



An Australian Government Initiative



Nutrient Management of Intensively Harvested Oil Mallee Tree Crops

**A report for the RIRDC/L&WA/FWPRDC
Joint Venture Agroforestry Program**

by Tim S. Grove, Daniel S. Mendham,
Stanley J. Rance, John Bartle and Syd Shea

June 2007

RIRDC Publication No 07/084
RIRDC Project No CSF-63A

© 2007 Rural Industries Research and Development Corporation.
All rights reserved.

ISBN 1 74151 481 9
ISSN 1440-6845

Nutrient management of intensively harvested oil mallee tree crops

Publication No. 07/084

Project No. CSF-63A

The information contained in this publication is intended for general use to assist public knowledge and discussion and to help improve the development of sustainable regions. You must not rely on any information contained in this publication without taking specialist advice relevant to your particular circumstances.

While reasonable care has been taken in preparing this publication to ensure that information is true and correct, the Commonwealth of Australia gives no assurance as to the accuracy of any information in this publication.

The Commonwealth of Australia, the Rural Industries Research and Development Corporation (RIRDC), the authors or contributors expressly disclaim, to the maximum extent permitted by law, all responsibility and liability to any person, arising directly or indirectly from any act or omission, or for any consequences of any such act or omission, made in reliance on the contents of this publication, whether or not caused by any negligence on the part of the Commonwealth of Australia, RIRDC, the authors or contributors..

The Commonwealth of Australia does not necessarily endorse the views in this publication.

This publication is copyright. Apart from any use as permitted under the *Copyright Act 1968*, all other rights are reserved. However, wide dissemination is encouraged. Requests and inquiries concerning reproduction and rights should be addressed to the RIRDC Publications Manager on phone 02 6272 3186.

Researcher Contact Details

Dr Tim Grove
CSIRO Forestry and Forest Products
PO Box 5
Wembley WA 6913

Tel: 08 9333 6664
Fax: 08 9387 8991
Email: Tim.Grove@csiro.au

In submitting this report, the researcher has agreed to RIRDC publishing this material in its edited form.

RIRDC Contact Details

Rural Industries Research and Development Corporation
Level 2
15 National Circuit
BARTON ACT 2600
PO Box 4776
KINGSTON ACT 2604

Phone: 02 6271 4100
Fax: 02 6271 4199
Email: rirdc@rirdc.gov.au
Web: <http://www.rirdc.gov.au>

Published in June 2007

Foreword

Planting of perennial woody species integrated with more conventional farming practices is a major thrust of current activities to address land degradation across Australia. The focus has been on identifying perennial crops that could develop into commercially viable industries. Broad-scale planting of oil mallee on farmland in the low to medium rainfall zone of south-western Australia commenced in the mid 1990s. The oil mallee industry in south-western Australia is approaching a milestone, with the release of an Information Memorandum seeking full commercial investment in an integrated processing plant, such as the pilot plant at Narrogin, to produce eucalypt oil, activated carbon and bioenergy.

Sustaining high growth rates in tree-belts is a key element to the economic viability of this new cropping system. To date there has been minimal research on the nutrition of oil mallee crops. Experience overseas has shown that the sustainability of short-rotation tree crops used for bioenergy production requires management of site nutrients to offset relatively high rates of nutrient removal in harvested material.

The results described in this report will assist landholders and investors to manage oil mallee biomass crops for sustained productivity. The study has developed methods to readily estimate biomass and nutrient composition of oil mallee tree-belts, and these are used to quantify potential nutrient export rates from tree-belt sites due to frequent harvesting. This is the first step in developing strategies for nutrient replacement to maintain soil fertility and sustain high productivity.

This project was funded by the Joint Venture Agroforestry Program (JVAP), which is supported by three R&D Corporations – Rural Industries Research and Development Corporation (RIRDC), Land & Water Australia (L&WA), and Forest and Wood Products Research and Development Corporation (FWPRDC), together with Murray-Darling Basin Commission (MDBC). The R&D Corporations are funded principally by the Australian Government. State and Australian Governments contribute funds to the MDBC.

This report is an addition to RIRDC's diverse range of over 1600 research publications. It forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems. The JVAP, under this program, is managed by RIRDC.

Most of our publications are available for viewing, downloading or purchasing online through our website:

- downloads at www.rirc.gov.au/fullreports/index.html
- purchases at www.rirc.gov.au/eshop

Peter O'Brien

Managing Director

Rural Industries Research and Development Corporation

Acknowledgments

We are grateful to the many farmers and members of the Oil Mallee Association on whose properties we measured and sampled trees. Ian Stanley deserves a special mention as many sites in the Kalannie region were sampled on his property. We also wish to thank David McFall, Angela and (the late) Max Waters and Elaine Hudson for help in locating suitable sites, and to Elva Rolinson and Mike Hesford on whose properties we excavated pits and conducted extensive tree-belt measurements. We also thank Geoff Dimmock for providing the soil descriptions, Tuyen Pham and Rae Lowther for chemical analysis of samples and Tuyen Pham and Shirley Snelling for help with the collection and processing of samples.

Contents

Foreword	iii
Acknowledgments	iv
Executive Summary	vi
1. Introduction	1
2. Objectives	2
3. Methods	3
3.1 Development and testing of allometric and nutrient content functions.....	3
3.1.1 Site selection and stratification.....	3
3.1.2 Tree measurement, sampling and chemical analysis.....	3
3.1.3 Development and testing of predictive functions.....	6
3.1.4 Toolkit development.....	7
3.1.5 Use of functions to predict coppice regrowth biomass and nutrient content.....	7
3.2 Tree belt biomass and nutrient composition at four sites	8
3.2.1 Sites and tree belt measurements.....	8
3.2.2 Soil nutrient stores.....	9
3.2.3 Nutrient properties in surface soils.....	9
4. Results	11
4.1 Regression functions to estimate biomass and nutrient composition	11
4.1.1 Dry matter and nutrient concentrations in sample trees	11
4.1.2 Regression functions	12
4.1.3 Examples of species and site factor effects on single stem relationships.....	17
4.1.4 Test of model predictions	22
4.1.5 OMEN Toolkit	24
4.1.6 Test of predictive functions with coppice growth	24
4.2 Tree belt nutrients in relation to site nutrient capital.....	28
4.2.1 Aboveground biomass and nutrient stores	28
4.2.2 Nutrient stores in soils under tree-belts	31
4.2.3 Comparison of above- and below-ground nutrient stores	34
4.2.4 Nutrient export rates in relation to amount of biomass and frequency of harvest.....	35
4.2.5 Differences in soil nutrient properties between tree and alley soils	38
5. Discussion	39
6. Implications	42
7. Recommendations	43
8. References	44
9. Appendix	46
Appendix 1 – Soil descriptions for the oil mallee sites	46

Executive Summary

What the report is about

This report develops generic methods for quantifying the biomass and nutrient composition of oil mallee, and evaluates potential nutrient export rates for different species and biomass harvest scenarios in relation to site nutrient capital. The need for ash recycling and nutrient application to conserve site nutrient capital and prevent onset of nutrient deficiencies is discussed. This study is an important first step in providing improved practices to manage the nutrition of mallee crops for optimum production.

Who is the report targeted at?

This report will be of use to landholders and mallee plantation managers in considering how to better manage site nutrition and maintain productivity growth of mallee belts. Use of the prototype toolkit, OMEN, will also be useful for landholders and farm forestry advisors.

Background

Establishment of woody perennial vegetation is an important part of the solution to dryland salinity, which is currently threatening a large proportion of the Australian agricultural landscape. The scale of planting necessary to achieve salinity amelioration requires that adoption of woody perennial vegetation is commercially driven. Woody perennials must be widely dispersed in order to intercept surplus water from adjacent crop or pasture planted areas. This is most effectively done using woody crops in a contour belt configuration. This allows agriculture to continue on interrow lands while adjacent woody perennial belts draw down the saline water table. Potential has been identified in WA for an industry based on oil mallee, and a large investment has been made in extensive planting of oil mallee in belts. Investment has also been made in development of a pilot processing plant to extract eucalyptus oil, energy, and activated charcoal from the oil mallee feedstock. Extraction of these products requires harvest and removal of all above-ground components of the tree. Experience in Australia and overseas has shown that short-rotation woody crops can deplete site nutrient reserves, especially where whole tops are removed. However, sustained productivity of oil mallee crops will be required over many rotations to ensure that the potential environmental and economic benefits are returned to farmers and the community. This project was established to develop techniques to readily assess site nutrient export, and to ensure that appropriate nutrient management can be implemented in oil mallee crops for longer term sustainability of the industry.

Aims and Objectives

The aims of this project were (1) to develop techniques for rapid assessment of the quantity of biomass and nutrients exported from intensively harvested oil mallee crops, (2) to apply these techniques to examine nutrient export scenarios at four representative oil mallee planting sites, and (3) to provide recommendations to ensure longer-term sustainability of the industry.

Methods Used

A series of regression functions were defined using trees from a range of sites within a matrix of 2 focus regions (Kalannie, Narrogin), 2 soil types within each region (high and lower fertility), 2 species within each region (including 1 species common to both regions), and a range of ages and tree sizes. The 3 species sampled were *Eucalyptus kochii* ssp. *plenissima* (Kalanni), *E. polybractea* (at Narrogin) and *E. loxophleba* ssp. *lissophloia*; the latter was in common to both soil types in each region. In total, 139 trees were harvested from 27 sites within this matrix. Each harvested tree was separated into a maximum of 7 fractions. The biomass and nutrient contents were assessed and related to non-destructive measurements through functions. These functions were incorporated into a computational tool, Oil Mallee Estimator of Nutrients (OMEN), for ready application. The OMEN tool was then used to predict belt-level biomass and nutrients at 4 representative focus sites, 2 in the Narrogin district, and 2 in the Kalannie district. Above-ground nutrient contents were compared with the stores in soil to 2 m

depth. OMEN can also be used as a scenario analysis tool, to examine the impacts of harvest frequency on site nutrient depletion.

Results and Key Findings

Regressions were developed to predict biomass and nutrients (N, P, K, Ca, Mg, and Na) from both individual stem measurements (heights and base diameters), and from whole-tree measurements (tree height, maximum canopy width and length, height to the base of the crown, number of stems) in uncut trees. Both regression types explained a high proportion of the variation in tree biomass and nutrient content. The individual-stem measurements were more strongly correlated to biomass and nutrients, explaining 94.9-97.1% of the variation in canopy contents of biomass and nutrients, and 95.0-97.6% of the variation in stem (wood, bark, branches) biomass and nutrients. The whole-tree measurements were also highly correlated with both canopy (93.7-97% of the variation explained), and stem (91-94.8% of the variation explained) components. The factors of region, fertility and species, and their 2nd order interactions were of variable significance, depending on the specific tree fraction and nutrient. Generally, site factors (fertility, region) showed significant effects on the biomass and nutrient composition of canopy fractions but not on stem and branch fractions. Full models were developed to account for these species, site, and interaction effects, with more than 5000 coefficients being generated within this suite of models. Due to the complexity of this data set, the OMEN computational tool was developed as part of this project. This integrates these models into a useful package and allows the user to enter basic site information (belt length, row width etc.), and tree-based measure information (either individual stem or whole tree). OMEN then integrates this measurement information with the regression model parameters to predict the standing biomass and nutrient content of the belt. The OMEN tool can also be used to predict impacts of variable harvest frequency on site nutrient export.

Regressions were developed based on uncut sapling trees. Their application to coppice regrowth was examined at one site. The coppice material showed broad agreement with model predictions, but foliage concentrations of cations were much lower in the coppice material at that site. Hence the model predictions overestimated the biomass and amounts of nutrients in coppice shoots, and more work is required to allow accurate prediction of coppice biomass and nutrient contents.

Using the OMEN tool, a 5-year old *E. polybractea* belt at Narrogin was predicted to have a total of 25 tonnes ha⁻¹ biomass, with 189 kg ha⁻¹ N, 12 kg ha⁻¹ P, 87 kg ha⁻¹ K, 241 kg ha⁻¹ Ca, and 25 kg ha⁻¹ Mg. This contrasted with a 4-year old *E. loxophleba* ssp. *lissophloia* tree belt at Kalannie, which had a predicted 4.0 t ha⁻¹ biomass, and 38 kg ha⁻¹ N, 2.5 kg ha⁻¹ P, 14 kg ha⁻¹ K, 49 kg ha⁻¹ Ca, and 4.3 kg ha⁻¹ Mg. The sites were assessed after two very dry years in the Kalannie region, which partly explained the large difference in biomass between the sites.

The quantity of nutrients in the tree belts at the focus sites were also related to the soil stores to 2 m depth. Above-ground nutrient stores were generally around 1% of the soil stores in the higher fertility soils, and up to 5% of the soil stores at the lower fertility sites, suggesting that the lower fertility sites may require nutrient amendment at an earlier stage to ensure optimal productivity over multiple rotations.

Implications

- The allometric regressions derived during this study can be used to estimate the amounts and distribution of biomass and major nutrients, from either whole tree or single stem measures.
- The prototype toolkit OMEN simplifies the calculation of amounts and allocation of biomass and nutrients in tree-belts using tree dimension measurements. OMEN could be used to generate lookup tables for tree size classes for application across the industry. There is potential to further refine and expand the toolkit through incorporation of information from other studies or by linkage to growth model output.

- Relationships developed for sapling trees were found to over-predict the biomass and nutrient contents of coppice regrowth at one site – further refinement of relationships will be required for use with coppice.
- Biomass removal over several harvesting cycles will significantly deplete total site stores of some nutrients unless replacement strategies (return of ash, fertilizer application) are implemented. Site depletion will be moderated by the potentially large depth of root penetration of mallee and the possible large amount of leached nutrients in deep subsoil storage. Site N fertilizing will be required to return N that is lost through burning of the biomass.
- The impacts of tree-belt management on labile (plant available or potentially available) forms of nutrients in soil is more important than the effects on total nutrient balances. Comparisons of nutrient properties of tree-belt and alley soils indicate that concentrations of labile forms of N and P are lower in tree-belt soil. If soil nutrient supply in tree belts is not managed, trees may increasingly rely on nutrients acquired from the alley soils. One form of management may be to provide greater inputs through modification to the annual crop and pasture rotations in the alley where greater proportions of legumes, or greater fertiliser inputs might be used.

Recommendations

- Procedures to assess oil mallee tree-belts and estimate amounts and relative proportions of different product categories will become increasingly important once the integrated processing plant is operational. The models and toolkit developed in this study are appropriate for providing this predictive capability.
- Choice of use of whole tree or single stem model should be based on accuracy required. The whole tree model using tree dimension measurements requires fewer measurements than the single stem model in providing estimates of the biomass and nutrient content of leaf, twig and whole canopy. The single stem model using stem dimension measurements provides more accurate estimates of the biomass and nutrient contents of woody components.
- The models and toolkit which have been developed for sapling trees, will need to be recalibrated for use in predicting the biomass and nutrient composition of coppice regrowth.
- The OMEN toolkit can be used to produce simple lookup tables for ready estimation of the biomass and nutrient composition of different tree size classes. It should be further refined through incorporation of biomass and tree measurement data from other studies.
- Ash return to sites is one way of maintaining site nutrient capital. The ash could be recycled selectively to sites, for example targeting sandy sites with relatively low reserves and acidic soils which may benefit from the liming effect of ash.
- Supplementary fertilizer application, particularly N and P, will be required to sustain high growth rates over several harvesting cycles.
- Knowledge of whether growth of oil mallee will respond to nutrient application on some sites is not available. Establishment of small trials is warranted to develop guidelines to help growers in targeting sites for ash recycling and fertilizer application.
- There is a need to define the size of the deep soil nutrient store and the scope for modification of the adjacent annual plant agriculture to better complement the tree crop by greater input of N from legumes or fertiliser.

1. Introduction

Broad-scale planting of woody perennials that are effectively integrated into farming systems is an essential strategy to reduce ground-water recharge and help mitigate the dryland salinity that is increasingly affecting agricultural landscapes in WA (State Salinity Council, 2000) and other regions of Australia. It is also recognised that revegetation at the scale necessary to manage this land degradation will need to be a commercially driven activity (Bartle, 1999; State Salinity Council, 2000). Increasing efforts are being made to assess the potential of a range of tree species and products for development of viable industries that will form the basis for broad-scale planting of tree crops on farmland in the low–medium rainfall zone (Bartle, 2001). The planting of oil mallee integrated into farming systems in low-medium rainfall areas is showing promise for developing into a viable industry that will meet the primary objectives of revegetation.

Following early research identifying the potential for production of leaf oils from mallee eucalypts in WA (Barton, 2000), broad-scale planting of oil mallee on farmland commenced in the mid 1990's, and approximately 20 million trees have now been established around six regional centres in the WA wheatbelt. From an early stage it was recognised that the industry could not rely on oil production alone, but commercial prospects have greatly improved with the identification of multiple products (oil, bioenergy, activated charcoal), as well as the environmental (managing salinity, C sequestration) and social benefits (employment, income diversification). Formation of the Oil Mallee Association by growers and subsequent establishment of the Oil Mallee Company have greatly helped to advance the development and coordination of harvesting, processing and marketing (Bartle, 2001). Further impetus was given to the industry with a feasibility study (Enecon Pty Ltd, 2001) showing that integrated wood processing of mallee feedstock to produce eucalypt oil, activated charcoal and electricity is financially viable. The construction of an integrated processing plant at Narrogin is nearly complete.

High rates of mallee eucalypt growth are important in maximizing economic returns to farmers (Holt, 1998). Maintaining production over several harvest cycles will be crucial if oil mallees are to provide a commercially viable crop and an ecologically sustainable system for managing salinity. Early research into growing oil mallee in tree belts focussed on species comparison and selection, and on genetic improvement of seedling material (Eastham et al., 1993; Wildy et al., 2000; Bartle, 2001). Recent research has evaluated effects of season and frequency of harvesting on coppice regeneration and growth, and water use by oil mallee tree belts (Wildy et al., 2003). At this stage, there has been minimal research on the nutrition of oil mallee species, or of the impacts of mallee crops on soil fertility.

With the intensive harvesting system to be used for oil mallee, nutrient export with biomass removal over several harvesting cycles is likely to be significant. Nutrient depletion of soils through extraction of timber has been extensively studied in conventional forest industries because of concerns that it will lead to declining productivity (eg. Kimmins, 1977; Fölster and Khanna, 1997; Heilman and Norby, 1998). In natural eucalypt forest managed for sawlog production over long rotations, nutrient export rates are relatively low. Where harvesting is intensified in these forests (Raison et al., 1982) or in eucalypt plantations grown over short rotations (Wise and Pitman, 1981), nutrient removal is much greater, and nutrient replacement strategies are recommended to ensure sustainable long-term productivity. Nutrient depletion rates are further increased in short-rotation plantations where tree components other than stemwood are extracted or where rotation lengths are very short, requiring fertilizer application to maintain production (Heilman and Norby, 1998). This occurs in many countries where foliage and branches are used for fuel, oil extraction and green manuring of crops. The much higher nutrient removal rates for whole tree harvesting of short rotation tree crops compared with long rotation forests is related to higher average nutrient concentrations and to greater proportions of nutrients in canopy tissues of younger trees.

Short-rotation crops where harvest residues or whole trees are used for bioenergy represent an extreme in this sequence of harvesting intensity. Experience with short-rotation bioenergy tree crops in the northern hemisphere has illustrated the vulnerability of these systems to nutrient depletion and the necessity for nutrient replacement strategies (Heilman and Norby, 1998; Abrahamson et al., 1998; Adegbedi et al., 2001). Management of tree crop nutrient requirements and site fertility to ensure that these tree crop systems are sustainable has received considerable attention (Kimmins, 1997; Proe et al., 1997; Abrahamson et al., 1998). In addition to use of fertilizers to offset nutrient removal, there has been extensive research into the properties of biofuel ash and its effectiveness in recycling nutrients (Steenari and Lindqvist, 1997; Lundborg, 1998).

The frequent harvesting and removal of all above-ground tree components from oil mallee crops in south-western Australia is also expected to result in export of significant amounts of nutrients. Additionally, reduced fertilizer inputs and changes to the nature of organic residues added to soils in tree belts are likely to have an impact on soil fertility. These changes may be particularly significant on the wheat-belt soils, which are naturally infertile (McArthur, 1991). On the other hand these soils have been greatly improved in fertility by agricultural use and there is likely to have been considerable leaching of some nutrients to depth where the deep roots of mallee (depths >10 m have been reported by Robinson et al 2001) may be able to recover them. Recycling of ash from the processing plant may help in maintaining soil fertility, not only by returning some exported nutrients to sites but through the liming effect on surface soil (Khanna et al., 1994). Finally there is potential to modify the adjacent annual crop rotation to include a greater leguminous proportion to enhance the yield of the woody crop. In this study we have focussed on developing generic methods for quantifying the nutrient composition of oil mallee and evaluating potential nutrient export rates for different species in relation to site nutrient capital. This provides information on the potential for ash recycling and nutrient application to conserve site nutrient capital and prevent onset of nutrient deficiencies. This is an important first step in providing improved practices to manage the nutrition of mallee crops for optimum production.

2. Objectives

The project aims were to provide:

- Generic methods for low cost and rapid evaluation of the nutrient composition of oil mallee species across a range in soils and climate in the wheatbelt of Western Australia;
- Estimates of nutrient depletion rates from oil mallee sites under different biomass harvest scenarios, and their relationship to site nutrient capital; and
- Recommendations for nutrient replacement strategies to maintain soil nutrient supply and sustain production.

3. Methods

The project objectives were addressed by a series of studies within two experimental frameworks.

- A suite of 27 sites, representing 2 regions, 2 soil types within each region, 3 species, and a range of age-classes, where trees were sampled and used to develop and test allometric and nutrient content functions for use in estimating tree belt biomass and nutrient composition
- Four representative sites that were more intensively measured to estimate nutrient content of tree belts and potential export rates in relation to site nutrient capital.

The experimental program was conducted in two of the six regional centres where planting of oil mallee was originally concentrated. The two areas (around Narrogin and Kalannie) provided a contrast in growing conditions (rainfall, temperature and evaporation) for oil mallee.

3.1 Development and testing of allometric and nutrient content functions

The aim was to develop regression functions which relate dry weights and nutrient contents of tree components to stem and canopy dimension measurements as a means for estimating tree belt biomass and nutrient composition. This was achieved by sampling trees within a framework of sites that would provide information on key oil mallee species and the effects of site factors (region, soils) on predictive functions. The main sampling program focussed on tree belts of uncut (1st rotation) saplings, where it was possible to obtain sites covering the range of soil types and age classes required.

3.1.1 Site selection and stratification

Within each region a series of sites was selected to provide for sampling of two species on contrasting soils (low fertility sandy soils and higher fertility heavier textured soils). One mallee species (*E. loxophleba* ssp. *lissophloia*) was sampled on both soil types in each region. The other species sampled were *E. kochii* ssp. *plenissima* at Kalannie and the *E. polybractea* at Narrogin. Within this stratification of sites (2 regions x 2 species per region x 2 soil types), the development of predictive functions for broad-scale application also required sampling of trees across different age categories. Trees were sampled from only one site in each age class, although more sites were initially chosen to allow for screening and selection of well-matched sites.

Information collected for each of the 53 sites initially selected included: location (with GPS coordinates), species, planting year, tree health/form/height range, tree-belt configuration, site slope/aspect/landscape position and soil type. Two bulk surface soil samples and a subsoil sample were collected at each site for analysis (pH, electrical conductivity, Bray-extractable P). Based on the initial chemical data 12 sites were rejected, primarily due to unacceptably high electrical conductivity (salinity). Further sites were culled on the basis of comparisons of physical and morphological soil properties. The location and properties of the sites finally selected for tree sampling are listed in Table 1. Site locations are shown in Figure 1.

