



Sustaining the Productivity of Tree Crops

on Agricultural Land in
South-Western Australia

A report for the RIRDC/Land & Water Australia/
FWPRDC Joint Venture Agroforestry Program

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FOREWORD

Pulpwood production from eucalypt plantations is set to become a major industry across southern Australia and will contribute to reversing the processes leading to land degradation. In Western Australia, the area of *Eucalyptus globulus* plantations has trebled in the past 5 years to the present level of about 150,000 ha. The majority of plantations are in the first rotation (aged <10 years) and are on land previously used for agriculture. The development of plantations represents a major change to land use and to the management of soils. An important issue for the industry is the consequence of continuous tree cropping on soil fertility and sustained productivity.

Primary objectives of the project ‘Sustaining the Productivity of Tree Crops on Agricultural Land in South-Western Australia’ were to quantify the changes to the fertility of agricultural soils planted to eucalypts and to evaluate strategies to maintain soil fertility and sustain long-term plantation productivity.

The project team addressed the objectives using two approaches. The first evaluated changes to nutrient forms and fluxes in surface soils at paired pasture-plantation sites covering the area in which *E. globulus* has been planted in south-western Australia. The second approach examined the effects of inter-rotation site management treatments on soil nutrients in experiments at two sites.

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This report, a new addition to RIRDC’s diverse range of over 600 research publications, forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems.

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Peter Core
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We are indebted to many CSIRO colleagues for their support through this project: Tuyen Pham who was responsible for managing the chemistry laboratory, Andrew Stillwell, Susan Beale, George Wan, Shirley Snelling, Longbin Huang, Kylie Lawrence, Paul Damon, Donna Campbell and Scott Walker. Geoff Dimmock provided the soil profile descriptions and soil classifications; Graham Donald and Mike Hill from CSIRO Animal Production produced climatic data for the sites from a predictive model, and maps locating sites in relation to climate and soils; Bert De Boer gave advice on some of the statistical analyses. Mick Poole, Head of the CSIRO Centre for Mediterranean Agricultural Research, and senior staff of the CSIRO Forestry and Forest Products, supported the project throughout.

Finally we would like to thank the many farmers who gave us access to their land, and willingly provided information on land management history. In particular Mr M Cox provided land for the inter-rotation experiments and assisted us with our tasks.

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Executive Summary

Planting of trees on agricultural land throughout Australia is being advanced to contain and reverse land degradation, develop a new timber resource and diversify and increase farm income. In south-western Australia, eucalypt plantations currently occupy about 150,000 ha of agricultural land and the rate of planting is escalating. The W.A. State Government, private sector, individual landowners and overseas investors are investing in this expanding hardwood industry, which will improve the local economy, increase export earnings and provide new job opportunities. Capturing these benefits will rely on continuing confidence in the industry. For this, increased and sustained productivity of successive tree crops is critical.

Eucalyptus globulus has been the preferred species because of its high growth rate, short rotation length for pulpwood (≈ 10 years) and favourable pulp properties. High tree growth rates are being achieved on farmland where rainfall is adequate and soil fertility has been increased by a long history of applications of phosphate fertiliser together with nitrogen-rich organic residues derived from legume pastures. Agricultural research has shown that where fertiliser applications are reduced, or where legumes are replaced by cropping systems, decreases in plant productivity are associated with declines in soil fertility within a period of several years. Similar effects are likely when continuous tree crops replace conventional agriculture. Maintenance of soil fertility will be a key element in sustaining productivity and the commercial viability of tree-growing enterprises. Objectives of the current project were to –

- (i) investigate and quantify changes to fertility of soils on farmland planted to eucalypts
- (ii) evaluate strategies to maintain soil fertility and sustain long-term productivity of trees planted on farmland
- (iii) relate measures of nutrient uptake and nutritional constraints to growth to measures of soil nutrient supply

Our studies have focussed on measuring changes to soil carbon (or soil organic matter), nitrogen and phosphorus in surface soil, although other chemical and physical properties were also determined. Carbon (C) is of particular interest in relation to greenhouse issues including C accounting and effects of land-use change on C sinks. Nitrogen (N) and phosphorus (P) are the nutrients that most commonly limit plant growth in this region. Furthermore, it is the plant-availability of these nutrients in soil that is likely to be most affected by the reduced input of P fertiliser and N-rich pasture residues associated with the change from conventional farming to plantation forestry. Our approach has been to measure changes to the forms and flux rates of these key elements within two experimental frameworks –

- Paired pasture-plantation sites: effects of eucalypt plantations on soil properties evaluated in later-age stands that are matched with adjacent pasture land.
- Designed experiments examining inter-rotation site management treatments: the impact of tree harvest residue treatments (residues burnt or residues removed, retained or increased) on soil fertility is being evaluated.

