also commonly known as blue gum).
E. nitens	*Eucalyptus nitens* (also commonly known as shining gum; and as silver top occasionally in New South Wales).
K	Potassium
KCl	Potassium chloride
LAI	Leaf area index
Mg	Magnesium
$m^3\ ha^{-1}$	Cubic metres per hectare
$mg\ g^{-1}$	Milligrams per gram
N	Nitrogen
NSW	New South Wales
P	Phosphorus
pH	A measure of acidity and alkalinity