3.1.2 Tree measurement, sampling and chemical analysis

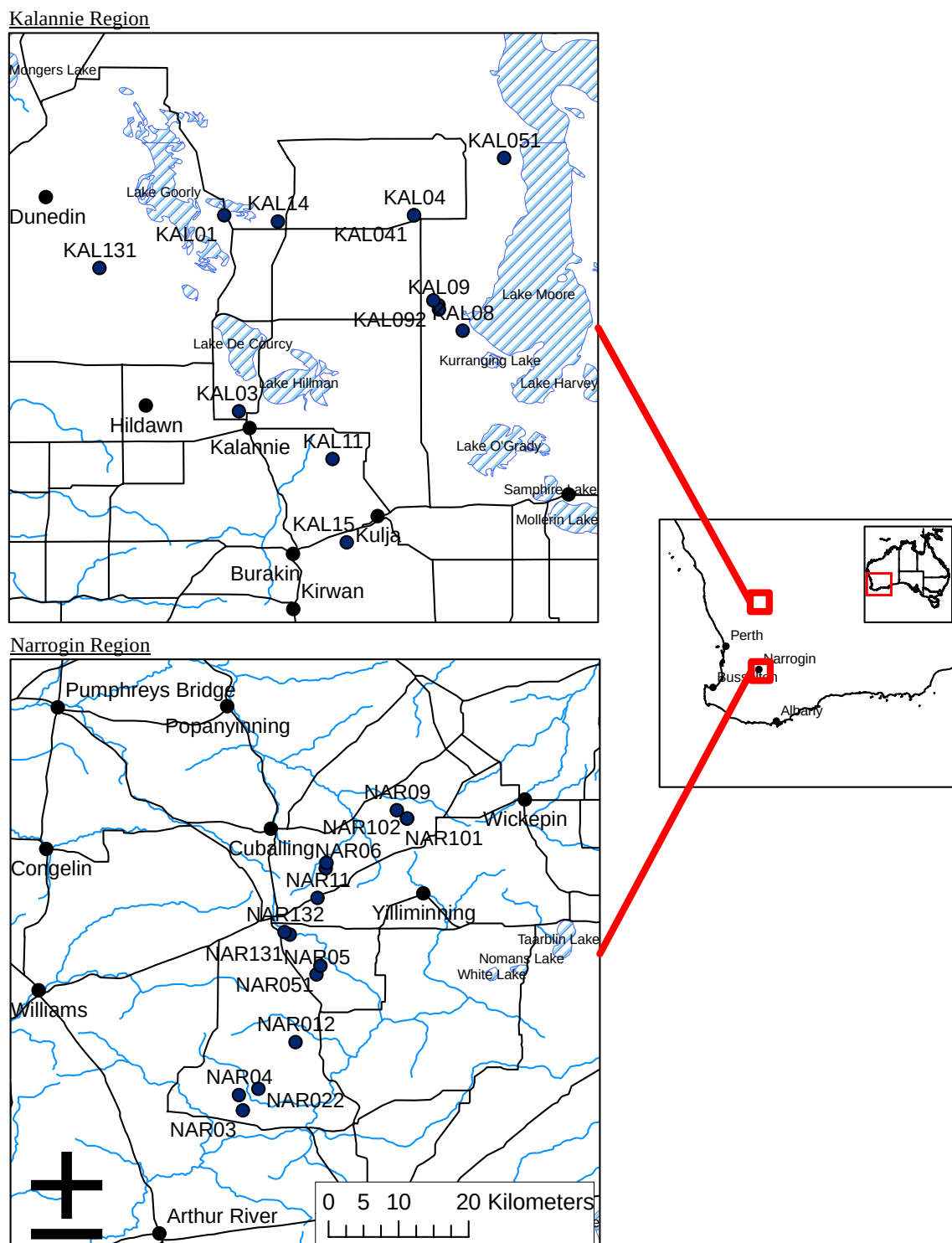
Trees were sampled from 27 sites that were chosen as being the most representative and within the matrix from among the 53 sites originally screened. The number and range in age of trees sampled for each of the 8 site categories are shown in Table 2. The range in tree age was achieved by sampling trees from 3 or 4 sites in each species and site category. Trees were selected at each site to provide a range in sizes that allowed for overlap across sites and therefore between age classes. Measurement,

sampling and processing of trees extended over the period from June to October 2003.

Table 1. Location, species, soil fertility class, soil texture, pH and electrical conductivity for 27 sites selected for tree sampling.

Region	Species	Fertility	Site code	Age (yr) when sampled	Latitude (decimal)	Longitude (decimal)	Surface field texture	pH surface soil	pH sub- surface soil	EC – surface soil (μS cm ⁻¹)	EC – sub- surface soil (μS cm ⁻¹)
<u>Kalannie</u>											
	<i>E. loxophleba</i> ssp. <i>lissophloia</i>	Lower	KAL11	2	-30.41	117.23	Sandy loam	5.51	4.13	87	61
			KAL08	5	-30.24	117.39	Sandy loam	5.63	4.19	86	110
			KAL03	10	-30.34	117.11	Loamy sand	5.14	4.48	57	29
		Higher	KAL14	2	-30.10	117.16	na	na	na	136	217
			KAL051	4	-30.02	117.45	Sandy loam	6.28	9.32	139	392
			KAL091	7	-30.21	117.36	Sandy loam	6.08	7.66	374	629
	<i>E. kochii</i>	Lower	KAL041	1	-30.09	117.33	Sandy loam	4.8	4.01	78	52
			KAL04	3	-30.09	117.33	Sandy loam	4.8	4.01	78	52
			KAL131	4	-30.16	116.93	na	na	na	100	24
			KAL092	7	-30.20	117.35	Sandy loam	4.59	4.93	940	525
		Higher	KAL01	2	-30.09	117.09	Sandy clay loam	5.59	8.08	122	77
			KAL15	4	-30.51	117.24	na	na	na	na	na
			KAL09	7	-30.21	117.36	Sandy clay loam	5.96	8.46	353	1090
<u>Narrogin</u>											
	<i>E. loxophleba</i> ssp. <i>lissophloia</i>	Lower	NAR05	1	-33.01	117.24	Loamy sand	5.51	7.32	149	62
			NAR131	2	-32.95	117.20	Sandy loam	5.27	6.29	126	55
			NAR09	4	-32.80	117.34	Loamy sand	5.07	6.26	58	258
			NAR012	6	-33.09	117.21	Loamy sand	5.73	5.79	65	74
		Higher	NAR051	1	-32.99	117.24	Sandy loam (gravelly)	5.96	7.2	139	59
			NAR132	2	-32.95	117.20	Sandy loam	5.23	7.03	283	67
			NAR101	4	-32.81	117.35	Sandy loam	5.82	6.69	117	83
			NAR11	5	-32.91	117.24	Sandy loam	5.97	6.65	105	351
	<i>E. polybractea</i>	Lower	NAR022	2	-33.15	117.16	Loamy sand	5.66	6.95	32	20
			NAR04	3	-33.16	117.14	Sandy loam	5.72	6.88	68	35
			NAR061	8	-32.86	117.25	Sand	5.52	5.72	32	11
		Higher	NAR03	1	-33.18	117.14	Light sandy loam	5.55	6.79	116	63
			NAR102	4	-32.81	117.35	Sandy loam	5.82	6.69	117	83
			NAR06	8	-32.87	117.25	Sandy loam	5.84	7.13	39	35

Figure 1. Location of sites where trees were sampled in the Kalannie and Narrogin regions. Sites are identified by codes (see Table 1)



The whole top of trees was harvested, except for some larger trees that were multi-stemmed. In these cases, one representative stem was measured and sampled, and remaining stems and their canopies were also measured to allow scaling up for whole tree biomass and nutrient content. Measurements taken prior to the harvesting tree stems included: stem diameters near the base (height above ground recorded) and at the crown base; heights of the tree and crown base, and crown width (along and across tree rows). A photographic record has been kept of each sampled tree. Harvested trees were sealed in plastic bags, returned to the laboratory, and stored at 4°C until sorted. Trees were partitioned into a maximum of seven fractions. Stem, branch and twig sizes were designated according to categories representative of the major classes of feedstock likely to be generated at the integrated processing plant at Narrogin, namely: larger piece sizes providing chips for activated carbon; leaf and twigs (branches <5 mm) for oil extraction; residues for bioenergy. On this basis the seven categories were stems > 20 mm diam. (further divided into wood and bark), branches 5-20 mm diam., twigs <5 mm diam., leaves, fruit (nuts and buds) and dead material (branches and bark). Sub-sampling strategies were employed for larger trees. Some of the youngest trees did not have a larger (>20 mm) stem component. In all 139 trees were harvested.

Table 2. Number and age of trees sampled

Region/Soil	Species	Number of trees/stems sampled	Age range (years)
Narrogin			
Low fertility	<i>E. loxophleba</i> ssp. <i>lissophloia</i>	20	1-6
	<i>E. polybractea</i>	16	2-8
High fertility	<i>E. loxophleba</i> ssp. <i>lissophloia</i>	20	1-5
	<i>E. polybractea</i>	15	1-8
Kalannie			
Low fertility	<i>E. loxophleba</i> ssp. <i>lissophloia</i>	17	2-10
	<i>E. kochii</i> ssp. <i>plenissima</i>	21	1-7
High fertility	<i>E. loxophleba</i> ssp. <i>lissophloia</i>	16	2-7
	<i>E. kochii</i> ssp. <i>plenissima</i>	14	2-7

For each fraction, fresh weights were recorded, samples oven-dried to constant weight, dry weights determined and samples ground for nutrient analysis. Concentrations of N and P in each fraction were determined by auto-analysis following Kjeldahl digestion. Concentrations of K, Ca, Mg and Na were determined by atomic absorption spectrometry. Concentration and dry weight data were used to calculate nutrient contents of tree components.

3.1.3 Development and testing of predictive functions

Predictive functions were developed for use in estimating tree-belt biomass and nutrient composition from non-destructive tree measurements. Due to the extensive data set generated, with several tree dimension measurements and dry weight and nutrient content parameters for each tree categorized by species, regions and soils, there was scope to evaluate a large number of alternative regression models. Initially a range of minimal-parameter multiple regression models were evaluated with different subsets of the data. Although this approach of incorporating only significant factor terms is more statistically valid, it was impracticable to develop a predictive capability based on a range of mixed models.

More comprehensive models were therefore tested that incorporated all species and site factors and the interactions among factors. The aim was to develop generic models for each of the nutrients and tree components that take account of effects of soil fertility, region and species. Comprehensive

regression models were developed for individual plant fractions and also for combined categories, namely total stems (stem-wood + stem-bark + branches >5mm diam.), canopy (leaf + fruit + twig), and the total of all aboveground components. The span in age of trees sampled means that regression functions cover the range of tree sizes that will be harvested operationally. Both the dependent (biomass, nutrient contents) and independent (tree dimension measurements) variables were transformed to the logarithmic scale for regression analysis due to the distribution of data values and to heteroscedasticity.

Two types of regression models were developed to explain variation in biomass and nutrient contents, one based on single stem dimension measurements (base diameter and height) and the other on whole-tree dimension measurements (primarily canopy width and tree height). The former relies on measurements of individual stems arising from the base of each tree and the primary independent variable was nominally termed the stem conical volume (calculated from diameter at the base and stem length or height). The model incorporates terms for species, region and soil fertility factors and all second order interactions among these factors.

The whole-tree model requires fewer dimension measurements for multi-stemmed trees and would be better suited for some applications such as rapid broad-scale assessments of tree belt composition prior to harvesting. For this model the primary independent variable was termed the tree cubic volume (TCV; product of tree height and maximum canopy width along and across rows), but height to crown base and numbers of stems per tree improved the model fit in a number of cases and were included in the full model. The model also incorporates terms for species, region and fertility factors and second order interactions among factors.

The goodness of fit of models was only evaluated internally by plotting observed against fitted values for the various tree fractions and for biomass and each of the nutrients. Model predictions were further tested by plotting the predicted values for whole top biomass or nutrient content against the sums of predicted values for individual tree fractions. A third internal test involved comparing model predictions from the single-stem model with those from the whole-tree model.

3.1.4 Toolkit development

A large set of model parameters were generated as a result of the stratified tree sampling across species, location and fertility status and the measurements of dry weight and nutrient contents for several tree components. Due to the complexity of this parameter set, it was difficult to apply manually for estimating belt-level biomass and nutrient content. A computational tool was therefore developed, based on an excel spreadsheet, which provides a ready means of calculating amounts of biomass and nutrients in tree belts expressed on both an areal or belt length basis for nominated species, soil fertility category, location and tree component. This calculation toolkit has been provisionally called OMEN (Oil Mallee Estimator of Nutrients). Input data can be either individual stem (height, diameter) or whole tree canopy (canopy width along and across rows, tree and crown base heights and number of stems) dimension measurements. These calculations can easily be applied to a block of dimension data for any number of trees in measured plots or lengths of belts, but requires entry of the number of rows in a belt and the number and length of belts measured.

3.1.5 Use of functions to predict coppice regrowth biomass and nutrient content

All regression models were developed from uncut saplings. The potential to use these relationships for estimating biomass and nutrient content of belts of coppice regrowth was assessed at one site. Tree stems were measured and sampled from 3-year old *E. kochii* ssp. *plenissima* coppice at a low fertility sandy site near Kalannie. The diameter and height of an inner and an outer dominant stem from each of four trees were measured. Each stem was harvested and separated into components according to the protocol previously used for saplings. Dry weights and nutrient contents of individual fractions were determined as described previously. All remaining stems (22 to 27 per tree) were individually

measured, harvested and dry weights recorded. Weights of whole tops of all individual stems and the component weights and nutrient contents of the selected inner and outer stems were compared with predicted values using the regression functions appropriate to the species, location and fertility status of the site.

3.2 Tree belt biomass and nutrient composition at four sites

The aim of this phase of the project was to apply the derived regression functions to estimate the biomass and nutrient content of tree belts at representative sites in the Kalannie and Narrogin regions and to evaluate tree belt nutrient contents in relation to soil stores of nutrients. The allocation of biomass and nutrients among major tree components was determined and effects of varying tree size (or tree belt age) on this allocation and on potential export rates from sites was evaluated. Differences in concentrations of total and labile nutrients between surface soils under tree belts and in adjacent alley zones were also assessed.

3.2.1 Sites and tree belt measurements

An average of 30 trees was measured in each of four replicate plots at four sites. Details of site locations and characteristics of soils and tree belts are given in Table 3.

Table 3. Location and properties of sites and tree belts for estimation of above-ground biomass and nutrients and stores of nutrients in soils.

Region	Species	Fertility	Short description	Age (yr) measured	Rows in tree belt	Soil [†]	Surface field texture
<u>Kalannie</u>							
	<i>E. loxophleba</i> ssp. <i>lissophloia</i>	High	Rolinson - red soil S of house	5	10	Red Kandosol	Sandy loam
	<i>E. kochii</i> ssp. <i>plenissima</i>	Low	Rolinson - Wodgil soil SE of house	3	6	Yellow Kandosol	Loamy sand
<u>Narrogin</u>							
	<i>E. polybractea</i>	High	Hesford - S of house	5	4	Red Kandosol	Sandy loam
	<i>E. loxophleba</i> ssp. <i>lissophloia</i>	Low	Hesford - W of house	4	6	Grey Chromosol	Sand to loamy sand

[†] Australian Soil Classification (Isbell, 1996)

The 4 replicate plots at each site were located at distances of >50m apart in 1 or 2 tree belts on comparable soils. Plots were 18m long by 3 or 4 tree rows wide, and stem and canopy dimensions required for model predictions were measured on each trees in each plot. Biomass and nutrient content of tree components and whole trees were calculated using the regression model parameters matching the specific site characteristics (ie. species, fertility, location factors). Biomass and nutrient contents were expressed on both an areal (kg ha⁻¹) and a length of row (kg m⁻¹) basis.

Nutrient contents of tree belts were compared to soil stores of nutrients to 2 m (see below) to provide an indication of the significance of repeated export of nutrients in harvested biomass in depleting site

nutrient capital. We also explored the impacts of harvesting at an earlier or later stage of tree belt growth, not only on the amounts of nutrients potentially exported with biomass removal but also the distribution of nutrients between canopy and stem components. It is the canopy fraction that is likely to be the major source of nutrients that can be returned to oil mallee sites in ash following processing at the integrated plant. Relationships of volume growth or biomass to stand age were not well defined in this study. Scenarios with varying tree size were therefore evaluated rather than varying tree belt age.

3.2.2 Soil nutrient stores

In each replicate plot at each site a soil pit was dug to 2 m depth between the outer 2 tree rows. The morphological characteristics of soils down the profiles were described (Appendix 1) and soils classified according to the Australian Soil Classification (Isbell, 1996). Soils were sampled over the 0-10, 10-20, 20-40, 40-70, 70-100, 100-150 and 150-200 cm depth intervals in each soil pit. Cores were taken vertically over each depth range to 40 cm depth, and then horizontally into the side of the pit at the mid-point of each of the lower depth ranges. Samples were taken with 5 or 7cm thin-walled tubing of known lengths to determine soil bulk density, which was required to calculate nutrient quantities from concentration data. Two duplicate soil cores were sampled about 30 cm apart at each depth and bulked.

Soils were air dried, passed through a 2mm sieve and the <2 and >2 mm fractions weighed. The <2 mm fraction was analysed to determine pH and concentrations of total C, N and P, Bray-extractable P and exchangeable K, Ca, Mg and Na. Soil pH was measured in a water suspension (1:5 soil:solution) after shaking for 1 h at 20°C. Total C was determined on a Leco analyser and total N and P using colorimetric procedures following digestion of soil in H₂SO₄/H₂O₂ at 360°C. Exchangeable K, Ca, Mg and Na were extracted by shaking 5 g soil in 100 mL 1M NH₄Cl for 1 h at 20°C and filtering of extracts. Concentrations of Ca and Mg in the filtrate were determined by atomic absorption spectrometry and K and Na by flame emission spectrometry. For Bray P, P was extracted with 0.03M NH₄F in 0.025M HCl using a 1:50 soil: solution ratio and a 5 minute shaking time (modified from Bray and Kurtz, 1945). Concentrations of P in filtered extracts were determined with a UV-Visible Spectrophotometer based on the method of Murphy and Riley (1962). Amounts of nutrients in each depth range and for the total soil profile to 2 m were calculated from concentrations in the <2mm fraction, gravel content and the bulk density of soils.

3.2.3 Nutrient properties in surface soils

In addition to determining nutrient stores in the soil profile, concentrations of total and labile nutrients were determined in surface 0-10 cm soils from within the tree belts and in adjacent agricultural alley areas. This was to provide an indication of whether the change in land-use and management of these soils in tree-belts were having impacts on the concentrations of soil C and concentrations of total and labile forms of nutrients in surface soils.

At each replicate plot at each site, bulked samples consisting of eight 0-10 cm soil cores were obtained from within the tree belts (undisturbed areas between the outer 3 tree rows) and from the alley 5 to 10 m away from the tree belt. The moist soils were kept chilled, sieved and a sub-sample of the <5mm fraction analysed for potentially mineralizable nitrogen. The procedure involved incubating 20 g of moist soil with 30mL of distilled H₂O for 7 days at 40°C (Keeney and Bremner, 1966). Ammonium was extracted by shaking for 1 hour after adding 30 mL 2M KCl. Potentially mineralizable N was calculated from the difference in ammonium content of pre- and post-incubated samples.

The remaining <5 mm soil fraction was air-dried, sieved and the <2 mm fraction analysed to determine pH and concentrations of total C, N and P, Bray-extractable P and exchangeable K, Ca, Mg and Na. The methods used are the same as those described previously for profile samples.

The significance of differences in soil properties between tree belt and alley soils were determined by analysis of variance using the statistical package Genstat (Rothamstead Experimental Station).

4. Results

4.1 Regression functions to estimate biomass and nutrient composition

4.1.1 Dry matter and nutrient concentrations in sample trees

The total above-ground biomass of sampled tree stems ranged up to 24 kg for both 5 year-old *E. loxophleba* ssp. *lissophloia* and 8 year-old *E. polybractea* growing on higher fertility sites at Narrogin. At Kalannie, total biomass ranged up to 18 kg for 7 year-old *E. kochii* ssp. *plenissima* and 33 kg for 10 year-old *E. loxophleba* ssp. *lissophloia*, both on lower fertility sites.

Concentrations of N and K in the different tree tissues varied less between species than for the other nutrients (Table 4). Concentrations of P were generally higher in *E. polybractea* than in the other two species. Tree to tree variability in nutrient concentrations indicated by coefficients of variation, was lowest for N and K and high for Ca, particularly in stem wood. Gradients in concentrations between tree components also differed markedly between nutrients. Largest differences in concentrations were for N, with 8- to 14-fold higher concentrations in foliage than in stem wood. In contrast, there were 4- to 5-fold differences for K and smaller differences for Ca and Mg. Concentrations of Ca were highest in bark, ranging from 2.5% to 3.6%.

Table 4. Nutrient concentrations in different tissues of the three oil mallee species. Values are the means for all sample trees of the specified age range, and coefficients of variation for each mean are shown in italics.

Species & location	Tree component		N	P	Na	K	Mg	Ca
			%	%	%	%	%	%
<i>E. polybractea</i> Narrogin 3-4yr	Leaf	Mean	1.66	0.105	0.59	0.52	0.16	1.09
		CV (%)	6	30	22	11	45	51
	Twig	Mean	0.43	0.051	0.24	0.33	0.13	1.00
		CV (%)	13	21	25	18	36	39
	Stem-wood	Mean	0.16	0.014	0.07	0.12	0.03	0.31
		CV (%)	14	24	62	16	22	77
	Stembark	Mean	0.53	0.035	0.19	0.29	0.19	2.92
		CV (%)	82	14	27	29	28	31
<i>E. kochii</i> ssp. <i>plenissima</i> Kalannie 3-7yr	Leaf	Mean	1.54	0.071	0.36	0.45	0.26	0.92
		CV (%)	18	29	17	16	26	29
	Twig	Mean	0.50	0.046	0.20	0.26	0.18	1.65
		CV (%)	22	77	39	31	27	59
	Stem-wood	Mean	0.19	0.013	0.04	0.12	0.05	0.67
		CV (%)	37	70	53	14	38	126
	Stem-bark	Mean	0.32	0.021	0.27	0.22	0.20	2.92
		CV (%)	14	22	18	36	21	53
<i>E. loxophleba</i> ssp. <i>lissophloia</i> Narrogin 4 yr	Leaf	Mean	1.53	0.085	0.60	0.49	0.13	0.70
		CV (%)	5	17	15	15	26	22
	Twig	Mean	0.50	0.059	0.33	0.50	0.09	0.69
		CV (%)	8	30	20	18	30	18
	Stem-wood	Mean	0.15	0.013	0.06	0.11	0.04	0.24
		CV (%)	17	35	16	22	30	74
	Stem-bark	Mean	0.38	0.033	0.25	0.20	0.11	2.46
		CV (%)	11	13	22	16	24	35
<i>E. loxophleba</i> ssp. <i>lissophloia</i> Kalannie 4-5yr	Leaf	Mean	1.74	0.093	0.45	0.47	0.22	1.05
		CV (%)	14	23	27	15	28	34
	Twig	Mean	0.43	0.041	0.29	0.35	0.15	2.30
		CV (%)	11	46	45	18	19	48
	Stem-wood	Mean	0.12	0.011	0.02	0.10	0.05	0.46
		CV (%)	14	46	30	19	37	103
	Stem-bark	Mean	0.33	0.024	0.15	0.19	0.13	3.64
		CV (%)	17	16	31	22	28	25

4.1.2 Regression functions

(a) Single stem regressions based on stem dimension measurements

The single regression model that was fitted to the 139 tree data set (encompassing species, region and fertility status) contained 11 variable and factor terms (Tables 5, 6). The model includes second order interactions among factors, except between region and species, even though for some tree fractions and individual biomass/nutrient parameters a number of factor terms and interactions were not significant.

The percentages of the variance accounted for by the model and the significance of differences among species, site factors and interactions between factors, are summarized for the biomass and nutrient content of individual and combined tree components in Table 5 and 6. Functions for biomass and nutrient contents of combined tree components (canopy, stems, total aboveground) explained a higher proportion of the variance than models for each of the five individual tree fractions. The fitted regression functions for total aboveground amounts accounted for between 95.7% (Na) and 99% (dry weight) of the variance across 139 trees. Functions for the branch (5-20mm) fraction were the least well defined with the percentage of variation accounted ranging from 88.6% for Na to 93% for dry weight. With all individual and combined tree components the goodness of fit of functions was always highest for dry weight, and better for N and K than for other nutrients.

There are lower numbers of significant factor terms in models describing variation in stem weight and nutrient content, than for models developed for canopy components and whole tops (Tables 5, 6). This is particularly so for the dry weight of the combined stem component, where there is no effect of fertility or region and only a significant difference among species in the slope of the relationship between dry weight and conical volume.