Paired Pasture-Plantation Study

First-rotation plantations of at least 6 years of age were chosen so that any differences in soil properties associated with change in land use could be distinguished from background spatial variation. It was also essential for adjacent pasture and plantation areas to have well matched soils and to have the same past land use history prior to plantation establishment. After evaluating 66 potential paired sites, 42 sites were identified for further assessment. A detailed history of past land use, including the amount and type of fertiliser applied, was obtained for each site. Subsequently, 31 paired sites were sampled to quantify soil N characteristics and a range of other physical and chemical properties. These properties were measured in bulk soils sampled from 4 replicate plots in each of the pasture and plantation areas. Plots were approximately 25 m from the plantation-pasture boundary to avoid edge effects. Sampling was confined to the 0-10 and 10-20 cm depths, as analysis of soil profiles to 1 m at 2 sites showed that 51-79% of the total N and P was held in this surface layer. The age of plantations at the 31 sites ranged from 6-11 years at the time of sampling. Subsets of these sites

that were also representative of the range in soils and climate were selected for measurement of forms and flux rates of C (10 sites) and P (18 sites). For C, an additional area of native vegetation (unmanaged) with matching soil was sampled near each of the 10 paired sites.

In addition to total concentrations of N, P and organic C, the more active or labile forms of C, N and P in soil that are expected to be more sensitive to land management effects and related to microbial and plant availability were determined. Soil measurements relying on microbial activity (microbial biomass C, respired C and N mineralization indices) used the < 5 mm soil fraction held at field moisture or adjusted to a moisture content at -25 kPa matric potential. All other analyses were on air-dried samples of the < 2 mm fraction.

Labile and microbially-available forms of soil organic C measured included permanganate oxidisable C, C respired in 96-day incubations and microbial biomass C. There was no detectable difference in these measurements, or in total organic C, between land-use types (native vegetation, pasture, plantation). Large differences in total organic C among 31 sites (range 1.9 – 9.9%, <2 mm fraction) could be explained by variation in soil texture and climatic variation, factors that will affect the productivity and accumulation of organic matter in the original vegetation and pasture. Soil organic C was also strongly correlated to concentrations of total N and P in surface soils.

Total soil N varied widely among sites (0.07- 0.68% in < 2mm fraction of 0-10 cm soil). Concentrations averaged over all sites did not differ between land-use types. However, there was a significant trend indicating that on poorly buffered sandy soils with low organic matter content, total N concentrations are lower in plantation soils than in pasture soils. N mineralization, the release of plant available mineral N forms (ammonium and nitrate) from organic matter by microbial activity, was measured in three ways. Long-term laboratory incubations to estimate mineralization rates and labile and resistant pools revealed no systematic difference between pasture and plantation soils. However, measurements of an index of mineralization (mineral N produced during incubation of intact cores) and potentially available N (from short-term anaerobic incubation) were generally lower in plantation soils than in pasture soils. This finding was supported by estimates over a full year at 2 paired sites which showed lower net annual N mineralization in soils under plantations.

The main approach in evaluating soil P was the measurement of P removed by a series of standard extractions coupled with equilibration studies to quantify P sorption properties. Concentrations of total P varied widely among sites (range 0.005-0.099%) and were highest in heavier textured soils that also had higher amounts of organic C. Pasture soils had P concentrations that on average were 15% higher than in plantation soils. Regression analysis showed that this difference in total soil P was well explained by the reduced input of P fertilizer to plantation soils. Effects of land-use change were also discernable in extractions with solutions of sodium bicarbonate (Olsen and Colwell) or acid-fluoride (Bray). These extraction procedures are commonly used in soil testing laboratories for predicting crop fertiliser requirements. For each of the 3 extraction methods, P concentrations were about 40% lower in plantation soils than in pasture soils. These differences can be explained partly by the reduced input of P fertiliser to plantation soils and to transformations of previously applied P that renders it less available with time. With measurement of P sorption properties the only consistent difference between pasture and plantation soils was a trend towards lower concentrations of a measure of 'desorbable' P in poorly buffered plantation soils.