In general, there are highly significant effects of soil fertility on the dry weight and N, P, K, Ca, and Na contents of individual canopy (leaf, twig) fractions but not in stem wood and bark components. The Mg composition of individual tree components is not affected by soil fertility, except for stem-wood. These effects are consistent with the functions developed for combined canopy and stem fractions, where soil fertility affects nutrient composition of canopy but not stems. These effects on the tree canopy are large enough to result in highly significant differences between low and high fertility soils in the N and K content of whole trees and a less significant effect for P.

Regional differences are also highly significant for dry weight and nutrient composition of canopy components. Effects on the composition of stems are restricted to P, K and Na. Despite these differences in tree nutrient content between the two regions, there is no effect of region on total aboveground biomass, where the model accounts for 99% of the variance (Table 6). Overall, the effects of site factors (fertility, region) on canopy mass and nutrient composition is much greater than effects on stem and larger branch components of trees.

There are also marked differences between species in the relationships for biomass and nutrient content. In contrast to the fertility and regional effects, species differences are commonly associated with significant interactions with stem conical volume, meaning that the slopes of the relationships differ among species. With canopy components and whole tops, differences among species were generally more significant for P, Ca, Mg and Na than for N and K.

Table 5. Probabilities for the effects of factors and factor interactions in single stem regression functions which account for variation in biomass (DW) and nutrient contents of individual above-ground tree components in relation to stem conical volume. Significant factors and factor interactions are indicated by shaded cells. The percentage of the variance accounted for by the full model for biomass and nutrients is shown in italics.

Tree component & model parameter	DW	N	P	K	Ca	Mg	Na
<u>Leaf</u>							
+Stem volume	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	<.001	<.001	0.012	<.001	0.043	0.071	0.001
+Species	0.072	0.32	<.001	0.749	0.02	<.001	<.001
+Region	<.001	0.004	<.001	<.001	0.194	0.04	<.001
+Stem vol. x Fertility	0.471	0.197	0.647	0.301	0.171	0.071	0.055
+Stem vol. x Species	0.002	0.003	0.295	0.007	0.703	0.01	<.001
+Stem vol. x Region	0.711	0.785	0.253	0.747	0.795	0.375	0.721
+Fertility x Species	0.901	0.927	0.756	0.956	0.314	0.174	0.344
+Fertility x Species x Stem vol.	<.001	<.001	0.171	<.001	<.001	<.001	0.057
+Fertility x Region	0.44	0.423	0.018	0.081	0.552	0.293	0.397
+Fertility x Region x Stem vol.	0.625	0.24	0.97	0.325	0.667	0.355	0.182
<i>% of variance accounted</i>	95.8	95.2	94.4	94.5	94.3	93.2	92.5
<u>Twigs (branch < 5mm)</u>							
+Stem volume	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.001	<.001	0.001	<.001	0.048	0.09	0.019
+Species	0.002	0.067	0.028	0.018	<.001	<.001	<.001
+Region	0.852	0.092	<.001	0.003	<.001	0.549	0.518
+Stem vol. x Fertility	0.028	0.09	0.058	0.286	0.001	0.015	0.425
+Stem vol. x Species	0.22	0.601	0.094	0.665	0.259	0.008	0.273
+Stem vol. x Region	0.006	0.068	0.095	0.036	0.111	0.222	0.101
+Fertility x Species	0.815	0.1	0.006	0.974	0.242	0.192	0.38
+Fertility x Species x Stem vol.	<.001	0.02	0.957	0.157	0.004	<.001	0.177
+Fertility x Region	0.38	0.122	<.001	0.002	0.889	0.021	0.279
+Fertility x Region x Stem vol.	0.42	0.885	0.067	0.638	0.269	<.001	0.982
<i>% of variance accounted</i>	96.7	95.8	92.5	94.8	92.9	94.4	92.7
<u>Branch 5-20mm</u>							
+Stem volume	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.341	0.101	0.014	0.017	0.317	0.212	0.317
+Species	0.524	0.348	0.179	0.287	0.213	<.001	0.017
+Region	0.207	0.052	<.001	0.001	0.096	0.075	0.045
+Stem vol. x Fertility	0.241	0.366	0.802	0.963	0.92	0.209	0.835
+Stem vol. x Species	<.001	<.001	0.003	<.001	0.007	<.001	<.001
+Stem vol. x Region	0.181	0.508	0.905	0.266	0.245	0.568	0.425
+Fertility x Species	0.856	0.692	0.449	0.736	0.785	0.707	0.628
+Fertility x Species x Stem vol.	0.118	0.366	0.686	0.103	<.001	0.034	0.55
+Fertility x Region	0.987	0.767	0.046	0.111	0.587	0.157	0.957
+Fertility x Region x Stem vol.	0.168	0.541	0.17	0.272	0.359	0.01	0.921
<i>% of variance accounted</i>	93	92.2	90.2	92.4	89.2	90	88.6
<u>Stem bark</u>							
+Stem volume	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.364	0.761	0.932	0.734	0.714	0.337	0.33
+Species	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Region	0.517	0.739	0.005	0.759	0.074	0.288	0.046
+Stem vol. x Fertility	0.926	0.676	0.838	0.78	0.453	0.162	0.689
+Stem vol. x Species	0.94	0.857	0.982	0.873	0.422	0.593	0.83
+Stem vol. x Region	<.001	0.003	0.003	0.001	0.005	0.013	0.101
+Fertility x Species	0.141	0.137	0.185	0.819	0.326	0.043	0.127
+Fertility x Species x Stem vol.	0.295	0.597	0.387	0.18	0.537	0.954	0.037
+Fertility x Region	0.656	0.882	0.141	0.216	0.574	0.051	0.467
+Fertility x Region x Stem vol.	0.068	0.257	0.133	0.014	0.016	0.027	0.316
<i>% of variance accounted</i>	95.5	95.4	95.1	95.2	94.6	91.5	92.8
<u>Stem wood</u>							
+Stem volume	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.857	0.829	0.856	0.449	0.912	0.006	0.535
+Species	0.013	<.001	0.005	0.223	0.008	<.001	0.933
+Region	0.011	0.918	0.007	0.92	0.008	0.783	<.001
+Stem vol. x Fertility	0.902	0.772	0.841	0.465	0.957	0.546	0.451
+Stem vol. x Species	0.623	0.645	0.889	0.743	0.033	0.673	0.522
+Stem vol. x Region	<.001	0.043	0.113	0.058	0.901	0.161	0.092
+Fertility x Species	0.543	0.125	0.442	0.704	0.037	0.158	0.377
+Fertility x Species x Stem vol.	0.643	0.961	0.619	0.452	0.453	0.898	0.413
+Fertility x Region	0.69	0.591	0.062	0.127	0.779	0.498	0.745
+Fertility x Region x Stem vol.	0.043	0.861	0.386	0.039	0.047	0.378	0.966
<i>% of variance accounted</i>	97.1	96	91.7	95.9	89.4	94.2	93

Table 6. Probabilities for the effects of factors and factor interactions in single stem regression functions which account for variation in biomass (DW) and nutrient contents of combined above-ground tree components in relation to stem conical volume. Significant factors and factor interactions are indicated by shaded cells. The percentage of the variance accounted for by the full model for biomass and nutrients is shown in italics.

Tree component & model parameter	DW	N	P	K	Ca	Mg	Na
<u>Canopy (leaves + twigs + fruit)</u>							
+Stem volume	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	<.001	<.001	0.011	<.001	0.041	0.09	0.001
+Species	0.015	0.26	0.003	0.74	<.001	<.001	<.001
+Region	<.001	<.001	<.001	<.001	<.001	0.007	<.001
+Stem vol. x Fertility	0.25	0.15	0.40	0.24	0.011	0.044	0.07
+Stem vol. x Species	0.005	0.005	0.67	0.031	0.53	0.005	<.001
+Stem vol. x Region	0.18	0.60	0.09	0.20	0.54	0.65	0.53
+Fertility x Species	0.77	0.73	0.34	0.89	0.23	0.18	0.28
+Fertility x Species x Stem vol.	<.001	<.001	0.29	<.001	<.001	<.001	0.022
+Fertility x Region	0.47	0.44	0.005	0.031	0.73	0.20	0.38
+Fertility x Region x Stem vol.	0.80	0.41	0.52	0.76	0.35	0.06	0.34
<i>% of variance accounted</i>	<i>97.1</i>	<i>96.1</i>	<i>95.3</i>	<i>95.8</i>	<i>95.8</i>	<i>94.9</i>	<i>94.2</i>
<u>Stems (wood + bark + branches >5mm diam.)</u>							
+Stem volume	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.55	0.69	0.18	0.24	0.76	0.43	0.66
+Species	0.20	0.008	0.006	0.98	0.01	<.001	<.001
+Region	0.82	0.11	<.001	0.012	0.50	0.05	<.001
+Stem vol. x Fertility	0.24	0.47	0.38	0.66	0.79	0.19	0.51
+Stem vol. x Species	<.001	<.001	0.13	<.001	0.008	<.001	<.001
+Stem vol. x Region	0.56	0.96	0.27	0.95	0.041	0.39	0.30
+Fertility x Species	0.95	0.51	0.42	0.48	0.97	0.61	0.85
+Fertility x Species x Stem vol.	0.28	0.63	0.91	0.19	0.004	0.12	0.41
+Fertility x Region	0.44	0.71	0.09	0.11	0.55	0.48	0.81
+Fertility x Region x Stem vol.	0.11	0.63	0.18	0.15	0.27	0.049	0.99
<i>% of variance accounted</i>	<i>97.6</i>	<i>96.8</i>	<i>95.3</i>	<i>97.0</i>	<i>95.2</i>	<i>95.5</i>	<i>95.0</i>
<u>Whole top</u>							
+Stem volume	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.055	<.001	0.021	<.001	0.384	0.126	0.003
+Species	<.001	0.021	0.006	0.989	<.001	<.001	<.001
+Region	0.157	<.001	<.001	<.001	<.001	0.009	<.001
+Stem vol. x Fertility	0.91	0.37	0.746	0.673	0.194	0.096	0.139
+Stem vol. x Species	0.553	0.012	0.915	0.027	0.222	0.016	<.001
+Stem vol. x Region	0.711	0.933	0.323	0.676	0.275	0.225	0.749
+Fertility x Species	0.667	0.623	0.308	0.681	0.69	0.17	0.348
+Fertility x Species x Stem vol.	<.001	<.001	0.425	0.004	<.001	<.001	0.044
+Fertility x Region	0.758	0.596	0.004	0.023	0.734	0.206	0.483
+Fertility x Region x Stem vol.	0.842	0.191	0.627	0.74	0.448	0.089	0.195
<i>% of variance accounted</i>	<i>99.0</i>	<i>97.4</i>	<i>96.7</i>	<i>97.4</i>	<i>97.9</i>	<i>97.0</i>	<i>95.7</i>

(b) Whole tree regressions based on canopy volume measurements

Functions relating biomass and nutrient content of tree components to more readily obtained whole-tree dimension measurements accounted for a high proportion of the variance across the full data set (Tables 7, 8). Comparison of these whole tree models with the single stem regressions shows that there are some marked differences in the significance of model factors and the proportions of the variance accounted for by the models. In general the regressions for canopy components (leaves, twigs, leaf+twig+fruit) based on whole tree measurements are comparable to those for single stem measurements in terms of the percentage of the variance that is explained. This percentage ranges from 92.6% (Mg) to ≥96% (dry weight, N) for leaves, 91.1% (Ca) to >96% (dry weight, N) for twigs and 93.7% (Mg) to 97% for the combined leaf and twig fraction.

Table 7. Probabilities for the effects of factors and factor interactions in whole-tree regression functions which account for variation in biomass (DW) and nutrient contents of individual above-ground tree components in relation to tree cubic volume. Significant factors and factor interactions are indicated by shaded cells. The percentage of the variance accounted for by the full model for biomass and nutrients is shown in italics.

Tree component & model parameter	DW	N	P	K	Ca	Mg	Na
Leaf							
+Tree cubic volume (TCV)	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.963	0.581	0.107	0.494	0.359	0.114	0.463
+Species	<.001	<.001	0.039	<.001	<.001	<.001	0.859
+Region	0.439	0.741	0.307	0.193	0.003	0.327	0.04
+TCV x Fertility	0.006	0.002	0.015	0.014	0.004	0.012	<.001
+TCV x Species	0.05	0.071	0.845	0.086	0.758	0.566	<.001
+TCV x Region	0.392	0.286	0.002	0.213	0.504	0.914	0.253
+Stemnumber	0.051	0.042	0.017	0.121	0.148	0.038	0.219
+TCV x Stemnumber	0.345	0.63	0.236	0.77	0.567	0.563	0.978
+Ht.crown-base	0.396	0.483	0.628	0.369	0.913	0.107	0.028
+TCV x Ht.crown-base	0.682	0.87	0.034	0.462	0.317	0.748	0.244
+Fertility x Species	0.269	0.105	0.031	0.095	0.002	0.003	0.865
+Fertility x Species x TCV	0.667	0.901	0.845	0.869	0.123	0.506	0.912
+Fertility x Region	0.44	0.243	0.868	0.866	0.026	0.885	0.535
+Fertility x Region x TCV	0.642	0.432	0.625	0.583	0.68	0.777	0.573
<i>% of variance accounted</i>	<i>96.4</i>	<i>96</i>	<i>94.8</i>	<i>95.5</i>	<i>93.7</i>	<i>92.6</i>	<i>94.3</i>
Twigs (branch < 5mm)							
+Tree cubic volume (TCV)	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.319	0.754	0.476	0.158	0.775	0.04	0.876
+Species	<.001	<.001	0.055	0.02	<.001	<.001	0.006
+Region	0.059	0.554	<.001	0.445	<.001	0.041	0.484
+TCV x Fertility	<.001	<.001	<.001	0.002	<.001	0.004	0.008
+TCV x Species	0.652	0.534	<.001	0.153	0.182	0.047	0.932
+TCV x Region	<.001	<.001	<.001	<.001	0.45	0.204	0.034
+Stemnumber	<.001	<.001	<.001	0.001	<.001	0.014	0.02
+TCV x Stemnumber	0.71	0.599	0.221	0.079	0.414	0.515	0.472
+Ht.crown-base	0.308	0.916	0.362	0.89	0.161	<.001	0.229
+TCV x Ht.crown-base	0.381	0.569	0.226	0.859	0.863	0.114	0.607
+Fertility x Species	0.139	0.62	0.181	0.079	0.04	0.008	0.327
+Fertility x Species x TCV	0.646	0.456	0.179	0.746	0.559	0.48	0.224
+Fertility x Region	0.516	0.903	0.019	0.34	0.564	0.191	0.681
+Fertility x Region x TCV	0.145	0.655	0.524	0.394	0.107	0.02	0.872
<i>% of variance accounted</i>	<i>96.9</i>	<i>96.3</i>	<i>92.4</i>	<i>95.6</i>	<i>91.1</i>	<i>93.6</i>	<i>92.5</i>
Branch 5-20mm							
+Tree cubic volume (TCV)	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.213	0.414	0.645	0.878	0.483	0.272	0.529
+Species	<.001	<.001	0.003	<.001	<.001	<.001	<.001
+Region	0.238	0.499	0.021	0.829	0.537	0.135	0.93
+TCV x Fertility	0.046	0.062	0.41	0.478	0.431	0.206	0.135
+TCV x Species	<.001	<.001	0.056	0.001	0.023	<.001	0.003
+TCV x Region	0.04	0.052	0.009	0.01	0.728	0.496	0.152
+Stemnumber	0.004	0.003	0.001	0.008	0.632	0.012	0.033
+TCV x Stemnumber	0.074	0.031	0.371	0.325	0.002	0.1	0.029
+Ht.crown-base	0.514	0.559	0.272	0.578	0.389	0.03	0.406
+TCV x Ht.crown-base	0.132	0.443	0.753	0.506	0.054	0.07	0.296
+Fertility x Species	0.297	0.618	0.672	0.087	0.358	0.469	0.509
+Fertility x Species x TCV	0.878	0.632	0.731	0.978	0.48	0.855	0.613
+Fertility x Region	0.741	0.942	0.264	0.618	0.936	0.238	0.839
+Fertility x Region x TCV	0.125	0.519	0.358	0.358	0.135	0.027	0.962
<i>% of variance accounted</i>	<i>91.9</i>	<i>90.6</i>	<i>87.8</i>	<i>91.3</i>	<i>88.5</i>	<i>88.5</i>	<i>87</i>
Stem bark							
+Tree cubic volume (TCV)	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.145	0.041	0.029	0.016	0.183	0.035	0.342
+Species	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Region	0.095	0.26	0.416	0.288	0.007	0.242	0.263
+TCV x Fertility	<.001	<.001	<.001	0.002	<.001	<.001	<.001
+TCV x Species	0.184	0.055	0.036	0.072	0.256	0.048	0.323
+TCV x Region	0.451	0.872	0.508	0.424	0.951	0.587	0.89
+Stemnumber	0.197	0.312	0.72	0.812	0.031	0.223	0.344
+TCV x Stemnumber	0.277	0.517	0.241	0.551	0.301	0.165	0.566
+Ht.crown-base	0.039	0.198	0.072	0.01	0.026	0.021	0.779
+TCV x Ht.crown-base	0.041	0.035	0.052	0.365	0.18	0.047	0.357
+Fertility x Species	0.051	0.276	0.304	0.074	0.143	0.004	0.455
+Fertility x Species x TCV	0.07	0.102	0.075	0.162	0.29	0.163	0.055
+Fertility x Region	0.738	0.853	0.451	0.417	0.621	0.171	0.604
+Fertility x Region x TCV	0.174	0.081	0.257	0.379	0.871	0.212	0.036
<i>% of variance accounted</i>	<i>92.3</i>	<i>92.3</i>	<i>91.7</i>	<i>91.7</i>	<i>89.1</i>	<i>90.6</i>	<i>89.9</i>
Stem wood							
+Tree cubic volume (TCV)	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.07	0.114	0.375	0.216	0.677	0.324	0.33
+Species	0.003	<.001	0.203	0.009	0.005	<.001	0.098
+Region	0.002	0.35	0.29	0.195	0.013	0.243	<.001
+TCV x Fertility	<.001	<.001	0.032	<.001	0.01	<.001	<.001
+TCV x Species	0.031	0.082	0.655	0.239	0.067	0.443	0.603
+TCV x Region	0.523	0.759	0.802	0.886	0.725	0.735	0.781
+Stemnumber	0.015	0.117	0.475	0.056	0.225	0.002	0.089
+TCV x Stemnumber	0.549	0.435	0.303	0.325	0.029	0.015	0.163
+Ht.crown-base	0.007	0.02	0.043	0.019	0.41	0.005	0.848
+TCV x Ht.crown-base	0.004	0.056	0.425	0.108	0.716	0.001	0.117
+Fertility x Species	0.044	0.322	0.262	0.096	0.081	<.001	0.145
+Fertility x Species x TCV	0.421	0.318	0.185	0.182	0.748	0.141	0.591
+Fertility x Region	0.731	0.571	0.135	0.099	0.311	0.263	0.949
+Fertility x Region x TCV	0.362	0.127	0.892	0.848	0.208	0.436	0.105
<i>% of variance accounted</i>	<i>93.8</i>	<i>90.8</i>	<i>83.8</i>	<i>92.5</i>	<i>81</i>	<i>91.8</i>	<i>89.6</i>

Table 8. Probabilities for the effects of factors and factor interactions in whole-tree regression functions which account for variation in biomass (DW) and nutrient contents of combined above-ground tree components in relation to tree cubic volume. Significant factors and factor interactions are indicated by shaded cells. The percentage of the variance accounted for by the full model for biomass and nutrients is shown in italics.

Tree component & model parameter	DW	N	P	K	Ca	Mg	Na
<u>Canopy (leaves + twigs + fruit)</u>							
+Tree cubic volume (TCV)	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.683	0.681	0.084	0.42	0.388	0.067	0.558
+Species	<.001	<.001	0.017	<.001	<.001	<.001	0.305
+Region	0.527	0.963	0.03	0.042	<.001	0.345	0.046
+TCV x Fertility	0.001	<.001	0.005	0.006	<.001	0.01	<.001
+TCV x Species	0.3	0.179	0.196	0.689	0.483	0.461	0.001
+TCV x Region	0.028	0.073	<.001	0.002	0.214	0.618	0.072
+Stemnumber	0.011	0.019	0.004	0.042	0.008	0.027	0.117
+TCV x Stemnumber	0.554	0.725	0.145	0.57	0.824	0.617	0.998
+Ht.crown-base	0.745	0.521	0.521	0.529	0.483	0.024	0.029
+TCV x Ht.crown-base	0.775	0.707	0.028	0.315	0.523	0.935	0.267
+Fertility x Species	0.195	0.119	0.057	0.086	0.004	0.002	0.715
+Fertility x Species x TCV	0.517	0.932	0.697	0.893	0.131	0.422	0.733
+Fertility x Region	0.395	0.254	0.772	0.987	0.128	0.89	0.622
+Fertility x Region x TCV	0.426	0.491	0.692	0.527	0.392	0.44	0.638
<i>% of variance accounted</i>	<i>97</i>	<i>96.5</i>	<i>95.4</i>	<i>96.4</i>	<i>94.2</i>	<i>93.7</i>	<i>95.1</i>
<u>Stems (wood + bark + branches >5mm diam.)</u>							
+Tree cubic volume (TCV)	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.151	0.254	0.454	0.518	0.464	0.44	0.479
+Species	<.001	<.001	0.028	<.001	<.001	<.001	<.001
+Region	0.02	0.234	0.154	0.365	0.068	0.164	0.51
+TCV x Fertility	0.015	0.035	0.405	0.286	0.201	0.068	0.028
+TCV x Species	0.006	<.001	0.195	0.004	0.035	<.001	0.012
+TCV x Region	0.235	0.213	0.07	0.117	0.659	0.724	0.21
+Stemnumber	0.803	0.451	0.209	0.798	0.278	0.716	0.668
+TCV x Stemnumber	0.147	0.041	0.512	0.452	0.005	0.119	0.135
+Ht.crown-base	0.055	0.168	0.067	0.094	0.124	0.021	0.968
+TCV x Ht.crown-base	0.007	0.059	0.287	0.093	0.064	0.005	0.091
+Fertility x Species	0.153	0.592	0.583	0.039	0.168	0.166	0.559
+Fertility x Species x TCV	0.335	0.234	0.399	0.527	0.94	0.39	0.488
+Fertility x Region	0.888	0.973	0.249	0.361	0.977	0.366	0.954
+Fertility x Region x TCV	0.522	0.91	0.712	0.589	0.142	0.218	0.614
<i>% of variance accounted</i>	<i>94.8</i>	<i>93.4</i>	<i>91</i>	<i>94.3</i>	<i>93.1</i>	<i>92.4</i>	<i>91.4</i>
<u>Whole top</u>							
+Tree cubic volume (TCV)	<.001	<.001	<.001	<.001	<.001	<.001	<.001
+Fertility	0.187	0.922	0.082	0.736	0.189	0.069	0.723
+Species	<.001	<.001	0.007	<.001	<.001	<.001	0.027
+Region	0.207	0.806	0.033	0.185	<.001	0.251	0.059
+TCV x Fertility	<.001	<.001	0.006	0.006	<.001	0.006	<.001
+TCV x Species	0.928	0.222	0.22	0.705	0.289	0.43	0.002
+TCV x Region	0.072	0.067	<.001	0.004	0.375	0.568	0.072
+Stemnumber	0.301	0.029	0.01	0.103	0.392	0.082	0.134
+TCV x Stemnumber	0.9	0.723	0.173	0.443	0.752	0.799	0.963
+Ht.crown-base	0.054	0.912	0.242	0.698	0.14	0.006	0.082
+TCV x Ht.crown-base	0.216	0.9	0.105	0.542	0.72	0.487	0.395
+Fertility x Species	0.046	0.113	0.069	0.033	0.008	0.003	0.683
+Fertility x Species x TCV	0.686	0.96	0.556	0.992	0.305	0.505	0.692
+Fertility x Region	0.344	0.268	0.594	0.954	0.33	0.76	0.579
+Fertility x Region x TCV	0.775	0.429	0.725	0.598	0.318	0.432	0.52
<i>% of variance accounted</i>	<i>97.4</i>	<i>96.8</i>	<i>95.5</i>	<i>96.8</i>	<i>95.5</i>	<i>94.6</i>	<i>95.5</i>

In contrast to canopy components, variation in stem components (branches, wood, bark) is not as well explained by the whole tree regressions as in the single stem functions. The whole tree functions explain only 87% (Na) to 91.7% (dry weight) of the variance for branches, 89.1% (Ca) to 92.3% (dry weight & N) for stem-bark and 81% (Ca) to 93.8% (dry weight) for stem-wood. The relationships for combined stem components (branch + bark + wood) account for 3% (Ca) to 5.1% (P) less of the variance for whole tree regressions than single stem regressions. This generally results in poorer functions for total above-ground biomass and nutrient content.

There is also a difference between whole tree and single stem relationships in the way that species and site factor effects are expressed. This is due to differences in the independent variable for whole tree

(primarily canopy volume) and single stem (stem dimension only) functions. Thus, for whole tree regressions there is no significant main effect of site fertility except with stem-bark (Table 7) although the slope of the relationships with TCV is for most fractions significantly different between fertility categories (i.e. significant TCV x fertility interaction). Regional differences are also a less significant factor in the whole-tree dimension functions, particularly for stem components. However, the species factor is as important as in the single stem models. Higher order interactions among factors (species, fertility, region) contribute less to the whole-tree functions than to the single stem models.

4.1.3 Examples of species and site factor effects on single stem relationships

Output from the single stem model provides a large number of relationships for individual combinations of tree components, species and site factors, and biomass and nutrient parameters. A selection of figures is provided here to illustrate the relationships obtained and effects of species, fertility and region on biomass and nutrient content of selected components of single stems. Biomass and nutrient content are related to the primary independent variable, stem conical volume, with both variables plotted on a logarithmic scale.

Aboveground dry matter

The effects of site fertility on the dry weight of tree components are illustrated for *E. loxophleba* ssp. *lissophloia* at Kalannie in Figure 2. Larger trees with comparable stem dimensions and biomass have significantly higher biomass of canopy components on higher fertility red soils than on the lower fertility sands. These differences are greater than the logarithmic transformed data indicated. A tree at the upper end of the relationships is predicted to have 87 % more leaf and 92 % more total canopy on higher fertility soil than a tree of the same stem dimensions on low fertility soil. This contributes to a 36% higher total above-ground biomass, despite a lack of difference in stem-wood. Although there was no significant fertility x volume interaction for canopy components (Tables 5, 6), differences between soils in the slopes of the relationships (Figure 2) are indicated by the significant three-way interaction term with species. This means that the effect of fertility on canopy biomass does change with tree size but is different among species.

There were also regional differences in the distribution of biomass between canopy and stem tissues. For *E. loxophleba* ssp. *lissophloia* growing on lower fertility soils, trees at Narrogin had about 30 % more leaf and canopy biomass than trees of the same stem size at Kalannie (Figure 3). However, there was no difference between regions in stem or total above-ground biomass. There were also no significant interaction terms with other site factors or tree size for these fractions.

Species differences were generally highly significant, either as a main effect and/or as an interactive term with stem volume and site fertility (Tables 5, 6). With sites on low fertility soils, this was most apparent for the canopy component, particularly with the higher slope and the higher canopy biomass of larger *E. kochii* ssp. *plenissima* trees (Figure 4).

Figure 2. Dry weights of leaf, canopy (leaf + twig), stem-wood and whole tops in relation to stem conical volume (fn stem diameter, height) of *E. loxophleba* ssp. *lissophloia* from low and high fertility sites at Kalannie. The lines are the fitted model values for high (solid) and low (dashed) fertility sites.

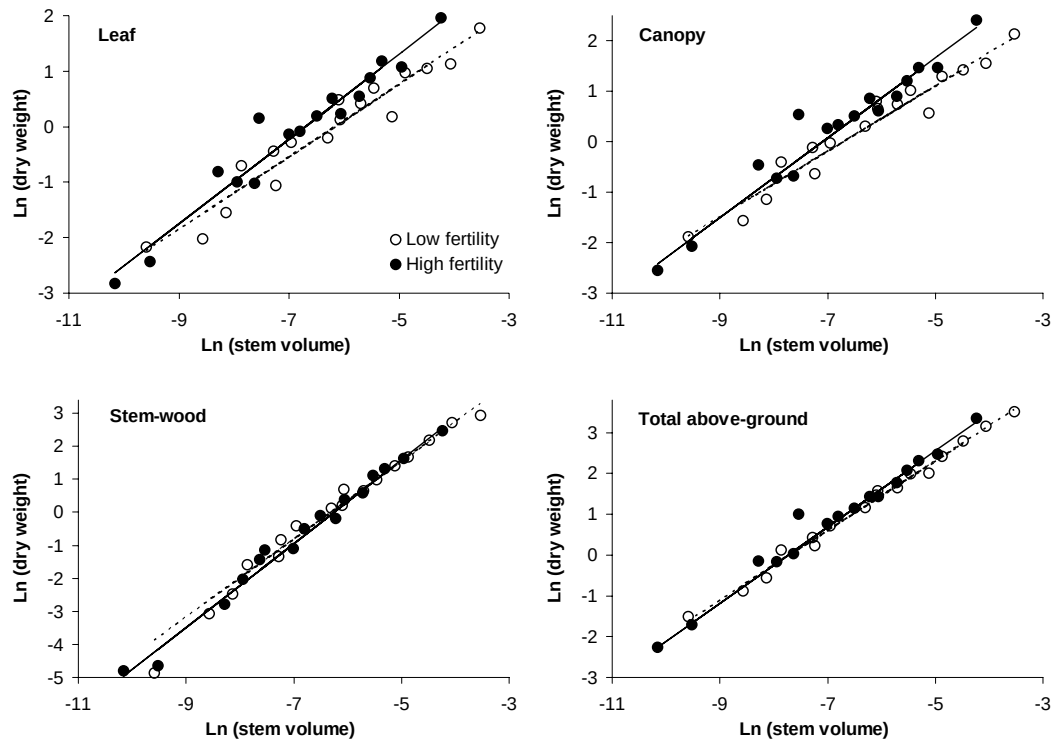


Figure 3. Dry weights of leaf, canopy (leaf + twig), stems and whole tops in relation to stem conical volume (fn stem diameter, height) of *E. loxophleba* ssp. *lissophloia* from low fertility sites at Kalannie and Narrogin. The lines are the fitted model values for Narrogin (solid) and Kalannie (dashed) sites. Data is plotted on a logarithmic scale.

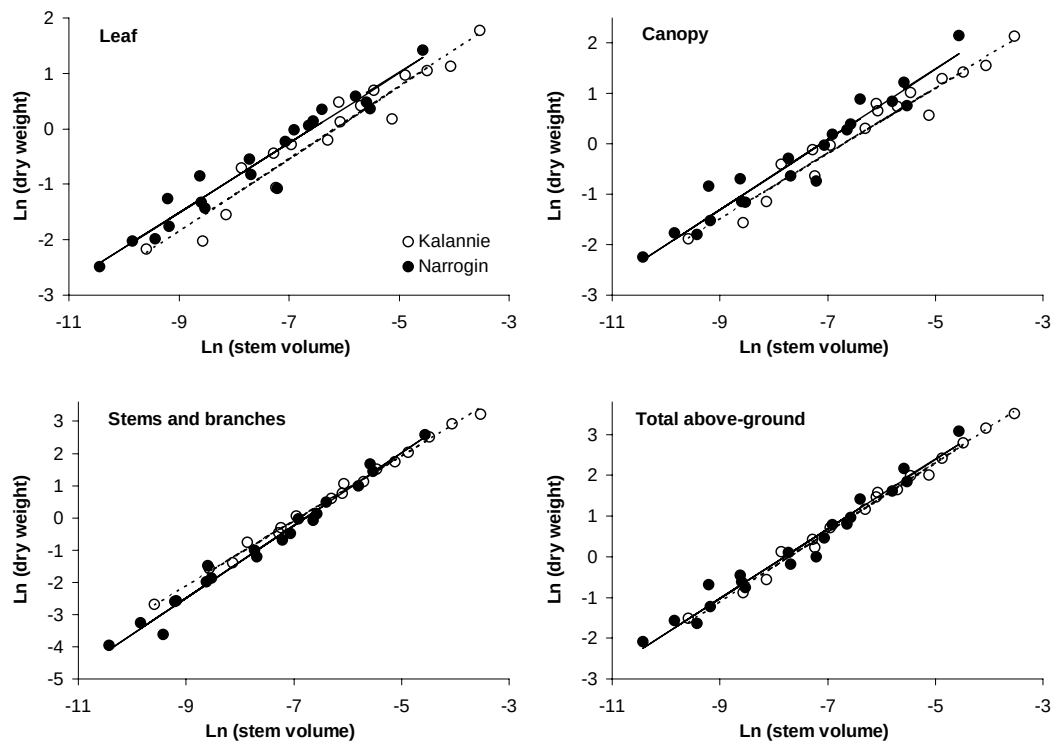
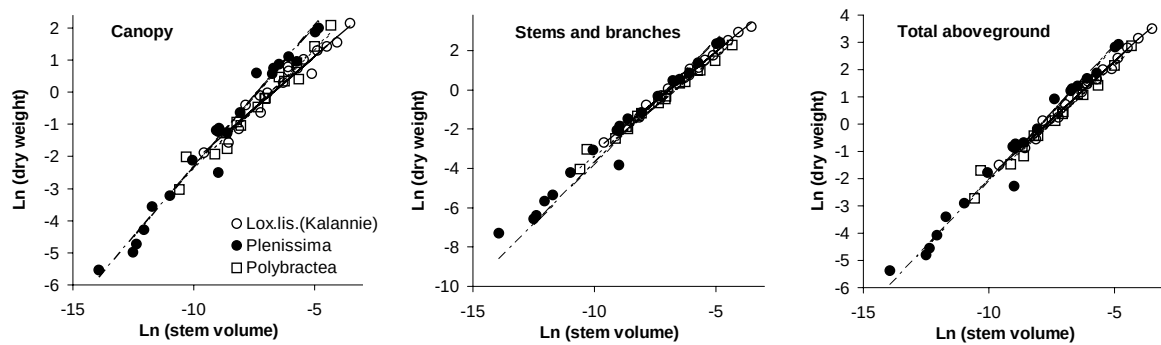


Figure 4. Dry weights of canopy (leaf + twig), stems and whole tops in relation to stem conical volume (π stem diameter, height) of *E. loxophleba* ssp. *lissophloia*, *E. kochii* ssp. *plenissima* and *E. polybractea* from low fertility sites at Kalannie and Narrogin. Data is plotted on a logarithmic scale.



Nutrient content

Trees on higher fertility soils had larger amounts of N, P, K and Na in whole tops than trees of comparable stem size on lower fertility soils. Differences were most marked for N and K. For larger *E. loxophleba* ssp. *lissophloia* at Kalannie, K content of the tree canopy on high fertility soil was about double the amount on low fertility soil, and there was a smaller (50 %) difference in total above-ground K content (Figure 5).

Differences in the nutrient composition of trees sampled at Kalannie and Narrogin were evident for each nutrient in the canopy and whole tops, and also for N, K and Na in stems. Tree content of each nutrient except Ca was higher at Narrogin than at Kalannie. P contents in all aboveground components of *E. loxophleba* ssp. *lissophloia* at Kalannie were higher than in trees with comparable stem dimensions at Narrogin, and the effect was more evident for the lower fertility sites (Figure 6, Tables 5, 6). In contrast to other nutrients, Ca content of the canopy was significantly higher at Kalannie than at Narrogin (Figure 7) and this was primarily due to differences in amounts of Ca in the twig fraction.

There were marked differences among species in the nutrient content of individual fractions and whole tops. Differences were relatively small for K and greatest for P, Ca, Mg and Na. The Mg contents of above-ground components of *E. kochii* ssp. *plenissima* were higher than in the other two species, with differences becoming larger as stem size increased (Figure 8).

Figure 5. Potassium content of leaf, canopy (leaf + twig), stems (wood + bark + branches) and whole tops in relation to stem conical volume (fn stem diameter, height) of *E. loxophleba* ssp. *lissophloia* from low and high fertility sites at Kalannie. The lines are the fitted model values for high (solid) and low (dashed) fertility sites. Data is plotted on a logarithmic scale.

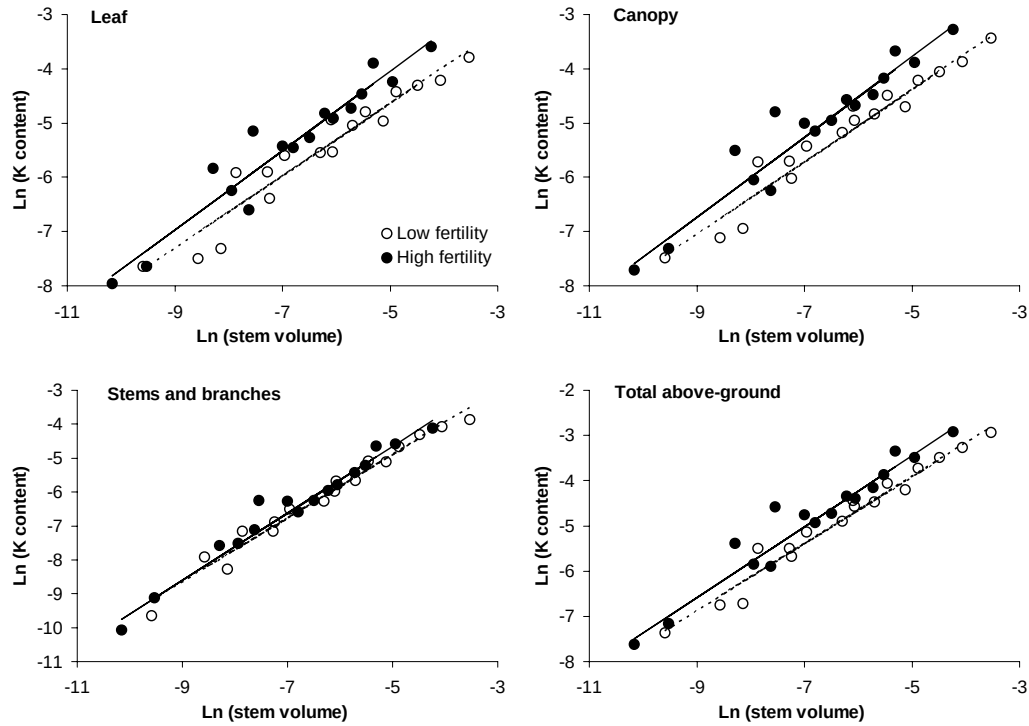


Figure 6. Phosphorus content of leaf, canopy (leaf + twig), stems (wood + bark + branches) and whole tops in relation to stem conical volume (fn stem diameter, height) of *E. loxophleba* ssp. *lissophloia* from low fertility sites at Kalannie and Narrogin. The lines are the fitted model values for Narrogin (solid) and Kalannie (dashed) sites. Data is plotted on a logarithmic scale.

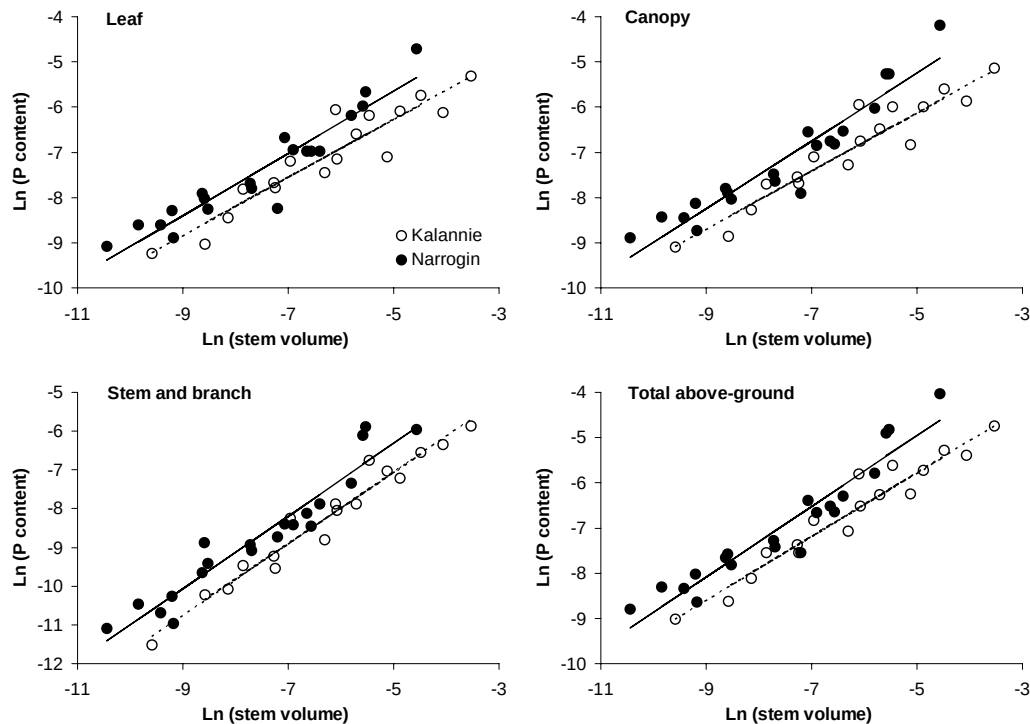


Figure 7. Calcium content of twigs, canopy (leaf + twig), stems (wood + bark + branches) and whole tops in relation to stem conical volume (fn stem diameter, height) of *E. loxophleba* ssp. *lissophloia* from low fertility sites at Kalannie and Narrogin. The lines are the fitted model values for Narrogin (solid) and Kalannie (dashed) sites. Data is plotted on a logarithmic scale.

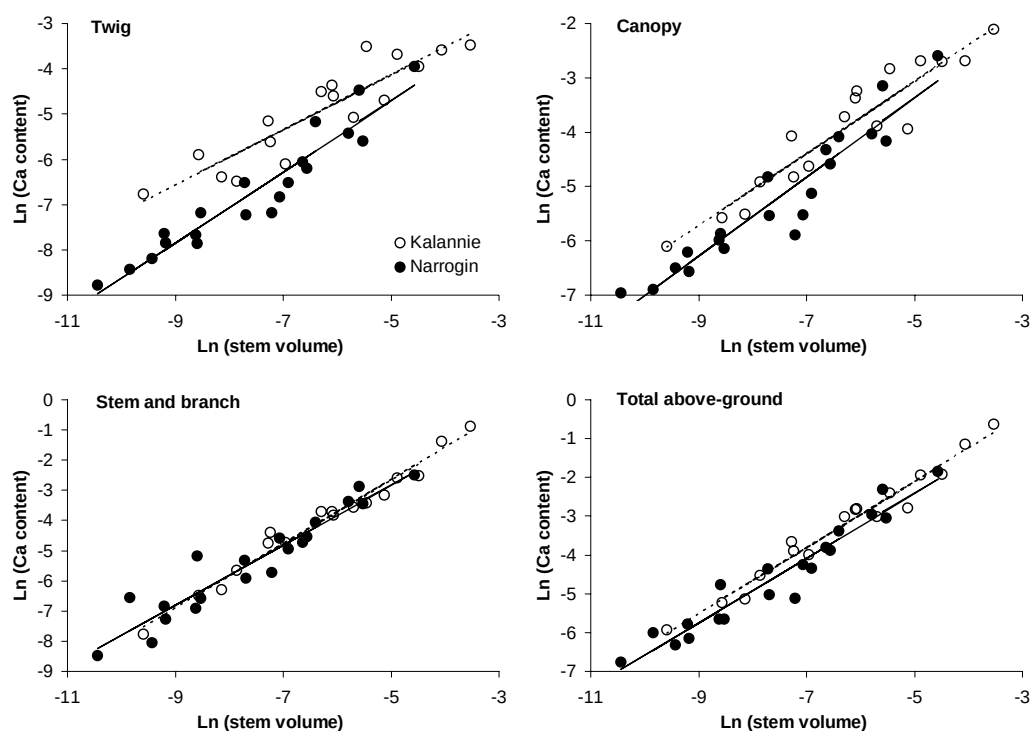
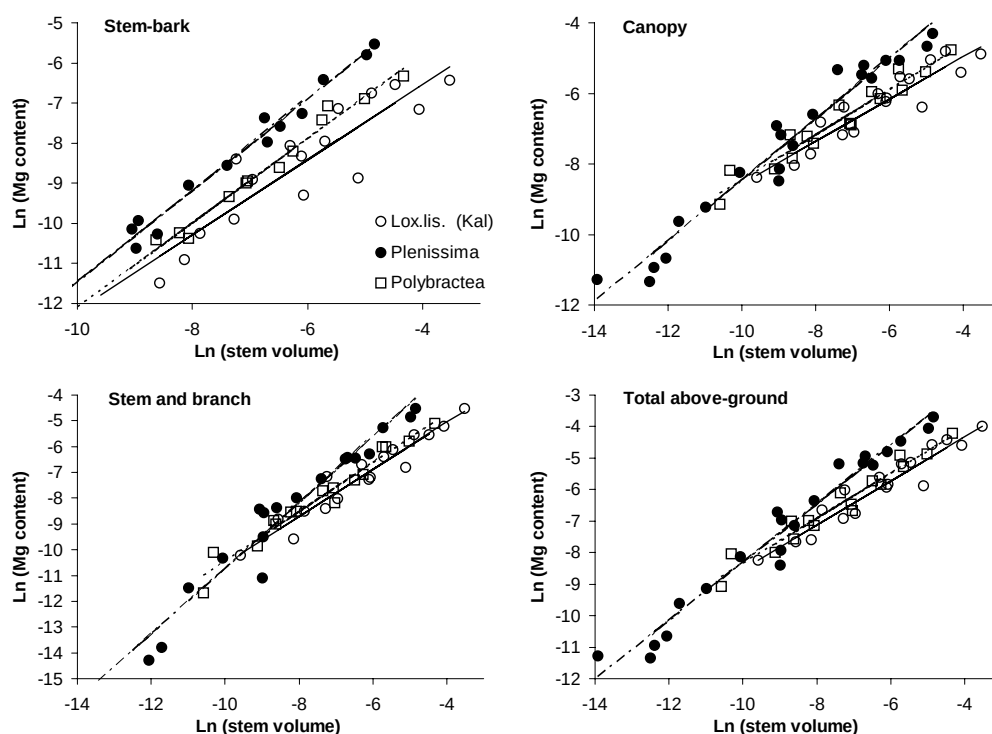


Figure 8. Magnesium contents of stem-bark, canopy (leaf + twig), stems (wood + bark + branches) and whole tops in relation to stem conical volume (fn stem diameter, height) of *E. loxophleba* ssp. *lissophloia* (solid line), *E. kochii* ssp. *plenissima* (long dash) and *E. polybractea* (dash) from low fertility sites at Kalannie and Narrogin. Data is plotted on a logarithmic scale.