Effects of land-use change on other chemical and physical properties were also evaluated for the 31 paired sites. There were no differences between pasture and plantation soils in physical properties (silt+clay content, % gravel, bulk density) indicating that the pairs were generally well matched with regard to intrinsic characteristics. There was also no effect of land-use change on soil pH, although there were large effects on cation concentrations. In pasture soils, concentrations of exchangeable calcium (Ca) were higher (28%) and concentrations of magnesium (Mg) and potassium (K) lower (29% and 21% respectively) than in plantation soils. This resulted in even larger differences in Ca:Mg ratios between pasture and plantation soils, which could only partly be attributed to the additional Ca

applied with P fertilizer to pasture soils since plantations were established. Mg and K were the only nutrients measured for which concentrations were higher in plantation soils.

In addition to the main study evaluating changes to soil properties, the productivity of eucalypt stands was measured at the 31 paired sites. Productivity of *E. globulus* was correlated with a number of soil properties, although it was best related to annual rainfall (86% of the variance accounted for). Productivity, measured as the mean annual increment in stem volume, ranged from 4.3 to 51 m³ ha⁻¹ yr⁻¹ across the 31 paired sites. Analysis of stem-bark showed that amounts of nutrients in this tree component varies greatly across sites, with a 22- to 25-fold variation in N, Ca and K, and a 15-fold variation in P and K. As bark is one component of residues left on the site following harvest, the impact of retaining these residues on site nutrient capital will therefore vary markedly with productivity. A plant bioassay study at 2 sites examined effects of land-use change on seedling growth and nutrient uptake. Seedling growth was better in pasture soil than plantation soil only at the lower fertility site. Similar responses to applied N and P in pasture and plantation soil indicated that the higher N and P status of pasture soil could not explain this difference in growth. More extensive plant growth studies incorporating a broader range of sites would be required to evaluate the impact of the measured changes in soil nutrient supply on seedling growth and nutrient uptake.

Inter-rotation Harvest Residue Management

The impact of alternative strategies for managing harvest residues in second rotation *Eucalyptus globulus* plantations is being examined at 2 sites of contrasting soil fertility status in south western Australia. First rotation stands of *E. globulus* were harvested at a relatively fertile (red earth) site in August 1994, and at a low fertility (grey sand) site in May 1995. The sites were replanted with seedlings in July-August 1995. During harvesting at the red earth site, over 50 t ha⁻¹ of residues were deposited on the forest floor and these contained large amounts (kg ha⁻¹) of N (347), P (23), Ca (597), Mg (59) and K (182). At the grey sand site, 31 t ha⁻¹ of residues remained following harvesting. There was a corresponding difference in the nutrient loads added in harvest residues. Markedly lower concentrations of total and labile P as well as exchangeable K in the coarse textured grey sand compared to the soil from the red earth site were the main features differentiating soil nutrient status of the two sites.

In randomized block experiments at the two sites, treatments include complete residue removal, residue retention, increased residue and residue burning. Soils from these treatments have been sampled annually and the < 2 mm fraction of the 0-5, 5-10 and 10-20 cm depths analysed for pH, C, P and cations. Mineral N status and N mineralization rates have been determined in 0-10 and 10-20 cm soils using field incubations every 4 weeks.

There were large changes in soil properties due to burning of residues, with increases of up to more than 1 unit in pH, more than 100% in some cation concentrations and a greater proportional change in labile P. However, the effects were relatively short-lived with these properties returning to near pre-burn levels within 1 to 2 years after treatment.

The main long-term impacts on soil nutrient status of harvest residue management relate largely to effects on soil cation concentrations and are primarily associated with the highest residue level (double normal residue levels). At each of the sites this treatment resulted in significantly increased surface soil concentrations of exchangeable Ca and Mg, and at the red earth site significantly increased exchangeable K. These effects were largely confined to the upper 5 cm of the soil profile. Despite the large amounts of residues added, there appears to have been limited impact on soil C status.