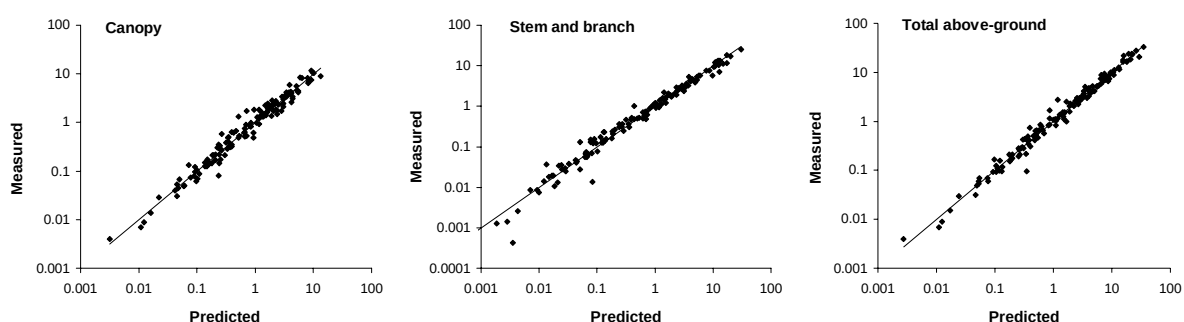


4.1.4 Test of model predictions

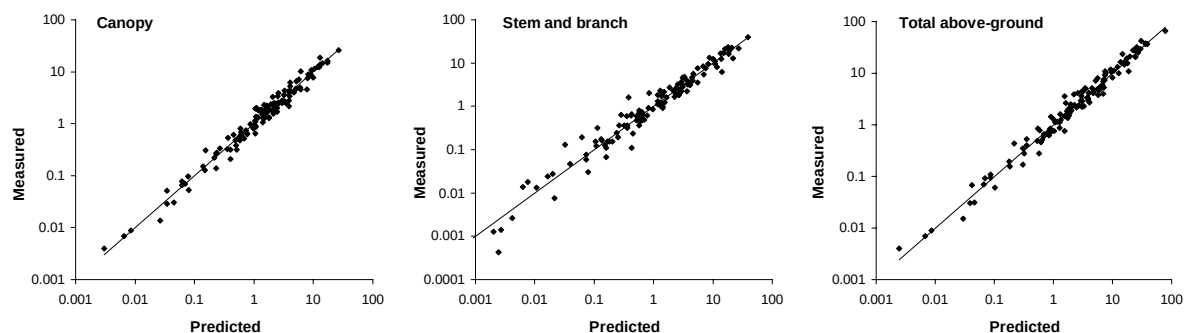
Predictions of biomass and nutrient content of tree components have not been tested against independently measured data sets. Some indication of the variance of measured values from predicted values derived from either the single stem (stem volume) or whole tree (tree cubic volume) dimension measurements is provided by plotting predicted against observed values for the 139 trees sampled to derive the functions. For the single stem functions, there was a marginally closer fit between predicted and measured total aboveground biomass ($R^2=0.984$) than for the biomass of canopy (0.969) and stem+branch (0.974) components (Figure 9). Comparable strong relationships were found for predictions based on the whole-tree measurements for canopy and total above-ground biomass. However, stem+branch biomass was less well predicted ($R^2=0.956$) by the regression function using whole-tree dimension measurements (Figure 9).

Figure 9. Relationships between measured biomass and values predicted from functions of (a) single stem and (b) whole tree dimension measurements for whole canopy, stems + branches and total above-ground biomass. Individual values are compared to a 1:1 line and are for 139 trees representing a range in age of 3 species from 2 locations and sites of different fertility status.

(a) Regressions using individual stem measurements

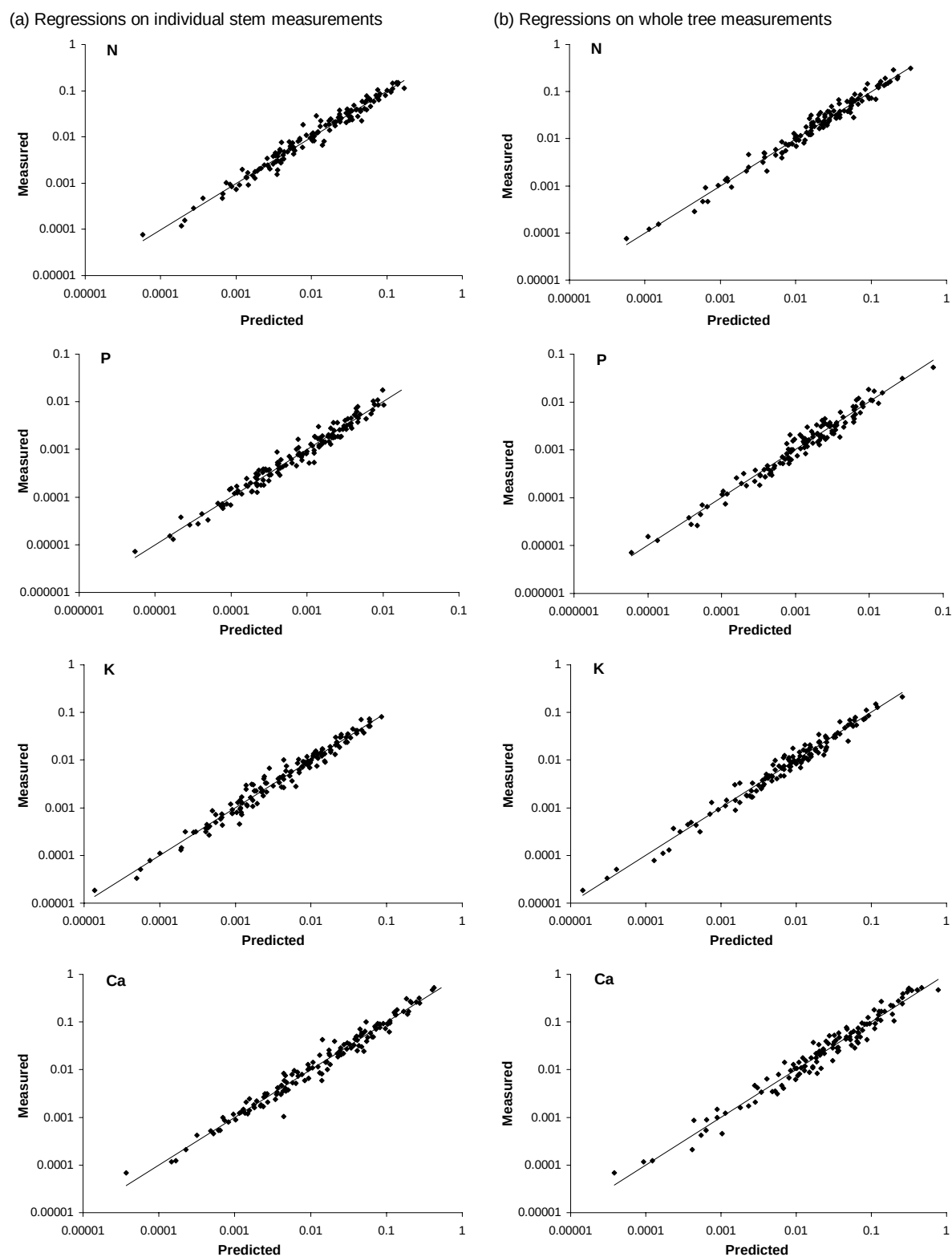


(b) Regressions using whole tree measurements



Relationships between measured and predicted nutrient contents of total above-ground matter show more scatter than those for above-ground biomass (Figure 10). Regression coefficients range from 0.965 for P to 0.973 for Ca where predictions are based on single stem measurements, and from 0.955 for Mg to 0.973 for N and K where predictions are based on the whole-tree dimension data.

Figure 10. Relationships between measured N, P, K, and Ca contents of whole tree and values predicted from functions of (a) single stem and (b) whole tree dimension measurements. Individual values are compared to a 1:1 line and are for 139 trees representing a range in age of 3 species from 2 locations and sites of different fertility status.



In a further test of the reliability of the predictive functions we evaluated how well the sum of predicted quantities for individual tree components matched the predicted amounts derived from regressions of total above-ground contents. The predicted quantity from whole top functions closely matched total amounts calculated from the sum of predicted amounts for individual tree components. Relationships between the two estimates had R^2 values of 0.999 or better for biomass and each of the nutrient elements (data not shown).

4.1.5 OMEN Toolkit

More than 5000 coefficients were generated from fitting two regression models to biomass and nutrient contents of several tree fractions across species and site categories. These make up the parameter set used by the prototype toolkit OMEN to calculate the biomass and nutrient content of tree belts, and their allocation to different tree components, from field measurements of stem or whole tree dimension measurements. The calculation takes account of variation in tree composition with species, site location and soil fertility.

An example of the OMEN spreadsheet for calculations based on single stem measurements and illustrating the input data and results produced are shown in Figure 11. For this example, tree measurement data from the first replicate plot of the 5 year-old *E. polybractea* tree belt on the higher fertility site at Narrogin (see Table 3) has been used. The first 5 of 85 stem measurements can be seen at the bottom of Figure 11a. In total there were 33 trees (not counting those recorded as missing) and 73 stems measured in 4 tree rows over the plot length of 18 m. Numbering of trees and stems is not essential.

Other input data is entered or selected in column B and rows 7 to 14. The number and spacing of rows in the tree belt, and the number and length of each row measured must be entered and the species, site fertility status, location and tree component selected from pull-down menus. The pull-down menu for tree fraction is shown in Figure 11b. A warning is shown if the combination of factors selected falls outside the experiment framework from which the parameters were derived e.g. *E. polybractea* at Kalannie.

With entry of the measurement data, the spreadsheet calculates the biomass and N, P, K, Ca, Mg and Na contents of individual stems to the right of the input stem data. These results are then summed and scaled to provide the main output on biomass and nutrient content of the tree belt expressed on both an areal or belt length basis. In this example there is estimated to be 32 t dry matter ha⁻¹, 227 kg N ha⁻¹ and 107 kg K ha⁻¹ in the tree-belt based on this 18 m length plot.

4.1.6 Test of predictive functions with coppice growth

The four *E. kochii* ssp. *plenissima* trees measured and sampled had on average 22 coppice shoots (range 19 to 24). For the eight coppice shoots that were partitioned into fractions for analysis, canopy (leaf and twig) tissue made up a smaller proportion (11% less) of total aboveground dry matter than saplings of an equivalent size from other sites on comparable soil (Figure 12). Stem-wood accounted for 8% more of the stem and branch fraction of coppice shoots than saplings.

Figure 11. The OMEN spreadsheet for estimates based on stem dimension measurements.

(a) Portion of the OMEN spreadsheet showing factors to be entered and part of entered measurement data (shaded areas)

	A	B	C	D	E	F	G	H	I	J
1	OMEN v.01 - Single stem estimator									
2	Instructions:									
3	1. Enter your site details and fraction of interest in following table (highlighted yellow cells)									
4	2. Measure height and basal diameter of each stem within the measure plot and enter into table below (highlighted yellow cells)									
5										
6										
7	Species:	<i>E. polybractea</i>								
8	Region:	Narrogin								
9	Soil Fertility:	Higher								
10	# of rows in belt:	4								
11	distance between rows (m):	2								
12	# of rows measured:	4								
13	Length of belt measured (m):	18								
14	Fraction of interest:	All components								
15										
16	Predicted contents (belt basis)									
17		Dry weight	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Sodium		
18	kg/ha:	32307.50	227.00	14.58	107.34	308.21	30.70	97.93		
19	kg/m of belt:	25.85	0.182	0.012	0.086	0.247	0.025	0.078		
20										
21		Tree #	Stem #	Stem height (m)	measure height <i>h</i> (m)	Stem diameter at height <i>h</i> (cm)	Predicted dry weight (kg)	Predicted N content (kg)	Predicted P content (kg)	Predicted K content (kg)
22		1	a	4.01	0.1	4.71	5.1086815	0.039052	0.002563	0.01791
23			b	3.63	0.1	5.93	7.2830037	0.052649	0.0034	0.0246
24		2	a	3.47	0.1	7.23	10.257823	0.07026	0.004467	0.0335
25			b	1.56	0.1	1.51	0.2454451	0.003026	0.000228	0.001
26		3	a	3.53	0.1	7.4	10.898537	0.07394	0.004687	0.0354
27		4	missing				0	0	0	
28		5	missing				0	0	0	

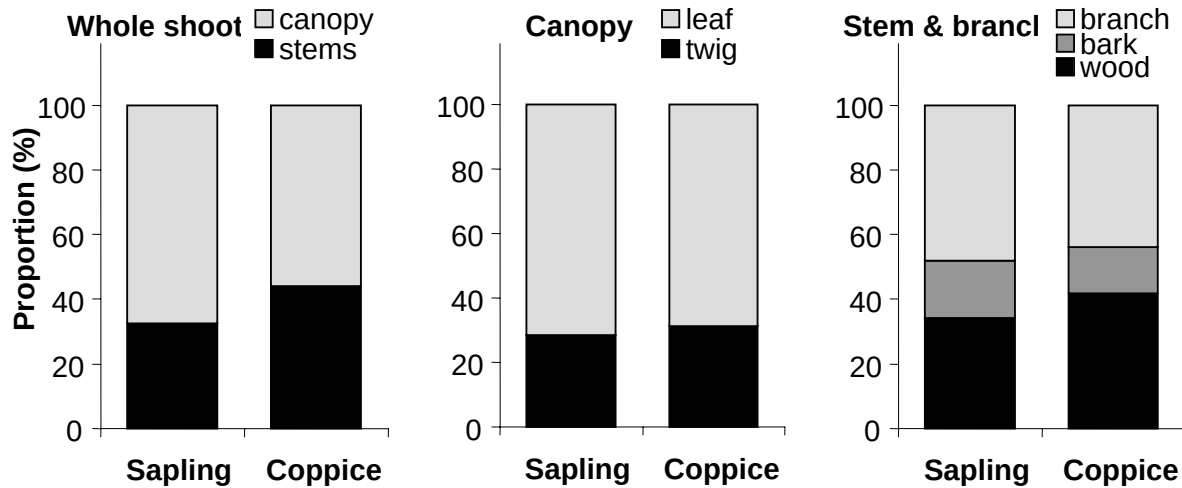
(b) Use of drop-down list to select a tree component

6										
7	Species:	<i>E. polybractea</i>								
8	Region:	Narrogin								
9	Soil Fertility:	Higher								
10	# of rows in belt:	4								
11	distance between rows (m):	2								
12	# of rows measured:	4								
13	Length of belt measured (m):	18								
14	Fraction of interest:	All components All components Canopy (Leaf+H) Woody component Leaf Branch <5mm Branch 5-20mm Stem bark Stem wood								
15										
16	Predicted contents (belt basis)									
17		Dry weight	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Sodium		
18	kg/ha:	32307.50	227.00	14.58	107.34	308.21	30.70	97.93		
19	kg/m of belt:	25.85	0.182	0.012	0.086	0.247	0.025	0.078		
20										

The slope of the relationship between stem volume and biomass for the eight coppice shoots is different to the relationship for sapling trees. The prediction of total dry weight of each shoot using the function derived from sapling trees shows that larger stems are over-predicted, while smaller stems

are under-predicted (Figure 13). However, inner and outer dominant stems appear to fall on a common line.

Figure 12. Distribution of biomass in uncut saplings and coppice shoots of *E. kochii* ssp. *plenissima*. Values are the means of eight sapling and coppice shoots covering the same range in total biomass.



Concentrations of N and P are consistent with those in the same fractions in saplings (Tables 9, 3). However, there were large differences between coppice and sapling fractions in the concentrations of the cation nutrients, with concentrations of K, Ca and Mg generally being much lower in coppice fractions. Potassium concentrations ranged from 3% lower in bark to 27% lower in wood fractions of coppice and the differences were much greater for Ca and Mg.

As a consequence of the differences between coppice shoots and saplings in (i) biomass allocation, (ii) the relationship between stem volume and dry matter, and (iii) nutrient concentrations in tree fractions, the predictive functions developed for saplings were relatively poor predictors of coppice biomass and nutrient contents for this site (Figure 14). This comparison is however limited to 4 trees at one site.

Figure 13. Relationship between total above-ground biomass of *E. kochii* ssp. *plenissima* predicted from single stem functions developed for saplings and the measured biomass of saplings (fitted line) and coppice (symbols). The 90 coppice stems are from 4 trees and include the dominant/codominant inner and out stems selected for fractionation and nutrient analysis.

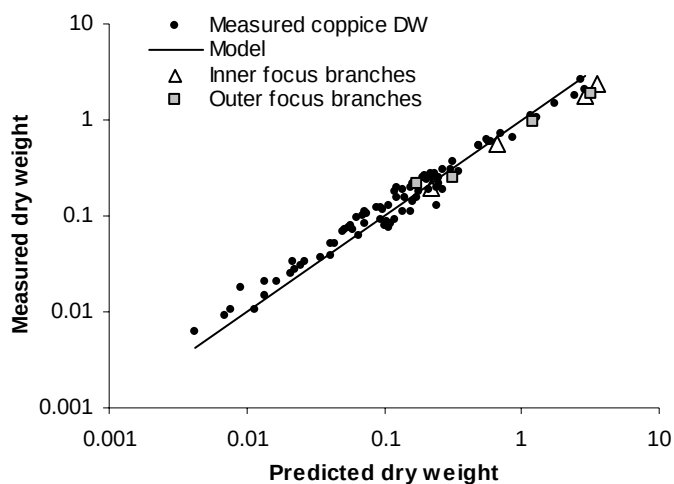
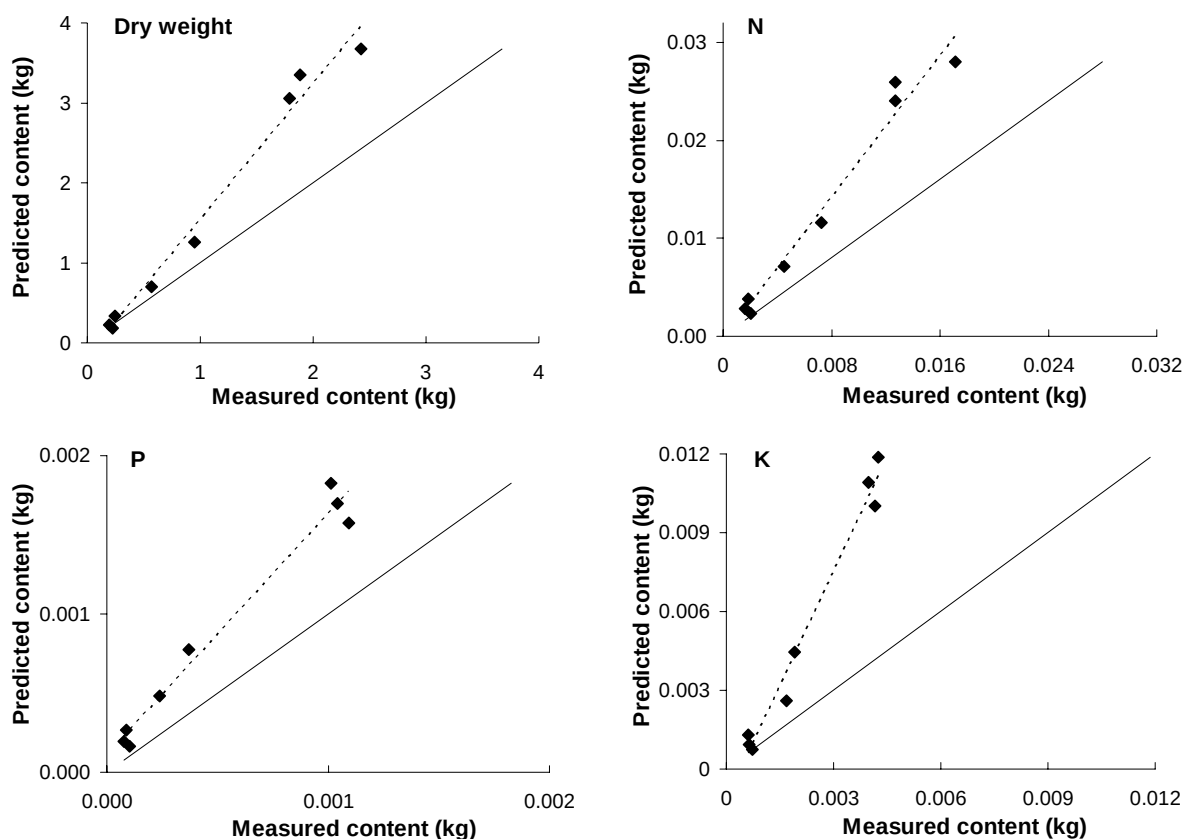


Table 9. Nutrient concentrations in different tissues of 3 year-old coppice stems of *E. kochii* ssp. *plenissima* at Kallanie. Values are the means for 8 coppice stems and coefficients of variation for each mean are shown in italics.

Tree component		N %	P %	K %	Ca %	Mg %	Na %
Leaf	Mean	1.30	0.062	0.36	0.65	0.14	0.40
	CV (%)	<i>8</i>	<i>21</i>	<i>16</i>	<i>29</i>	<i>24</i>	<i>16</i>
Twig	Mean	0.46	0.049	0.21	0.62	0.08	0.23
	CV (%)	<i>7</i>	<i>41</i>	<i>19</i>	<i>41</i>	<i>31</i>	<i>12</i>
Stem-wood	Mean	0.20	0.016	0.09	0.13	0.04	0.06
	CV (%)	<i>8</i>	<i>38</i>	<i>42</i>	<i>30</i>	<i>24</i>	<i>17</i>
Stem-bark	Mean	0.35	0.023	0.21	1.16	0.12	0.32
	CV (%)	<i>10</i>	<i>9</i>	<i>19</i>	<i>20</i>	<i>25</i>	<i>9</i>

Figure 14. Relationships between measured dry weight, N, P and K contents of *E. kochii* ssp. *plenissima* coppice shoots and values predicted from functions for saplings on similar soils in the Kalannie region. The solid line represents the 1:1 relationship.



4.2 Tree belt nutrients in relation to site nutrient capital

4.2.1 Aboveground biomass and nutrient stores

Above-ground biomass of the 5 year-old *E. polybractea* on the higher fertility site at Narrogin (25.2 t ha⁻¹ dry weight) was more than double the biomass of 4 year-old *E. loxophleba* ssp. *lissophloia* on the lower fertility site (10.9 t ha⁻¹) and 6 times greater than biomass at the two Kalannie sites (Table 10). These predictions are based on the more intensive measurements of diameters and heights of individual stems for each tree. At Kalannie the biomass of the 3 year-old *E. kochii* ssp. *plenissima* tree belt was similar to the biomass of 5 year-old *E. loxophleba* ssp. *lissophloia*. Despite the large variation in biomass across sites, the canopy component made up a relatively constant proportion (51 to 57%) of the total.

Amounts of nutrients in aboveground material were greatest at the high fertility site, where the *E. polybractea* tree belt contained (kg ha⁻¹): 189 N, 12 P, 87 K, 241 Ca, 25 Mg and 77 Na (Table 10). This was about 60% more P and more than double the amount of N, K, Ca, Mg and Na contained in the younger *E. loxophleba* ssp. *lissophloia* tree-belts on the low fertility site in the same region. Amounts of nutrients in tree belts at Kalannie were much lower than at Narrogin, with the highest amounts on an areal basis being (kg ha⁻¹): 38 N, 2.5 P, 14 K, 49 Ca, 4 Mg and 13 Na.

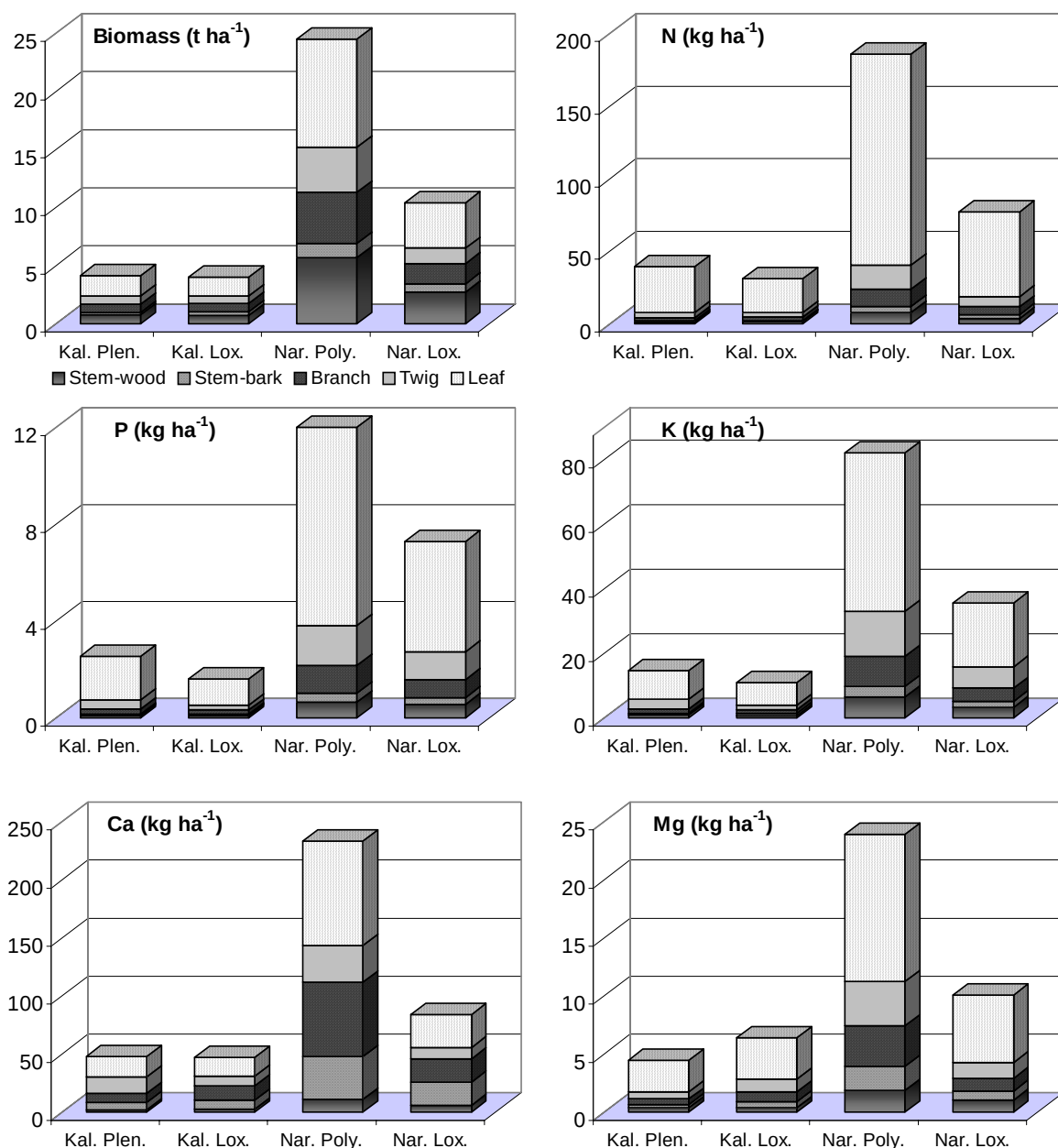
There were greater proportions of nutrients than biomass in the canopy components of the tree belts, except for Ca which was approximately equally distributed between canopy and woody components at three of the four sites (Table 10). The canopy fraction at each of the sites contained more than 75% of the aboveground N, P, K and Na.

Table 10. Biomass and nutrient content (areal basis) of canopy (leaf, twig, fruit), stems (branch, stem-wood, stem-bark) and total aboveground components of tree belts at the high and low fertility sites at Kalannie and Narrogin

Site and tree component	Biomass (t ha ⁻¹)	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)	Ca (kg ha ⁻¹)	Mg (kg ha ⁻¹)	Na (kg ha ⁻¹)
<u>Kalannie, high fertility (Lox.lis.)</u>							
Canopy (leaf, twig, fruit)	2.3	33	2.1	11	31	3.2	11.9
Stem and branch	1.6	4	0.4	3	16	1.0	1.3
Total above-ground	4.0	38	2.5	14	49	4.3	13.3
SE mean - total A/G	(0.6)	(5)	(0.3)	(2)	(8)	(0.6)	(1.6)
% in canopy	57.3	89	84.0	80	63	74.4	89.9
<u>Kalannie, low fertility (Plenissima)</u>							
Canopy (leaf, twig, fruit)	2.4	27	1.4	9	26	5.0	7.6
Stem and branch	1.8	5	0.3	3	25	1.8	1.9
Total above-ground	4.3	33	1.8	12	53	6.9	9.7
SE mean - total A/G	(2.4)	(16)	(0.8)	(6)	(29)	(3.6)	(5.2)
% in canopy	55.6	84	78.1	77	50	71.4	78.2
<u>Narrogin, high fertility (Polybractea)</u>							
Canopy (leaf, twig, fruit)	13.5	164	10.1	67	124	17.0	66.6
Stem and branch	11.4	24	2.2	19	120	7.5	9.3
Total above-ground	25.2	189	12.4	87	241	24.7	76.6
SE mean - total A/G	(3.3)	(20)	(1.2)	(10)	(31)	(2.9)	(10.0)
% in canopy	53.6	87	81.7	77	51	68.6	86.9
<u>Narrogin, low fertility (Lox.lis.)</u>							
Canopy (leaf, twig, fruit)	5.6	68	6.1	29	42	7.6	28.1
Stem and branch	5.2	12	1.6	9	48	2.9	5.0
Total above-ground	10.9	81	7.8	39	91	10.7	33.3
SE mean - total A/G	(1.3)	(8)	(0.9)	(4)	(11)	(1.2)	(3.5)
% in canopy	51.4	85	78.6	75	45	71.6	84.5

Leaves account for about 70% of the biomass and Ca contained within the canopy component, and higher proportions of the K (78%), P (82%) and N (90%) (Figure 15). Approximately three-quarters of the total above-ground N and two-thirds of the P are in the leaves. Within the woody components, branches accounted for 40% of the biomass and about 50% of the N, P, K and Ca.

Figure 15. Biomass, N, P, K, Ca and Mg content of (from base) stem-wood, stem-bark, branches, twigs and leaves of the low (Kal. Plen.) and high (Kal. Lox.) fertility sites at Kalannie, and the high (Nar. Poly.) and low (Nar. Lox.) fertility sites at Narrogin (see Table 3 for details of sites and species).

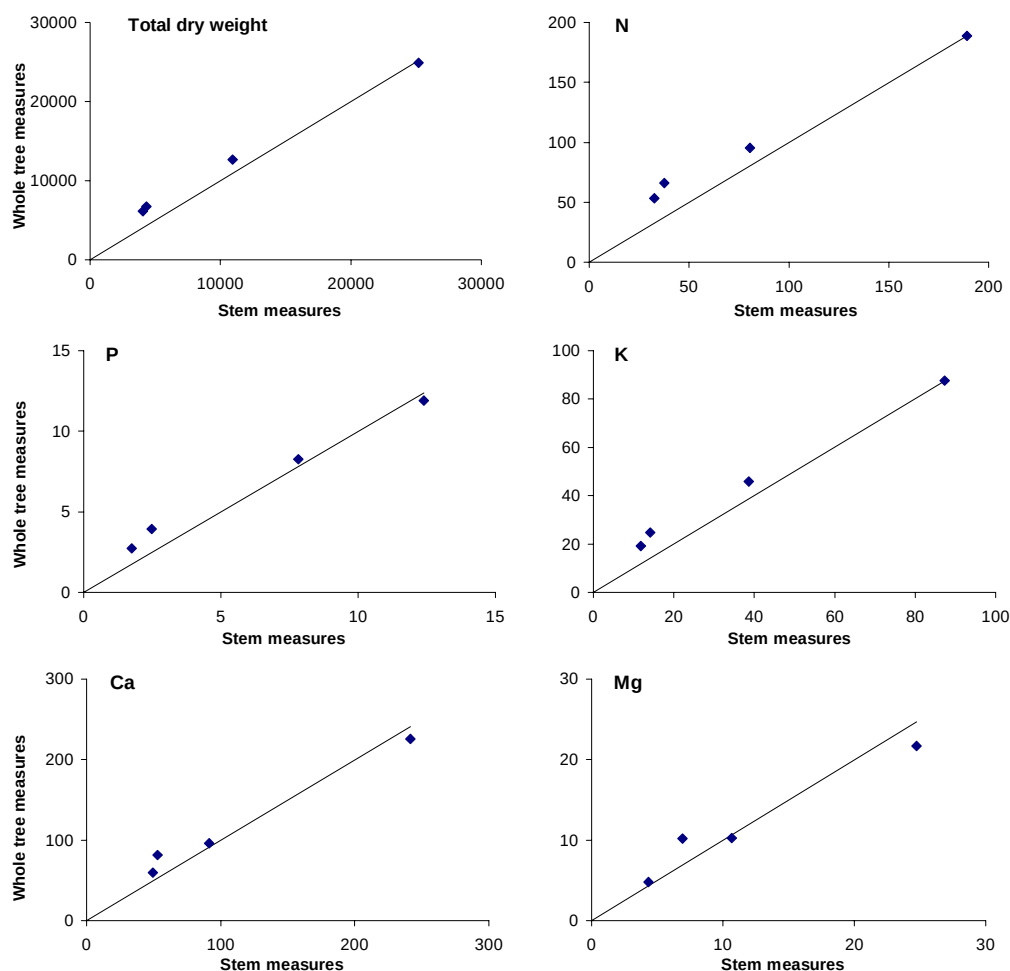


All of the above estimates were based on individual stem measurements in replicate plots at each site and use of the predictive functions derived for single stems. These estimates agreed well with those derived from predictive functions for whole tree measurements at the higher productivity *E. polybractea* site at Narrogin (Figure 16). Estimates from the two procedures were in close agreement (<4 % difference) for total biomass and N, P and K contents, although differences for Ca, Mg and Na were larger (7-13 %). At the other Narrogin site (*E. loxophleba* ssp. *lissophloia*), the two methods produced similar estimates for P, Ca and Mg (4-6 % differences). However, biomass and N and K contents were 15 to 17 % higher when estimated from the whole-tree regression functions.

At the lower yielding Kalannie sites, estimates from the two different procedures were not as well matched, with values from the whole-tree functions always being higher than those from the single stem models (Figure 16). For *E. loxophleba* ssp. *lissophloia* (higher fertility site) differences between

the estimates ranged from 11 % (Mg) to 55% (N and K) and for *E. kochii* ssp. *plenissima* (lower fertility site) from 38 % (Mg) to 48 % (N).

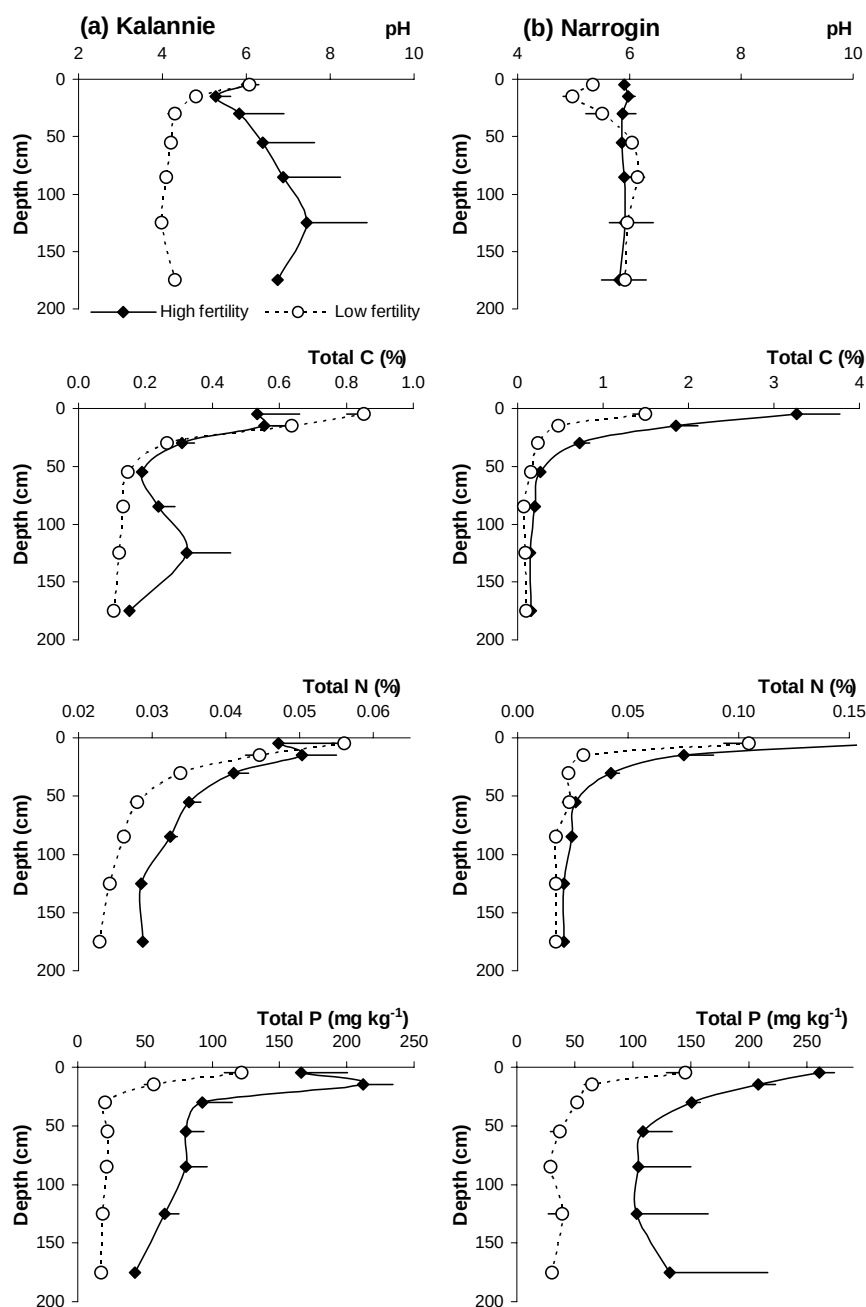
Figure 16. Estimates of total above-ground biomass and nutrient content (kg ha^{-1}) of tree belts derived from whole tree measurements in relation to estimates from single stem measurements. Values are the means of 4 replicate plots and the lines indicate the 1:1 ratio between the two estimates.



4.2.2 Nutrient stores in soils under tree-belts

Trends in concentrations of total C, N and P and extractable forms of P, K, Ca, Mg and Na in soil profiles to 2 m depth show that there are generally much lower concentrations of nutrients in low fertility sites than in high fertility sites at each location (Figures 17, 18). There are large differences among sites in trends in nutrient concentrations down the profile but the variation across the replicate soil pits (indicated by error bars) is generally low.

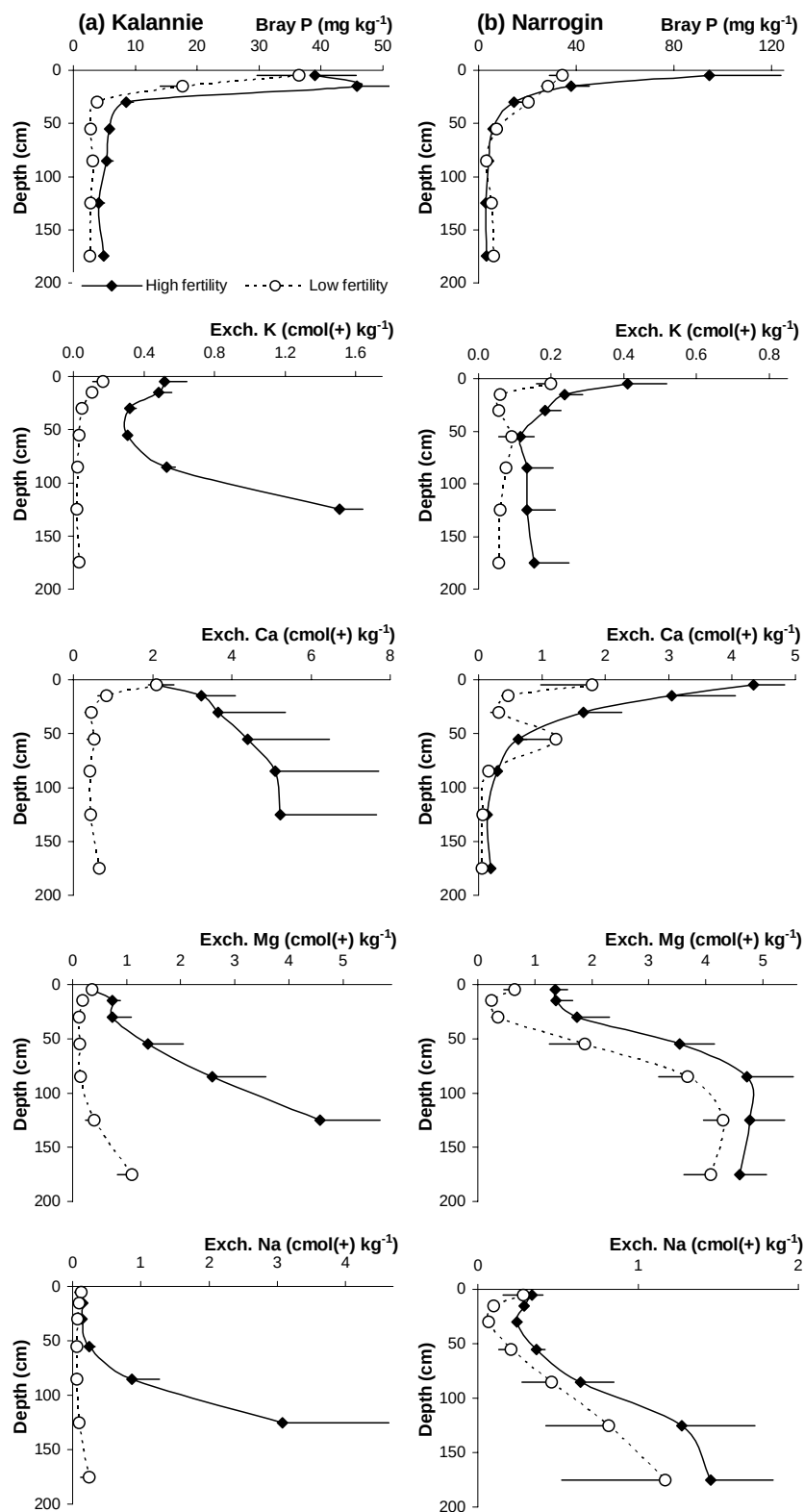
Figure 17. Variation in pH and concentrations of total C, N and P in profiles of the high (closed symbols) and low (open symbols) fertility soils at Kalannie and Narrogin. Bars are the se of the means of 4 profiles.



Trends in pH are different for the two Kalannie sites, with a strongly acid subsoil at the lower fertility sandy site and a neutral to alkaline trend in the higher fertility red soil. At Narrogin, the sandy site becomes less acidic with depth and pH of the red soil is constant throughout. Total C, N and P and Bray-P show a more typical trend towards low concentrations with depth at all four sites, although concentrations of total P are relatively high in subsoils at the more fertile sites.

Gradients down the profile in concentrations of exchangeable cations are highly variable across the four sites (Figure 18). At the lower fertility sites in both regions, concentrations of K and Ca decrease with depth, while concentrations of Mg increase, particularly at the Narrogin site.

Figure 18. Variation in concentrations of Bray P and exchangeable K, Ca, Mg, and Na in profiles of the high (closed symbols) and low (open symbols) fertility soils at Kalannie and Narrogin. Bars are the se of the means of 4 profiles.



Concentrations of exchangeable cations at the higher fertility red soil at Narrogin were higher, but followed similar trends, to concentrations in the low fertility soil (Figure 18). In the red soil at Kalannie, concentrations of K, Ca, Mg and Na increased with depth and were markedly higher than

concentrations in the low fertility site. The higher variability in the red soil profile is probably associated with the variation between soil pits in depth to calcrete (Appendix 1).

The quantities of total and extractable forms of nutrients to a depth of 2 m estimated from concentrations and bulk density measurements were markedly different across sites (Table 11). There were comparable amounts of C and N in soils at the two Kalannie site and the low fertility site at Narrogin. Amounts of C and total P in soil at the high fertility Narrogin site were more than double the amounts in soils at the other three sites. There were larger amounts of total P and exchangeable cations in the higher fertility soils were greater than in lower fertility soils in each location. The two Narrogin soils were richer in P (total and extractable), Mg and Na, but lower in Ca than their counterparts at Kalannie. Amounts of K in the low fertility soil at Kalannie were only 14% of the amount in the high fertility site in the same region, and about half the amounts in the low fertility soil at Narrogin.

A major proportion of total C to 2 m depth is in the surface 40 cm of soil at each of the 4 sites. There is a higher proportion of P in the surface 40cm of soil at the Kalannie sites (44-45%) than at Narrogin (29-36%), and this contrasts with the distribution of total N. The surface 40 cm soil contains a low proportion (< 10%) of the Mg and Na but much higher proportions of K (24-48 %) and Ca (30-69 %) across the 4 sites.

Table 11. Amounts of total C and total and extractable nutrients in soil profiles to 2m depth, and the proportion in the surface 40 cm of soil, at the high and low fertility sites at Kalannie and Narrogin

Site	Depth (cm)	Total C (t ha ⁻¹)	Total N (kg ha ⁻¹)	Total P (kg ha ⁻¹)	Bray P (kg ha ⁻¹)	Exch. K (kg ha ⁻¹)	Exch. Ca (kg ha ⁻¹)	Exch. Mg (kg ha ⁻¹)	Exch. Na (kg ha ⁻¹)
Kalannie, high fertility									
	0-200 cm	59	8168	2007	269	3243	12704	5978	3603
	% in 0-40cm	45	33	44	65	30	30	8	5
Kalannie, low fertility									
	0-200 cm	58	8051	794	169	464	3437	1474	766
	% in 0-40cm	53	31	45	62	48	35	10	16
Narrogin, high fertility									
	0-200 cm	138	10278	4139	330	1923	4457	14970	6351
	% in 0-40cm	66	44	29	71	29	69	8	5
Narrogin, low fertility									
	0-200 cm	62	7388	1378	308	868	2278	12370	4916
	% in 0-40cm	59	36	36	54	24	41	2	3

4.2.3 Comparison of above- and below-ground nutrient stores

Quantification of nutrient stores in trees provides a basis for estimating likely export rates over several harvesting cycles and the impact this may have on site nutrients without adopting nutrient replacement strategies. However, such a budgeting approach must recognize that a significant proportion of total nutrient stores are unavailable for uptake by trees and comparisons with labile or potentially labile nutrient forms are more meaningful, particularly for soil N and P. In this study, therefore, the amounts of N and P in trees provide some guide to tree requirements and export rates with frequent harvesting, but are less useful for evaluating long term impacts on soil supply of total N and P. However, comparisons of the extractable P and cation nutrient balances are more meaningful in this regard.

At the two sites at Narrogin tree belts contain higher proportions of the soil stores of nutrients than at Kalannie, except for Mg where there are large amounts in Narrogin soils (Table 12). However this

difference between regions is associated with the much lower tree belt biomass at the two Kalannie sites.

The amounts of N and P in tree belts are small compared to the total amounts in soils to 2 m (Tables 11, 12). However, the P contained in trees ranged up to 4% of the amount of Bray P in soil at the highest yielding site at Narrogin. At the high fertility site at Kalannie, trees contain the equivalent of <1 % of total stores of N, P, and of the exchangeable stores of K, Ca and Mg to 2 m depth, and up to 1.5% of the amounts in surface soil (0-40 cm). At the lower fertility site in the same region there are much larger proportions of soil K (2.5 %) and Ca (1.5 %) held in trees (Table 12), although total aboveground biomass is only 4.3 t ha⁻¹ (Table 10). At Narrogin, tree belts at the two sites contain between 4 % and 5.4 % of the K and Ca to 2 m depth and up to 19 % of the K in surface 0-40 cm soil.

Table 12. Comparison of amounts of nutrients in the tree belt and in soil to 2 m depth at the 4 study sites.