Variation in some soil properties was related to time since harvest rather than residue treatment effects. Exchangeable K concentrations declined in all treatments during successive sampling periods at both sites, the decrease being greatest (2.1 to 2.8 fold) in the surface 0-5 cm soil. This decline appears to be counter to the trend observed at the paired sites where soil K levels were generally higher in plantation soils than pasture soils. However, it is unclear whether differences at the paired sites were due to an increase in plantation soils or a decrease with time in pasture soils. Labile C concentrations, which

were also not affected by harvest residue treatments, decreased in the first one to two years after harvest and then gradually increased in subsequent years to approach levels similar to those in immediate post-harvest soil samples. Measurements of different forms of P showed that concentrations of inorganic forms were generally higher, and organic forms lower, at the grey sand site than at the red earth site. There was little effect of harvest residue treatment on concentrations of different P forms. However, CaCl_2 -extractable P at the grey sand site, and organic P (NaOH extract) at both sites, decreased significantly with time after harvest.

Mineral N dynamics in soils were significantly affected by residue treatments. High concentrations of mineral N were present in soil immediately following harvest, but these pools declined in subsequent years. Mineral N pools were significantly higher where residues had been removed at the red earth site, but the opposite was the case at the sandy site where treatment differences were less. At both sites cumulative annual rates of N mineralization were significantly higher on high residue treatments compared to low residue treatments in the third and fourth years of measurement. High residue treatments also resulted in significantly higher concentrations of potentially mineralizable N at both sites during each measurement period. These results show that the potential for loss of N by leaching is higher where residues have been removed or burnt on the heavier textured soil, and that the supply of N for tree growth can be enhanced by retaining harvest residues.

Tree growth responses to treatments were limited at the two sites. At the more fertile site there were no impacts of harvest residue management on growth 4 years after planting. At the less fertile site, highest levels of retained residues were associated with trends of increased growth, but differences in growth rates between treatments were significant at only a limited number of measurement periods.

Conclusions

Changes in the management of agricultural soils through conversion of land from traditional farming systems to continuous tree cropping have resulted in significant changes to concentrations of some forms of N and P, and to concentrations and the balance of cations (Ca, Mg and K) in surface soils. While changes to some properties have appeared across the range of sites, others (e.g. total N, desorbable P) are only becoming evident on the sandy soils that are less well buffered. There were no detectable effects of land-use change on soil acidity, or on various measures of soil C. The observed changes have occurred within a relatively short time frame and were detectable despite being measured against a relatively high initial fertility level. They are consistent with our initial hypothesis that soil N and P supply for plant growth are likely to decline with changes in land management involving reduced input to soils of both P fertiliser and nutrient rich organic residues derived from legume-based pastures.

These findings emphasise the importance of introducing site management practices, particularly during the inter-rotation period, which conserve organic matter and nutrients and correct nutrient deficiencies so that the productivity of future rotations can be sustained. Our experiments in second rotation establishment have shown that retention of harvest residues has beneficial effects on mineral N dynamics and on concentrations of Ca, Mg and K in surface soils. Implementing practices which offset declining soil nutrient status will be critical to maintaining site fertility and productivity in the long-term, even though benefits to tree growth on some sites may not be apparent immediately.

1. Introduction

Eucalypt plantations currently occupy about 150,000 ha of land in south-western Australia and the rate of planting is escalating. Most plantations are on farmland and are in the first rotation. The industry has developed over the past decade in an economic environment where Australia has a trade deficit in forest products of approximately \$2 billion, largely from import of pulp and paper products. Production of pulpwood from plantations will help to redress this position. The W.A. State Government, private sector, individual landowners and overseas investors are investing in the expanding hardwood plantation industry, which is expected to increase the local economy, export earnings and new job opportunities. Capturing these benefits will rely on continuing confidence in the industry. For this, increased and sustained productivity of successive tree crops is critical.

The initial impetus for planting trees on farms in south-western Australia has been to ameliorate lands degraded by salinity, waterlogging, acidity and erosion. The condition of agricultural land in this region is deteriorating (Landcare Review Committee, 1995). Incorporating trees into agricultural landscapes is recognised as a key element for reversing the processes leading to degradation. Such strategies also need an assured commercial focus.

Eucalyptus globulus has been the desired species because of its high growth rate, short rotation length for pulpwood (≈ 10 years) and favourable pulp properties. The environment in south-western Australia is rated as one of the best in the world for growth of *E. globulus*. High growth rates are being obtained on suitable sites due to favourable temperatures, high amounts of incident radiation (Beadle and Inions, 1990), and to the capacity of deep soil profiles to store water required to maintain growth during the hot and dry summer period.