Site	Nutrient store	N (kg ha ⁻¹)	P [#] (kg ha ⁻¹)	K (kg ha ⁻¹)	Ca (kg ha ⁻¹)	Mg (kg ha ⁻¹)	Na (kg ha ⁻¹)
Kalannie, high fertility							
	Tree belt	38	2	14	49	4	13
	Soil to 2 m	8168	269	3243	12704	5978	3603
Kalannie, low fertility							
	Tree belt	33	2	12	53	7	10
	Soil to 2 m	8051	169	464	3437	1474	766
Narrogin, high fertility							
	Tree belt	189	12	87	241	25	77
	Soil to 2 m	10278	330	1923	4457	14970	6351
Narrogin, low fertility							
	Tree belt	81	8	39	91	11	33
	Soil to 2 m	7388	308	868	2278	12370	4916

Bray -extractable P

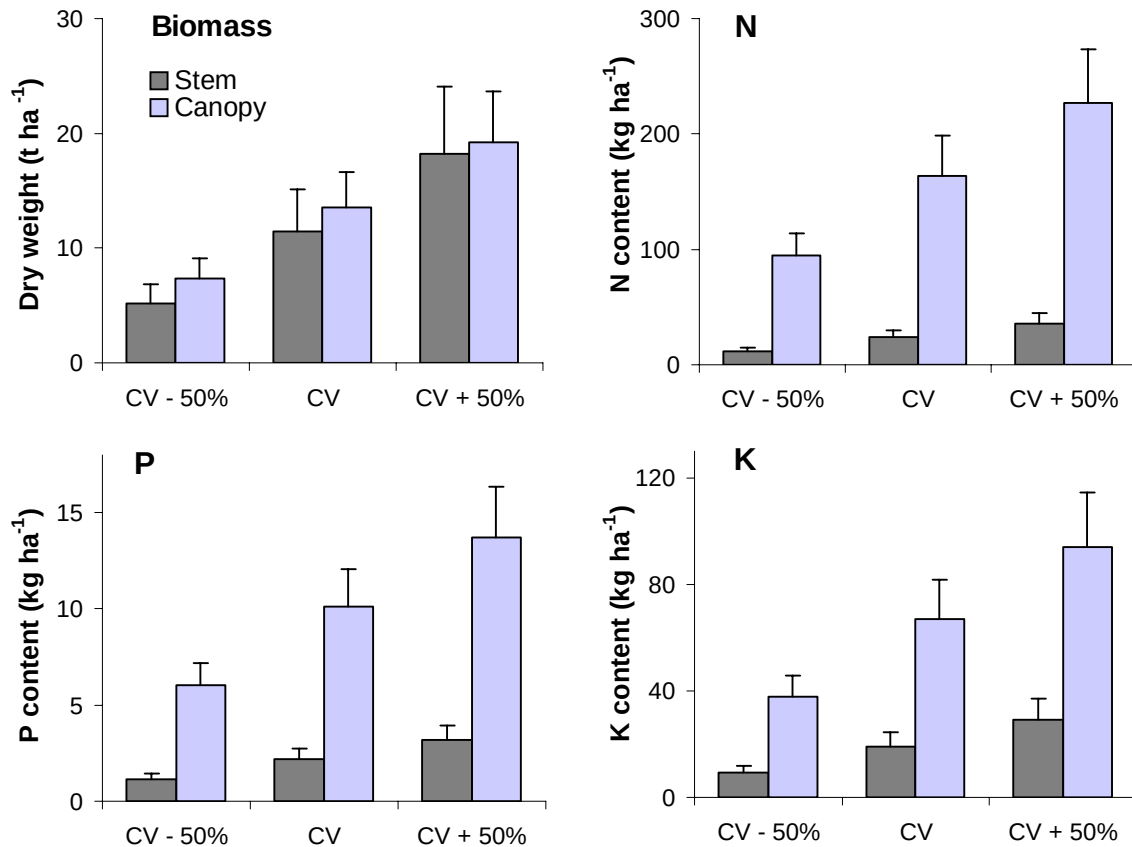
4.2.4 Nutrient export rates in relation to amount of biomass and frequency of harvest

The predictive functions that have been derived can be used to estimate effects of varying tree belt age or tree size on biomass and nutrient contents and distribution among components and the potential for nutrient export over several harvesting cycles. We have developed relationships between above-ground biomass or nutrient content and tree belt age based on the sampling of trees from sites across the age range. However, these growth curves are not reliable for several reasons, notably (i) growth in the 2 years prior to sampling had been severely affected by drought, and (ii) the selective sampling of a range in tree sizes did not give a good estimate of average tree size at each site.

As an interim approach we look here at the effect that varying the size of trees has on the amounts and allocation of biomass and major nutrients in tree belts. Biomass of the 5 year-old *E. polybractea* tree belts on the high fertility site at Narrogin is at a level that would be suitable for harvesting (J. Bartle, personal communication). The measurements at this site have been used to evaluate the effect of reducing or increasing individual tree stem volume (i.e. earlier or later harvesting) on the amount and allocation of biomass, N, P and K (Figure 19). The changes in stem volume resulted in commensurate changes in total biomass, although the canopy fraction was a higher proportion of total biomass for the

smaller trees (59 %) than the larger trees (51 %). The changes to the amounts and allocation of the three nutrients were less than the changes to biomass. The nutrient data again illustrates the high proportion of N, P and K that is in the canopy tissues.

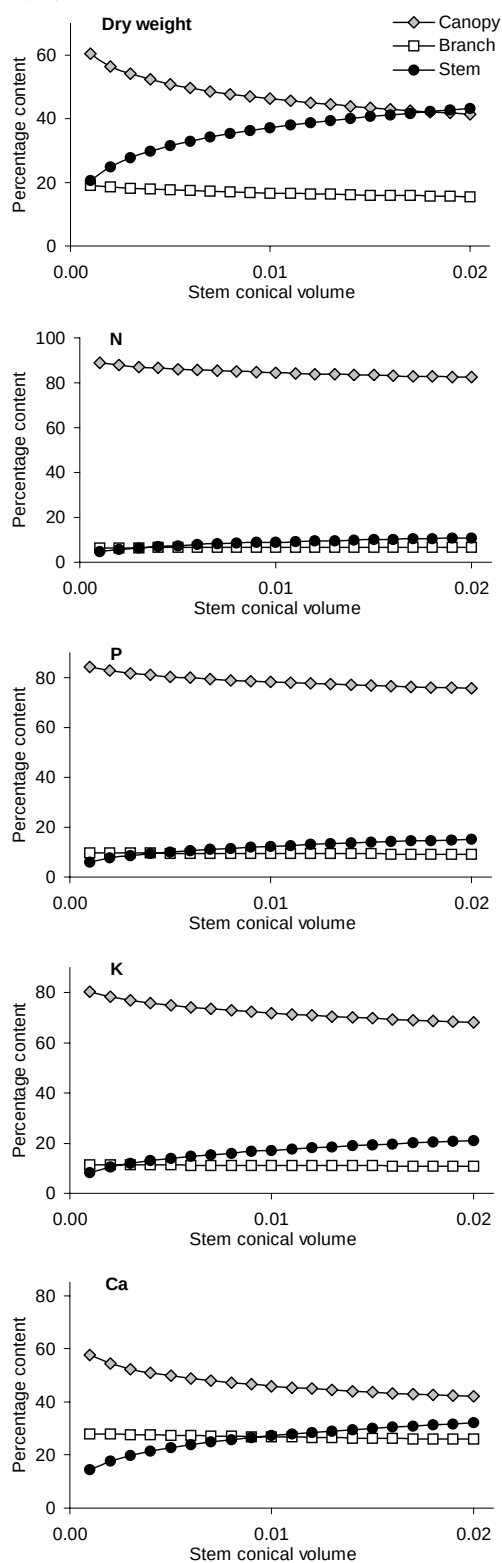
Figure 19. Biomass and N, P and K contents of the canopy (leaf + twig + fruit) and stem (stem + branch) components of *E. polybractea* predicted from stem conical volume (CV) when measured at 5 years and estimated with 50 % lower or 50 % higher volume of each tree.



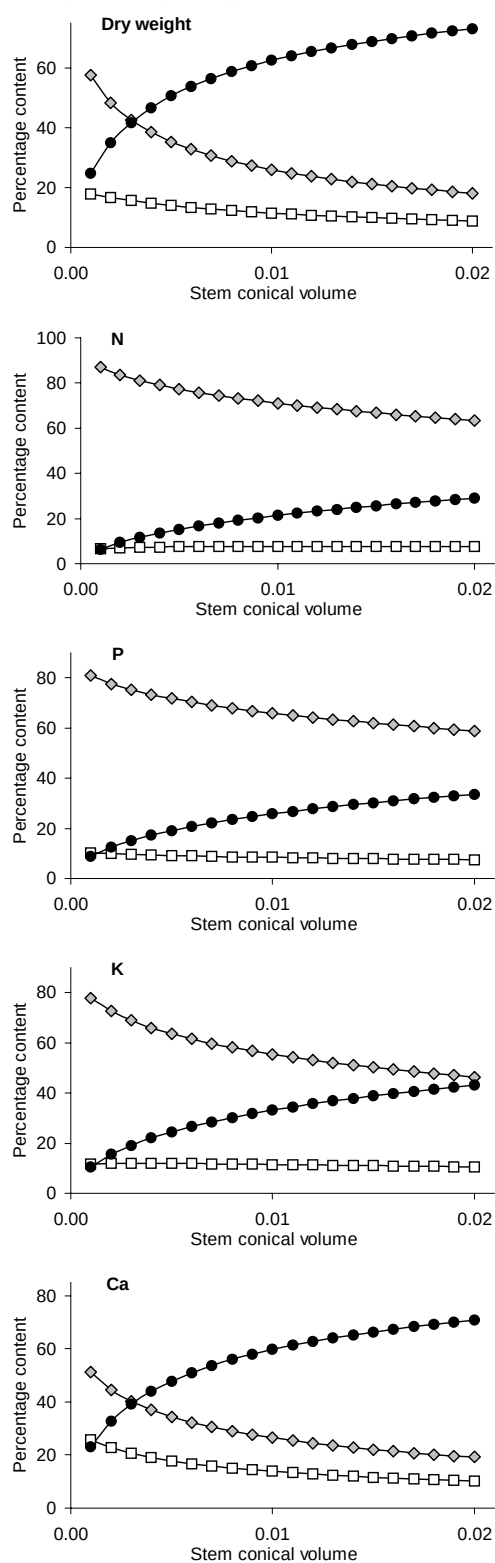
The relative insensitivity of the allocation of nutrients between tree components to changes in tree size (Figure 19) can also be evaluated over a wider range in tree size using predictions from the fitted single-stem functions. The changes in allocation of biomass and nutrients among canopy, stem (wood + bark) and branch (5-20 mm diam.) components for *E. polybractea* growing on high fertility soils and *E. loxophleba* ssp. *lissophloia* growing on low fertility soils at Narrogin up to a maximum stem volume of 0.02 m³ is shown in Figure 20. This is close to the maximum stem size in the *E. polybractea* plots and 3 times higher than the maximum size of *E. loxophleba* ssp. *lissophloia*, although average stem sizes are much lower (0.002 and 0.001 m³ respectively). In *E. polybractea*, biomass and Ca show the greatest changes in allocation with increasing stem size while the distribution of N, P and K are relatively insensitive. The changes in *E. loxophleba* ssp. *lissophloia* are much greater, with stems becoming the dominant component and containing increasing proportions of the nutrients as tree size increases.

Figure 20. Changes in the distribution of biomass, N, P, K and Ca among canopy (grey symbol), branch (5-20 mm diam.; open symbol) and stem (solid symbol) components of *E. polybractea* and *E. loxophleba* ssp. *lissophloia* with increasing stem size.

E. polybractea



E. loxophleba* ssp. *lissophloia



Harvesting of the *E. polybractea* tree belts at Narrogin were estimated to remove the equivalent of about 5 % of the exchangeable K and Ca in soil to 2 m depth (see above). In the longer term, four harvesting cycles over 20 years (assuming nutrient content of regrowth is similar to saplings) could have significant impacts on site nutrient resources, particularly on soils with low nutrient reserves. Biomass on the two sites at Kalannie was only about one-sixth of the biomass of *E. polybractea* tree-belts at Narrogin, probably due to lower average rainfall, and the impacts of two years of drought. A single harvest of a tree-belt on the sandy site at Kalannie with an equivalent biomass to the Narrogin site could remove more than 10 % of the K in soil to 2 m.

4.2.5 Differences in soil nutrient properties between tree and alley soils

There was no significant difference between tree-belt and alley soils in concentrations of total N and exchangeable K and Na at any of the sites (Table 13). The higher concentrations of organic C and total P in alley soil at the Narrogin sandy site suggest there may be some intrinsic difference between soils, as conversion of the land to tree belts would not be expected to have an effect on total stores in such a short time frame. The largest differences between the land uses were in concentrations of labile forms of N and P. At the Narrogin sites, concentrations of potential (anaerobic) N in alley soils were 30% higher (red soil) and double (sand) the concentrations in tree-belt soils. Concentrations of Bray-extractable P were higher in alley soils at three of the four sites, with differences ranging from 24% at the Kalannie high fertility site to 57% at the Narrogin high fertility site. Concentrations of exchangeable Ca and Mg were also higher in alley soils at the Kalannie high- and Narrogin low-fertility sites.

Table 13. Chemical properties of surface 0-10 cm soils sampled from within tree-belts and in adjacent cropping alleys at the four study sites. Values are the means and standard deviations for the 4 replicate plots at each site.

Region	Soil fertility	Land use		pH	Organic C (%)	Total N (%)	Anaerobic N (mg kg ⁻¹)	Total P (mg kg ⁻¹)	Bray P (mg kg ⁻¹)	Exch. K cmol(+) kg ⁻¹	Exch. Ca cmol(+) kg ⁻¹	Exch. Mg cmol(+) kg ⁻¹	Exch. Na cmol(+) kg ⁻¹
Kalannie													
	High	Tree	Mean	5.77	0.61	0.049	6.9	190	51.7	0.57	2.00	0.37	0.10
			sd	0.19	0.26	0.019		27	14.5	0.27	1.18	0.19	0.04
		Alley	Mean	5.50	0.69	0.051	13.6	193	65.5	0.50	2.36	0.43	0.09
	sd		0.43	0.15	0.014		66	13.9	0.36	1.02	0.18	0.02	
	ANOVA signif. †			ns	ns	ns	ns	ns	*	ns	*	**	ns
	Low	Tree	Mean	5.91	0.94	0.056	9.9	152	51.0	0.13	2.37	0.43	0.11
			sd	0.28	0.16	0.007		27	19.8	0.02	0.17	0.02	0.01
		Alley	Mean	6.05	0.97	0.061	13.9	168	48.4	0.26	2.53	0.42	0.11
sd	0.10		0.29	0.014		33	10.8	0.12	0.38	0.07	0.03		
ANOVA signif.			ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	
Narrogin													
	High	Tree	Mean	5.90	3.74	0.188	23.1	384	90.4	0.44	4.29	1.56	0.34
			sd	0.10	0.88	0.053		115	45.6	0.19	0.68	0.38	0.15
		Alley	Mean	5.65	3.75	0.198	30.4	509	161.7	0.44	5.63	1.54	0.23
	sd		0.18	0.55	0.029		88	31.1	0.16	1.60	0.52	0.06	
	ANOVA signif.			*	ns	ns	+	ns	**	ns	ns	ns	ns
	Low	Tree	Mean	5.23	1.43	0.102	12.7	170	41.0	0.20	1.37	0.53	0.24
			sd	0.11	0.15	0.012		29	8.0	0.08	0.19	0.22	0.09
		Alley	Mean	5.47	1.63	0.114	25.7	226	70.9	0.21	3.00	0.72	0.16
sd	0.05		0.14	0.009		29	11.2	0.05	0.45	0.14	0.03		
ANOVA signif.			*	*	ns	*	*	*	ns	**	*	ns	

† ANOVA significance of differences between land uses: ns not significant; + P < 0.10; * P < 0.05; ** P < 0.01

5. Discussion

Regression models relating biomass and nutrient contents of tree components to tree dimension measurements explained a high proportion of the variability across the full data set. This was despite a high variability in tree to tree structure and form which is caused by genotypic variation, damage by animals and insects, and to variable rainfall including two years of drought in the course of their growth. The variability in tree form is compounded by the lack of canopy closure that gives a more uniform architecture to fast growing high productivity plantation species. This tree to tree variability contributes to greater variability in relationships for individual components compared to relationships where components are combined (canopy, stem + branch). Functions for total above-ground biomass and N, P, K, Ca, Mg and Na contents always accounted for a higher proportion of the variance than functions for individual tree components. The relatively high proportion of the variability accounted for in all relationships is partly associated with the large span in tree size and age and the requirement to transform values to a logarithm scale for regression analysis. There is greater scatter in the untransformed data, and differences between factors are larger than is apparent for relationships presented on a logarithmic scale.

Differences among species and site factors in the single stem regressions were highly significant despite the underlying variability in the amount and allocation of biomass and nutrients in trees. This highlights the benefit of incorporating all the sample trees into single comprehensive models. The linear form of relationships obtained for any combination of the species/fertility/region categories gives confidence that the 3 or 4 sites sampled to cover the age and size range were representative of the broader dataset.

For the single stem functions, largest effects of site factors (fertility, region) were on the individual (leaf, twig) and combined canopy components. Tree sampling in the Kalannie and Narrogin regions, which incorporated comparison of alternative species, was primarily designed to provide a contrast in growing conditions, with higher rainfall and lower evaporation at Narrogin. However, it is clear through this study that there are also marked differences in the soils and their chemical properties between the two regions. For example, the deep yellow ‘wodgil’ soils on which many of the low fertility sites were selected at Kalannie have very different characteristics to the low fertility soils at Narrogin. This is exemplified by the descriptions and chemistry of profiles at the representative sites studied in the second phase of the project (Table 11, Appendix 1). In particular the soils at Narrogin have a higher P and Mg status than their counterparts at Kalannie. Thus, for the regional effects identified in the biomass and nutrient relationships there is likely to be a confounding of climate and soil effects.

Differences in tree nutrient content between species and in relation to site factors is influenced by the effects of these factors on the distribution of biomass as well as by variation in tissue nutrient concentrations. However, the effects on biomass allocation do not necessarily explain site effects on nutrient contents. For example, there were marked regional differences in the total above-ground contents of all nutrients but no effect on total biomass, where the regression accounted for 99 % of the variance (Table 6). The greater tree to tree variation in tissue concentration of Ca, compared with N and K (Table 4) did not appear have any marked negative effect on the fit of the regression models, particularly for combined canopy and stem components.

Overall the single stem relationships provide a better prediction of the amount and allocation of biomass and nutrients within the tree. The whole tree regression functions which rely on measurements of canopy dimensions, tree height and numbers of stems are more appealing for practical application than the more measurement-intensive single stem functions which rely on individual stem data. The inferior fit of whole tree regression functions to stem components is understandable, given that they rely primarily on canopy volume measurements and there is little account taken of stem size. However, functions for canopy component biomass and nutrients based on the whole tree measurements are as good as the functions using single stem measurements and would

be the preferred approach if the primary interest is in predicting canopy composition in tree-belts. The possibility of using even fewer tree-belt measurements (eg. average estimated dimensions or size class dimensions) together with site categorization to make more rapid assessments of tree belt canopy biomass and nutrient composition could also be evaluated in future studies.

The prototype OMEN toolkit that was developed simplifies the estimation of amounts of biomass and nutrients in tree-belts and their distribution in the different product categories. Although the experimental framework for this study has covered a broad range of sites with measurements of three key species, the predictive capacity of the toolkit still relies on, and is restricted by, the range of the empirical information. It may be possible in future to parameterize and use a growth model in conjunction with this empirical nutrient data to extend the capacity of the toolkit and provide estimates beyond the range of the current data sets. OMEN could also be used to generate a series of look-up tables covering tree size-class categories for different species and site types that could be used more readily across the industry.

The initial assessment of the applicability of the predictive functions developed for saplings to estimating biomass and nutrient composition of coppice shoots showed there was poor agreement between measured and predicted values. The functions over-predicted biomass and the quantities of nutrients in coppice. However, this component of the study was very restricted, with only 4 trees sampled at one site. Until more sampling comparisons are made it will not be known whether the magnitude of the difference is representative of other situations. Differences between coppice and sapling can be expected, given the contrast in tree structure and the competition among coppice shoots. Comparisons of sapling and coppice composition at a limited number of sites may provide sufficient information to incorporate an adjustment factor into the toolkit for coppice regrowth estimates.

Where the single stem and whole tree functions were used to estimate biomass and nutrient composition of tree belts in 4 replicate plots at the 4 representative sites, there was generally good agreement between the two procedures for the Narrogin sites but not as good for the Kalannie sites. At both Kalannie sites, the whole-tree functions predicted larger amounts of biomass, N, P and K than the single-stem functions. A possible explanation for this disparity at Kalannie is that growth of the canopy and stems are out of phase. Tree canopies may have expanded to a greater extent relative to stem volume in the period between destructive sampling to establish regression functions and the time that tree dimension measurements were taken in replicate plots. This is consistent with the sampling being done at the end of a 2-year period of drought while plot measurements were made after a period of higher rainfall. It is also consistent with the discrepancy in estimates being evident at Kalannie but not in the moister environment at Narrogin. In other studies of oil mallee growth, seasonal effects on allometric functions have been observed (Huxtable and Bartle, unpublished data).

Biomass and nutrient contents of tree belts at the Kalannie sites were low relative to quantities at the two Narrogin sites. Only the 5 year-old *E. polybractea* tree belts at Narrogin had grown to a size suitable for feedstock to the integrated wood processing plant, although farmers in the Kalannie region have been harvesting much smaller trees for eucalyptus oil extraction. Tree biomass at the higher fertility Narrogin site was 6-times higher than the biomass at the Kalannie sites. A sequence of dry years would have affected productivity of younger stands in this region, although other factors (genetics, nutrients, pest and animal damage) may also have contributed to low productivity. The biomass of 4.3 t ha⁻¹ for the 3 year-old *E. kochii* site compares with a biomass of 7 t ha⁻¹ for another 3 year-old tree-belt in the Kalannie region reported by Wildy *et al.* (2003). They measured growth through time and found biomass increased 5-fold between 3 and 6 years of age. If the tree belt we measured followed a similar growth pattern then biomass could be about 20 t ha⁻¹ at 6 years on this low fertility soil. While the proportional increase in nutrient content of the tree-belt at 6 years will be less than for biomass, export of K and Ca in harvested biomass may be as high as 10 % of the exchangeable K and Ca and about 5 % of the extractable P in soil to 2 m depth at this site.

The distribution of nutrients in the major tree components (or product categories) is advantageous in terms of the potential to recycle nutrients back to the sites in ash produced at the processing plant.

Relatively low amounts of nutrients will be lost in the activated carbon product because of the low amounts in stem and branch components, an exception being Ca. The largest loss will be N, all of which will be volatilized during combustion of canopy components for bioenergy production. Harvesting of the 5 year-old *E. polybractea* tree belts at Narrogin would result in losses of about 189 kg N ha and 120 kg Ca ha from the site that could not be returned in ash. Some losses of other nutrients including P can occur through high temperature combustion but most of the other nutrients other than N measured in this study are likely to be retained in the ash (Raison *et al.*, 1985). With the integrated processing plant at Narrogin not yet in operation, the properties of the ash produced and the method of application of ash back onto tree belt sites has still to be evaluated. It may be strategically and economically advantageous to target sites with lower fertility soils, where the greatest benefits of ash in terms of nutrient replenishment and liming effects will be achieved.

Nutrient depletion through biomass harvesting and the effect on site nutrient balance is only one factor that may impact on the sustained productivity of mallee tree belts. Decline in supply of labile forms due to changes in management of soils under tree-belts is likely to be more significant to sustaining productivity through several harvesting cycles. In a study of impacts of changes in land use from managed pasture to blue gum plantations in the high rainfall region of south-western Australia concentrations of labile forms of N and P were found to have declined markedly in plantation soils during the first rotation (Grove *et al.*, 2001; O'Connell *et al.*, 2003). The balance of cation nutrients in surface soils was also affected by the change in land use. The effects were attributed primarily to reduced fertilizer applications and to the lower quantity and quality of organic matter input to soils under plantations. Our evaluation of differences in nutrient supply properties between surface soils from tree-belts and alleys at the 4 sites suggest that there may be a similar general trend towards lower concentrations of plant available N, P and cations in tree-belt soils. However, this conclusion is based on limited sampling at this stage and further evaluation is required. On sites where nutrient supply in tree-belt soils does become more limiting for tree growth and is not corrected by nutrient inputs, oil mallee trees are likely to acquire more of their nutrient requirements from uptake in adjacent alley soils, which may increase competition and affect the yield of agricultural crops. Alternatively, oil mallee trees may draw upon deeper reserves of nutrients that have been leached beyond the rooting zone of agricultural crops, thus bringing more nutrients into the agricultural system, and/or delaying the demand for nutrients from the adjacent alley soils.

6. Implications

- Estimates of the amounts and distribution of biomass and major nutrients can be made from both the whole tree and single stem regression functions. The single stem functions provide more reliable estimates for the stem and branch components of trees.
- Site factors (fertility, region) have much greater effects on the amounts and nutrient composition of canopy (leaf, twig) components than on the stem and branch components of oil mallee.
- Relationships developed for sapling trees were found to over-predict the biomass and nutrient contents of coppice regrowth at one site – further refinement of relationships will be required for use with coppice.
- The prototype toolkit OMEN simplifies the calculation of amounts and allocation of biomass and nutrients in tree-belts using tree dimension measurements. OMEN could be used to generate lookup tables for tree size classes for application across the industry. There is potential to further refine and expand the toolkit through incorporation of information from other studies or by linkage to growth model output.
- Estimates of above-ground nutrient stores in tree-belts of harvestable size indicate that biomass removal over several harvesting cycles will significantly deplete site stores of some nutrients unless replacement strategies (return of ash, fertilizer application) are implemented. Site depletion will be moderated by the potentially large depth of root penetration of mallee and the possible large amount of leached nutrients in deep subsoil storage.
- The impacts of tree-belt management on labile (plant available or potentially available) forms of nutrients in soil is more important than the effects on total nutrient balances. Comparisons of nutrient properties of tree-belt and alley soils indicate that concentrations of labile forms of N and P are lower in tree-belt soil. If soil nutrient supply in tree belts is not managed, trees may increasingly rely on nutrients acquired from the alley soils. One form of management may be to provide greater inputs through modification to the annual crop and pasture rotations in the alley where greater proportions of legumes, or greater fertiliser inputs might be used.
- More than 75 % of N, P and K and about 50 % of the Ca in trees are in canopy (leaf, twig) components that will be separated from woody components and used in oil extraction and fuel for energy at the integrated processing plant. Thus, there is potential to return large amounts of nutrients other than N (volatilized during combustion) to tree-belt sites in ash.

7. Recommendations

- Procedures to assess oil mallee tree-belts and estimate amounts and relative proportions of different product categories will become increasingly important once the integrated processing plant is operational. The models and toolkit developed in this study are appropriate for providing this predictive capability.
- Choice of use of whole tree or single stem model should be based on accuracy required. The whole tree model using tree dimension measurements requires fewer measurements than the single stem model in providing estimates of the biomass and nutrient content of leaf, twig and whole canopy. The single stem model using stem dimension measurements provides more accurate estimates of the biomass and nutrient contents of woody components, although either model can be used to predict all components.
- The models and toolkit which have been developed for sapling trees, will need to be recalibrated for use in predicting the biomass and nutrient composition of coppice regrowth.
- The OMEN toolkit can be used to produce simple lookup tables for ready estimation of the biomass and nutrient composition of different tree size classes. It should be further refined through incorporation of biomass and tree measurement data from other studies.
- Ash return to sites is one way of maintaining site nutrient capital. The ash could be recycled selectively to sites, for example targeting sandy sites with relatively low reserves and acidic soils which may benefit from the liming effect of ash.
- Supplementary fertilizer application, particularly N and P, will be required to sustain high growth rates over several harvesting cycles.
- Knowledge of whether growth of oil mallee will respond to nutrient application on some sites is not available. Establishment of small trials is warranted to develop guidelines to help growers in targeting sites for ash recycling and fertilizer application.
- There is a need to define the size of the deep soil nutrient store and the scope for modification of the adjacent annual plant agriculture to better complement the tree crop by greater input of N from legumes or fertiliser.

8. References

- Abrahamson, L.P., Robison, D.J., Volk, T.A., White, E.H., Neuhauser, E.F., Benjamin, W.H. and Peterson, J.M. (1998). Sustainability and environmental issues associated with willow bioenergy development in New York (U.S.A.). *Biomass and Bioenergy* **15**, 17-22.
- Adegbidi, H.G., Volk, T.A., White, E.H., Abrahamson, L.P., Briggs, R.D. and Bickelhaupt, D.H. (2001). Biomass and nutrient removal by willow clones in experimental bioenergy plantations in New York State. *Biomass and Bioenergy* **20**, 399-411.
- Bartle, J.R. (1999). The new hydrology: new challenges for landcare and tree crops. WA State Landcare Conference, Esperance, September, 1999, pp. 52-63.
- Bartle, J.R. (2001). New perennial crops: mallee eucalypts, a model, large-scale perennial crop for the wheatbelt. In: Managing Agricultural Resources 3 Proceedings Outlook Conference 2001. ABARE Canberra, pp 117-128.
- Barton, A. (2000). The Oil Mallee Project: A multifaceted industrial ecology case study. *Journal of Industrial Ecology* **3**, 161-176.
- Bray, R.H. and Kurtz, L.T. (1945). Determination of total organic and available forms of phosphorus in Soil. *Soil Science* **59**: 39-45.
- Eastham, J. Scott, P.R., Steckis, R.A., Barton, A.F.M., Hunter, L.J. and Sudmeyer, R.J. (1993). Survival, growth and productivity of tree species under evaluation for agroforestry to control salinity in the Western Australian wheatbelt. *Agroforestry Systems* **21**, 223-237.
- Fölster, H. and Khanna, P.K. (1997). Dynamics of nutrient supply in plantation soils. In: Management of Soil, Nutrients and Water in Tropical Plantation Forests (Editors E.K.S. Nambiar & A. G. Brown). Australian Centre for International Agricultural Research, pp 339-378
- Enecon Pty Ltd. (2001). Integrated tree processing of mallee eucalypts. RIRDC Publication No 01/160 RIRDC Project No OIL-3A.
- Grove, T.S., O'Connell, A.M., Mendham, D., Barrow, N.J. and Rance, S.J. (2001). Sustaining the productivity of tree crops on agricultural land in south-western Australia. RIRDC Publication No 01/09; RIRDC Project No CSF-53A.
- Heilman, P. and Norby, R.J. (1998). Nutrient cycling and fertility management in temperate short rotation forest systems. *Biomass and Bioenergy* **14**, 361-370.
- Isbell, R.F. (1996). The Australian soil classification. 143 pp. (CSIRO Publishing, Melbourne).
- Keeney, D.R. and Bremner, J.M. (1966). A chemical index for soil nitrogen availability. *Nature* **211**: 892-893.
- Khanna, P.K., Raison, R.J. and Falkiner, R.A. (1994). Chemical composition of ash derived from *Eucalyptus* litter and its effects on forest soils. *Forest Ecology and Management* **66**, 107-125.

- Kimmins, J.P. (1977). Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting, *Forest Ecology and Management* **1**, 169-183.
- Kimmins, J.P. (1997). Predicting sustainability of forest bioenergy production in the face of changing paradigms. *Biomass and Bioenergy* **13**, 201-212.
- Lundborg, A. (1998). A sustainable forest fuel system in Sweden. *Biomass and Bioenergy* **15**, 399-406.
- McArthur, W.M. (1991). Reference soils of south-western Australia. Department of Agriculture, Western Australia, 265 pp.
- O'Connell, A.M., Grove, T.S., Mendham, D., and Rance, S.J. (2003). Changes in soil N status and N supply rates in agricultural land afforested with eucalypts in south western Australia. *Soil Biology and Biochemistry* **35**: 1527-1536.
- Proe, M.F., Dutch, J.C., Pyatt, D.G. and Kimmins, J.P. (1997). A strategy to develop a guide for whole-tree harvesting of Sitka spruce in Great Britain. *Biomass and Bioenergy* **13**, 289-299.
- Raison, R.J., Khanna, P.K. and Crane, W.J.B. (1982). Effects of intensified harvesting on rates of nitrogen and phosphorus removal from *Pinus radiata* and *Eucalyptus* forests in Australia and New Zealand. *New Zealand Journal of Forestry Science* **12**, 394-403.
- Raison, R.J., Khanna, P.K. and Woods, P.V. (1983). Transfer of elements to the atmosphere during low-intensity prescribed fires in three Australian subalpine eucalypt forests. *Canadian Journal of Forest Research* **15**, 657-664.
- Robinson N., Harper R.J., Smettem K.R.J., Archibald R., Stilwell A., Oliver Y. (2002) Recharge reduction on degraded agricultural soils with agroforestry systems. In '17th World Congress of Soil Science 14-21 August 2002'. Bangkok, Thailand
- Steenari, B.M. and Lindqvist, O. (1997). Stabilisation of biofuel ashes for recycling to forest soil. *Biomass and Bioenergy* **13**, 39-50.
- State Salinity Council (2000). The Salinity Strategy. Government of Western Australia.
- Wildy, D.T., Bartle, J.R., Pate, J.S. and Arthur, D.J. (2000). Sapling and coppice biomass production by alley-farmed 'oil mallee' *Eucalyptus* species in the Western Australian wheatbelt. *Australian Forestry* **63**, 147-157.
- Wildy, D.T., Pate, J.S. and Bartle, J.R. (2003). Silviculture and water use of short-rotation mallee eucalypts. RIRDC Publication No 03/033; RIRDC Project No OIL-4A.
- Wise, P.K. and Pitman, M.G. (1981). Nutrient removal and replacement associated with short-rotation eucalypt plantations. *Australian Forest* **44**, 142-152.

9. Appendix

Appendix 1 – Soil descriptions for the oil mallee sites

Kalannie – lower fertility site

Plot 1 Australian Soil Classification: Yellow Kandosol

Depth (cm)	Horizon	Description
0 – 10	A11	Dark yellowish-brown [10YR 4.5/4] loamy sand (10% clay); single grain; loose when moist
10 – 20	A12	Yellowish-brown [10YR 5/6] loamy sand (10% clay); single grain; loose when moist
20 – 40	B11	Brownish-yellow [10YR 6/6] sandy loam; single grain (15% clay); loose when moist
40 – 70	B12	Brownish-yellow [10YR 6/8] sandy loam (15% clay); single grain; loose when moist
70 – 100	B21	Brownish- yellow [10YR 6/8] light sandy clay loam (20% clay); single grain; loose when moist
100 – 150	B22	Brownish-yellow [10YR 6/8] sandy clay loam (25% clay); massive; soft when moist. Occasional pisolitic ferruginous gravel, 5mm dia.
150 – 200	B23	Brownish-yellow [10YR 6/8] sandy clay loam (25% clay); massive; soft when moist. Low amounts of ferruginous gravel and moderate amounts of hardened red [2.5YR 4/8] mottles

Plot 2 Australian Soil Classification: Yellow Kandosol

Depth (cm)	Horizon	Description
0 – 10	A11	Yellowish-brown [10YR 5/5] light sandy loam (10% clay); single grain; loose when moist
10 – 20	A12	Yellowish-brown [10YR 5/5] sandy loam (15% clay); single grain; loose when moist
20 – 40	B11	Brownish-yellow [10YR 6/6] sandy loam (15% clay); single grain; loose when moist
40 – 70	B12	Brownish-yellow [10YR 6/6] light sandy clay loam (20% clay); single grain; loose when moist
70 – 100	B21	Brownish-yellow [10YR 6/6] sandy clay loam (25% clay); massive; slightly coherent when slightly moist
100 – 150	?B31	Reddish-yellow [7.5YR 6/6] sandy loam (15% clay); single grain; loose when slightly moist. Low amounts of pisolitic ferruginous gravel to 1cm dia. and common irregular hardened red mottles
150 – 200	?B32	Yellowish-red [5YR 5/8] sandy loam (15% clay); single grain; loose when slightly moist. Low amounts of irregular ferruginous gravel, 2 to 5mm dia. and common hardened red mottles

Plot 3 Australian Soil Classification: Yellow Kandosol

Depth (cm)	Horizon	Description
0 – 10	A11	Brown [10YR 4.5/3] loamy sand (10% clay); single grain; loose when moist
10 – 20	A12	Yellowish-brown [10YR 5/4] loamy sand (10% clay); single grain; loose when moist
20 – 40	B11	Brownish-yellow [10YR 6/6] sandy loam (15% clay); single grain; loose when moist
40 – 100	B12	Brownish-yellow [10YR 6/6] light sandy clay loam (20% clay); single grain; loose when moist
100 – 150	B21	Brownish-yellow [10YR 6/8] light sandy clay loam (20% clay); single grain; loose when moist
150 – 225	B22	Brownish-yellow [10YR 6/8] sandy clay loam (25% clay); massive; slightly coherent when moist

Plot 4 Australian Soil Classification: Yellow Kandosol

Depth (cm)	Horizon	Description
0 – 10	A11	Dark yellowish-brown [10YR 4/4] light sandy loam (10% clay); single grain; loose when moist
10 – 20	A12	Yellowish-brown [10YR 5/6] sandy loam (15% clay); single grain; loose when moist
20 – 40	B11	Brownish-yellow [10YR 6/6] sandy loam (15% clay); single grain; loose when moist
40 – 70	B12	Brownish-yellow [10YR 6/6] light sandy clay loam (20% clay); single grain; loose when moist
70 – 100	B21	Brownish-yellow [10YR 6/8] sandy clay loam (25% clay); massive; loose when moist. Occasional irregular ferruginous gravel to 1cm dia.
100 – 150	B22	Brownish-yellow [10YR 6/8] sandy clay loam (25% clay); massive; loose when slightly moist
150 – 200	B23	Brownish-yellow [10YR 6/8] sandy clay loam (25% clay); massive; slightly hard when slightly moist. Some hard but crushable lumps to 2cm dia.

Kalannie – higher fertility site

Plot 1 Australian Soil Classification: Supracalcic Red Kandosol

Depth (cm)	Horizon	Description
0 – 10	A1	Dark red [2.5YR 3/6] loamy sand (10% clay); single grain; loose when moist
10 – 20	B1	Dark red [2.5YR 3/6] light sandy clay loam (20% clay); single grain; hard when slightly moist
20 – 70	B21	Dark red [2.5YR 3/6] sandy clay loam (25% clay); single grain; hard when slightly moist
70 – 100	B31	Red [2.5YR 4/6] loamy sand (10% clay); single grain; very hard when dry. Abundant angular gravel (to 4 cm dia.); many small (2mm dia.) black inclusions; slight soft carbonate
100 – 150	B32k	Red [2.5YR 4/6] loamy sand (10% clay); single grain; very hard when dry. Abundant pinkish-grey [5YR 7/2] angular lumps of hard calcrete to 5cm dia.
150 – 200	B33k	Mainly large angular lumps (to 5cm dia.) of hard calcrete with a matrix of red [2.5YR 4/6] sand

Plot 2 Australian Soil Classification: Red Kandosol

Depth (cm)	Horizon	Description
0 – 10	A1	Dark red [2.5YR 3/6] loamy sand to sandy loam (10% clay); single grain; loose to slightly coherent when moist
10 – 20	A3	Dark red [2.5YR 3/6] light sandy clay loam (20% clay); single grain; hard when moist
20 – 40	B11	Red [2.5YR 4/8] sandy clay loam (30% clay); single grain; hard, with easily crushable lumps, when moist
40 – 70	B12	Red [10R 4/8] sandy clay loam (30% clay); single grain; hard when moist
70 – 100	B21	Dark red [10R 3/6] with red [10R 4/8] surfaces, sandy clay (35% clay); massive; hard when moist. Few harder lumps of same material
100 – 150	B22	Dark red [10R 3/6] sandy clay (35% clay); massive; very hard when slightly moist

Plot 3 Australian Soil Classification: Supracalcic Red Kandosol

Depth (cm)	Horizon	Description
0 – 10	A1	Dark red [2.5YR 3/6] sandy loam (15% clay); single grain; coherent when moist
10 – 20	B1	Dark red [10R 3/6] sandy clay loam (25% clay); single grain; coherent when slightly moist
20 – 70	B21	Red [10R 3.5/6] light sandy clay (30% clay); massive; coherent when slightly moist
70 – 100	B22k	Red [10R 3.5/6] light sandy clay (30% clay); massive; coherent when slightly moist. Moderate lumps of very hard calcrete to 5cm dia.
100 – 150	B23k	Mainly angular calcrete fragments with a matrix of red [2.5YR 4/6] sand with numerous black inclusions

Plot 4 Australian Soil Classification: Red Kandosol

Depth (cm)	Horizon	Description
0 – 10	A11	Yellowish-red [5YR 4/6] sand (8% clay); single grain; loose when moist
10 – 20	A12	Yellowish-red [5YR 4/6] sandy loam (15% clay); single grain; loose when moist
20 – 40	A3	Yellowish-red [5YR 4/6] sandy clay loam (25% clay); single grain; loose when moist
40 – 100	B1	Red [2.5YR 4/6] sandy clay loam (25% clay); single grain; loose when moist
100 – 150	B21	Red [10R 4/6] sandy clay loam to sandy clay (30% clay); massive; coherent when moist
150 – 200	B22	Red [10R 4/6] sandy clay loam; massive; very hard when slightly moist. Common angular lumps of dark cemented material similar to matrix

Narrogen lower fertility site

Plot 1 Australian Soil Classification: Grey Chromosol

Depth (cm)	Horizon	Description
0 – 10	A1	Very dark grey-brown [10YR 3/2] coarse sand (5% clay); single grain; slightly coherent when moist
10-20	A1-2	Grey-brown [10YR 5/2] coarse sand (5% clay); single grain; loose when moist
20 –40	A21	Light brownish-grey [10YR 6/2] coarse sand (5% clay); single grain; loose when moist
40-70	A22	Light brownish-grey [10YR 6/2] coarse sand (5% clay); single grain; loose when moist. Abundant rounded and irregular ferruginous gravel to 2cm dia.
70-100	B21t	Abrupt irregular boundary to Light grey [10-YR 7/2] with diffuse strong brown [7.5YR 5/8] mottling sandy clay (40% clay); massive; firm when moderately moist
100-150	B22t	Light grey [10YR 7/2] with diffuse strong brown [7.5YR 5/8], red [2.5YR 4/6] and white mottling sandy clay (40% clay); massive; very firm when slightly moist
150-200	B23t	As above, with increasing red mottling

Plot 2 Australian Soil Classification: Grey Chromosol

Depth (cm)	Horizon	Description
0-10	A1	Very dark grey-brown [10YR 3/2] loamy coarse sand (10% clay); single grain; coherent when moist. Occasional pisolitic ferruginous gravel
10-20	A1-2	Grey-brown [10YR 5/2] coarse sand (5% clay); single grain; loose when moist. Slight pisolitic ferruginous gravel to 5mm dia.
20-30	A2	Pale brown [10YR 6/3] coarse sand (5% clay); single grain; loose when moist. Abundant pisolitic ferruginous gravel to 1cm dia.
30-40	B21t	Abrupt irregular boundary to Light grey [10YR 7/2] with distinct strong brown [7.5YR 5/8] and subordinate red [2.5YR 4/6] mottles, sandy clay (40% clay); massive; firm when moderately moist. Low amount of pisolitic ferruginous gravel.
40-70	B22t	Light grey [10YR 7/2] with diffuse strong brown [7.5YR 5/8] mottles, sandy clay (40% clay); massive; firm when moderately moist. Common ferruginous gravel.
70-100	B23t	Light grey [10YR 7/2] with diffuse strong brown [7.5YR 5/8], red [2.5YR 4/6] and white mottles, sandy clay (40% clay); massive; very firm when slightly moist
100-150	B24t	Diffusely mottled light reddish-brown [2.5YR 6/4], strong brown [7.5YR 5/8] and yellowish-red [5R 4/6] sandy clay (40% clay); massive; hard when dry
150-200	B25t	Mottled strong brown [7.5YR 5/8], light grey [10YR 7/2] and red [2.5YR 4/6] sandy clay (40% clay); massive; very firm when slightly moist

Plot 3 Australian Soil Classification: Grey Chromosol

Depth (cm)	Horizon	Description
0-10	A1	Very dark grey-brown [10YR 3/2] loamy sand (10% clay); single grain; slightly coherent when moist.
10-20	A1-2	Grey-brown [10YR 5/2] loamy coarse sand (10% clay); loose when moist. Occasional pisolitic ferruginous gravel
20-40	A2	Light brownish-grey [10YR 6/2] loamy coarse sand (10% clay); single grain; loose when moist. Common pisolitic ferruginous gravel to 1cm dia.
40-200	B2t	Abrupt, irregular boundary to Diffusely mottled light grey [10YR 7/2] and strong brown [7.5YR 5/8] with subordinate red [2.5YR 4/6], sandy clay (40% clay); massive; very firm when slightly moist

Plot 4 Australian Soil Classification: Grey Chromosol

Depth (cm)	Horizon	Description
0-10	A1	Very dark grey-brown [10YR 3/2] loamy sand (10% clay); single grain; slightly coherent when moist
10-20	A1-2	Grey-brown [10YR 5/2] sand (5% clay); single grain; loose when moist. Low amounts of ferruginous gravel
20-40	A2	Light brownish-grey [10YR 6.5/2] sand (5% clay); single grain; loose when moist. Abundant ferruginous gravel to 1cm dia.
40-70	B21t	Abrupt, irregular boundary to Mottled light grey [10YR 7/2] and strong brown [7.5YR 5/8] with subordinate red [2.5YR 4/6], sandy clay (40% clay); massive; very firm when slightly moist
70-100	B22t	Mottled light grey [2.5Y 7/2] and strong brown [7.5YR 5/8] with subordinate red [2.5YR 4/6], sandy clay (40% clay); massive; extremely firm when slightly moist
100-150	B23t	Light grey [5Y 7/1] with distinct strong brown [7.5YR 5/8] and subordinate red [2.5YR 4/6] mottles, sandy clay (45% clay); massive; extremely firm when slightly moist
150-200	B24t	Coarse distinctly mottled red [2.5YR 4/6] and light grey [5Y 7/1] with subordinate strong brown [7.5YR 5/8], sandy clay (45% clay); massive; extremely firm when slightly moist

Narrogen higher fertility site

Plot 1 Australian Soil Classification: Red Kandosol

Depth (cm)	Horizon	Description
0-10	A1	Dark reddish-brown [5YR 3/3] sandy loam (20% clay); single grain; coherent when moist
10-20	B1	Dark red [2.5YR 3/6] sandy clay loam (30% clay); massive; very compact when slightly moist
20-40	B21	Red [2.5YR 4/6] sandy clay (40% clay); massive; very hard when dry
40-100	B22	Red [2.5YR 4/6] sandy clay (40% clay); massive; extremely hard when dry
100-150	B23	Mottled strong brown [7.5YR 5/6] and dark red [2.5YR 3/6] sandy clay (35% clay); massive; very hard when dry
150-200	B24	Dark red [2.5YR 3/6] with strong brown [7.5YR 5/6] mottles, sandy clay (35% clay); very hard when dry

Plot 2 Australian Soil Classification: Red Kandosol

Depth (cm)	Horizon	Description
0-10	A1	Dark reddish-brown [5YR 3/3] sandy loam (20% clay); single grain; coherent when moist
10-20	B11	Reddish-brown [5YR 4/3] sandy clay loam (25% clay); massive; firm when slightly moist
20-40	B12	Reddish-brown [2.5YR 4/5] sandy clay loam (25% clay); massive; firm when slightly moist
40-70	B21	Red [2.5YR 4/6] sandy clay (40% clay); massive; hard when dry
70-100	B22	Red [2.5YR 4/6] with strong brown [7.5YR 5/6] mottles, sandy clay (40% clay); massive; hard when dry
100-150	?BC	Red [2.5YR 4/6] with many discrete white angular particles, sandy clay (40% clay); massive; hard when dry
150-200	BC	Red [2.5YR 4/6] with white and strong brown [7.5YR 5/6] mottles, sandy clay loam (25% clay); massive; hard when dry

Plot 3 Australian Soil Classification: Red Kandosol

Depth (cm)	Horizon	Description
0-10	A11	Dark reddish-brown [5YR 3/3] sandy loam (15% clay); single grain; slightly coherent when moderately moist. Water-repellent
10-20	A12	Reddish-brown [2.5YR 4/3] sandy loam (15% clay); single grain; slightly coherent when slightly moist. Water-repellent. Occasional pisolitic ferruginous gravel to 5mm dia.
20-40	B1	Reddish-brown [2.5YR 4/4] sandy clay loam (25% clay); single grain; slightly coherent when slightly moist. Occasional ferruginous gravel (as above)
40-70	B21	Red [2.5YR 4/6] sandy clay (40% clay); massive; hard when slightly moist
70-100	B22	Yellowish-red [5YR 5/6] sandy clay (40% clay); massive; hard when slightly moist
100-150	B23	Diffuse, finely mottled red [2.5YR 4/6] and strong brown [7.5 YR 5/6] sandy clay (45% clay); massive; very hard when dry
150-200	?BC	Coarsely mottled red [2.5YR 4/6] and strong brown [7.5YR 5/6] with subordinate white, sandy clay (45% clay); massive; very hard when dry

Plot 4 Australian Soil Classification: Red Kandosol

Depth (cm)	Horizon	Description
0-10	A11	Dark reddish-brown [5YR 3/4] light sandy loam (10% clay); single grain; slightly coherent when moderately moist. Water-repellent
10-20	A3	Reddish-brown [5YR 4/3] sandy loam (15% clay); single grain; slightly coherent when moderately moist
20-40	B1	Reddish-brown [2.5YR 4/4] sandy clay loam (25% clay); massive; slightly coherent when moderately moist
40-70	B21	Red [2.5YR 4/6] sandy clay (40% clay); massive; hard when moderately moist
70-100	B22	Mottled red [2.5YR 4/6] and yellowish-red [5YR 5/8] sandy clay (45% clay); massive; hard when dry
100-200	?BC	Red [2.5YR 4/6] and strong brown [7.5YR 5/8] with subordinate white, sandy clay (45% clay); massive; very hard when dry