Productivity of plantations also depends on adequate supplies of nutrients from the soil. In south-western Australia, *E. globulus* plantations are being established primarily on agricultural land, where productivity is much greater than on land recently cleared of native vegetation. The soils over much of this region are derived from the erosion of an ancient plateau mantled by laterite soils and the profiles are deep and highly leached (McArthur, 1991). Consequently, they are inherently low in nutrients and organic matter, and generally contain high levels of iron and aluminium oxides that are strongly reactive with applied phosphorus (Turton *et al.*, 1962; McArthur, 1991; Tennant *et al.*, 1992). Large responses in plant growth have been observed following application of phosphorus (P) and other major and minor nutrients to these soils following clearing of natural vegetation (Robson and Gilkes, 1980; Grove *et al.*, 1991).

The fertility of soils in south-western Australia has been improved by repeated applications of phosphate fertilisers (McArthur, 1991) and the accumulation in soils of organic residues from improved legume pastures and crops (Rowland *et al.*, 1988; Mason and Rowland, 1992). High growth rates of plantations are dependant in part on utilization by trees of this storage bank of nutrients. Agricultural research has shown that where fertiliser applications cease, or become less frequent, the fertility of these soils declines within a period of several years. For example, the relative effectiveness of superphosphate fertiliser, calculated from yields of pasture and wheat in several experiments, decreased by 30-60% in the year after application (Bolland and Bowden, 1986). Concentrations of extractable P in surface soils were also shown to decrease by about 50% between 1 and 3 years after P application ceased on a site where wheat and lupin crops were being grown in rotation (Bolland, 1992). Similar trends can be expected under plantation forests where fertiliser application ceases after planting, or is much lower than rates used in conventional farming practices.

Where legumes have been replaced by cropping systems on relatively infertile sites, reductions in productivity have ensued on sandy soils due to a reduction in soil nitrogen (N) supply (Tuohey and Robson, 1980; Rowland *et al.*, 1984; see Rovira, 1992). Birk (1992) also reported a significant decline

in N availability in soils with increasing age of a radiata pine stand established on an ex-improved pasture site in eastern Australia.

Soil nutrient supply will decline with increased removal of nutrients under intensive cropping (Rovira, 1992), and from nutrient transformations in soils. The latter includes: the slow reactions of phosphorus with soils (Barrow, 1980a) which lowers concentrations of labile P; losses of N by denitrification and leaching (Fillery and McInnes, 1992), and; changes in the nature of organic matter pools due to a decrease in nutrient-rich legume residues and an increase in lignified litter from the plantation eucalypts. In first rotation eucalypt crops, nutrient supply will be high due to past regular top-dressing with phosphate fertilisers and high N residues from previous legume-based pastures. The practice of mounding will also concentrate nutrient-rich surface soil near to the tree and accelerate mineralisation of nutrients. Any decline over time in soil nutrient supply is unlikely to limit growth in later stages of the first rotation because nutrient requirement of the stand decreases with age (Grove *et al.*, 1996). However, at the early stages of second and subsequent rotations, nutrient deficiencies can be expected to be more prevalent. Development of methods to identify and correct these is essential for achieving sustained and high production.

Decreased productivity between rotations in other forest regions has been largely attributed to declining soil fertility (e.g. Keeves, 1966; Farrell *et al.*, 1986; Zen and de Couto, 1991). Decline in the productivity of second rotation plantations of *Pinus radiata* in South Australia (Keeves, 1966) led to a large research effort to understand and ameliorate the problem. New silvicultural practices with increased rates and frequency of fertiliser application were initially adopted to correct the decline, which was largely attributed to loss of N and organic matter (Woods, 1976, 1980). Research over the past decade has shown that retention of logging residues and litter, together with fertiliser application and other silvicultural practices, are the most appropriate methods to maintain organic matter and nutrients in soil and to avoid a decline in productivity in the second and subsequent rotations (e.g. Cellier *et al.*, 1985; Farrell *et al.*, 1986; Smethurst and Nambiar, 1990; Bekunda *et al.*, 1990).

The widespread planting of *E. globulus* in timber belts and blocks on agricultural land since the late 1980's in the higher rainfall (>600mm) zone has provided an ideal framework to investigate the effects of plantation forests on the fertility of farm soils. Furthermore, the first processing and exporting of *E. globulus* woodchips by Sotico Treefarms during 1994, and commencement of second rotation plantings, has provided the opportunity to evaluate effects of silvicultural treatments imposed in the inter-rotation period on soil nutrient supply processes and tree growth. Our studies have focussed on measuring changes to soil carbon (or soil organic matter), nitrogen and phosphorus. Soil organic matter strongly influences soil nutrient supply, as well as other soil chemical, physical and biological properties, and is the focus of attention in issues regarding management for sustainable production (Syers and Craswell, 1995). It is also of particular interest in relation to greenhouse issues including carbon (C) accounting and effects of land-use change on C sinks. Nitrogen (N) and phosphorus (P) are the nutrients that most commonly limit plant growth in this region. Furthermore, it is the plant-availability of these nutrients in soil that is likely to be most affected by the reduced input of P fertiliser and N-rich pasture residues associated with the change from conventional farming to plantation forestry. Our approach has been to measure changes to the forms and flux rates of these key elements within two experimental frameworks –

- (a) *Paired plantation-pasture sites*: effects of eucalypt plantations on soil properties evaluated in later-age stands that are matched with adjacent pasture land having the same history prior to tree planting: paired sites represent the range in soils and climate where *E. globulus* is growing in south-western Australia.
- (b) *Designed experiments examining inter-rotation site management treatments*: the impact of tree harvest residue treatments (residues burnt or residues removed, retained or increased) on soil fertility are being evaluated at two sites in experiments that commenced two years prior to the current project.

2. Objectives

- Investigate and quantify changes to fertility of soils on farmland planted to eucalypts
- Evaluate strategies to maintain soil fertility and sustain long-term productivity of trees planted on farmland
- Relate measures of nutrient uptake and nutritional constraints to growth to measures of soil nutrient supply

3. Methods

Project objectives were addressed by a series of studies within the two experimental frameworks.

3.1 Paired plantation-pasture sites

- 3.1.1 Selection and description of paired sites.
- 3.1.2 Measurements of carbon, nitrogen, phosphorus and other properties in surface soils
- 3.1.3 Seasonal variation in nitrogen and carbon indices
- 3.1.4 Plant bioassay study
- 3.1.5 Plantation productivity and nutrient uptake

3.2 Inter-rotation Harvest Residue Experiments

- 3.2.1 Measurement of harvest residue treatments on soil carbon, nitrogen and phosphorus
- 3.2.2 Tree growth

3.1 Paired Plantation-Pasture Study

3.1.1 Selection, description and preliminary soil survey of paired sites

Site selection

E. globulus plantations with adjacent land under pasture were identified throughout the higher rainfall region of south-western Australia. Criteria for selection were –

- (i) first-rotation plantations to be at least 6 years of age so that any changes to soil properties associated with the tree crop would be better distinguished from background spatial variation.
- (ii) sites to be representative of the range in climate and soils where *E. globulus* is grown
- (iii) adjacent pasture and plantation areas to have the same past land use history before plantation establishment
- (iv) pasture adjacent to the plantation should be managed according to traditional agricultural practices
- (v) areas of pasture and plantation should be large enough for representative soil sampling and well matched in terms of topographic and soil profile characteristics.

The majority of sites were identified and farmers contacted with the assistance of staff from Sotico Treefarms Pty Ltd and CALM (W.A. Department of Conservation and Land Management), the organizations responsible for establishment of many of the plantations. We initially examined 66 potential paired sites on 50 farms, and 42 sites that met the above criteria were retained for further assessment (Figure 1). Information obtained on each of the sites included land-use history of pasture and plantation areas, current pasture management and amounts and types of fertilizers applied for each year prior to and since plantations were established. Surface soils in the plantations had not been disturbed since being under pasture, except along the planting rows that had been deep-ripped. There was only one site where soil was mounded along the planting row, and in this case soil sampling was confined to the undisturbed inter-row area.

Site characteristics

There was a large variation in plantation productivity across the climatic gradient (Plate 1). Mean annual rainfall and summer (December, January, February) evaporation were estimated for each site by interpolation from historical records using a climate analysis model (Hutchinson, 1990). These data are used in examining relationships between climate, soil properties, and tree growth. Location of the 42 sites is shown in relation to rainfall, summer evaporation and broad soil groups in Figure 2.

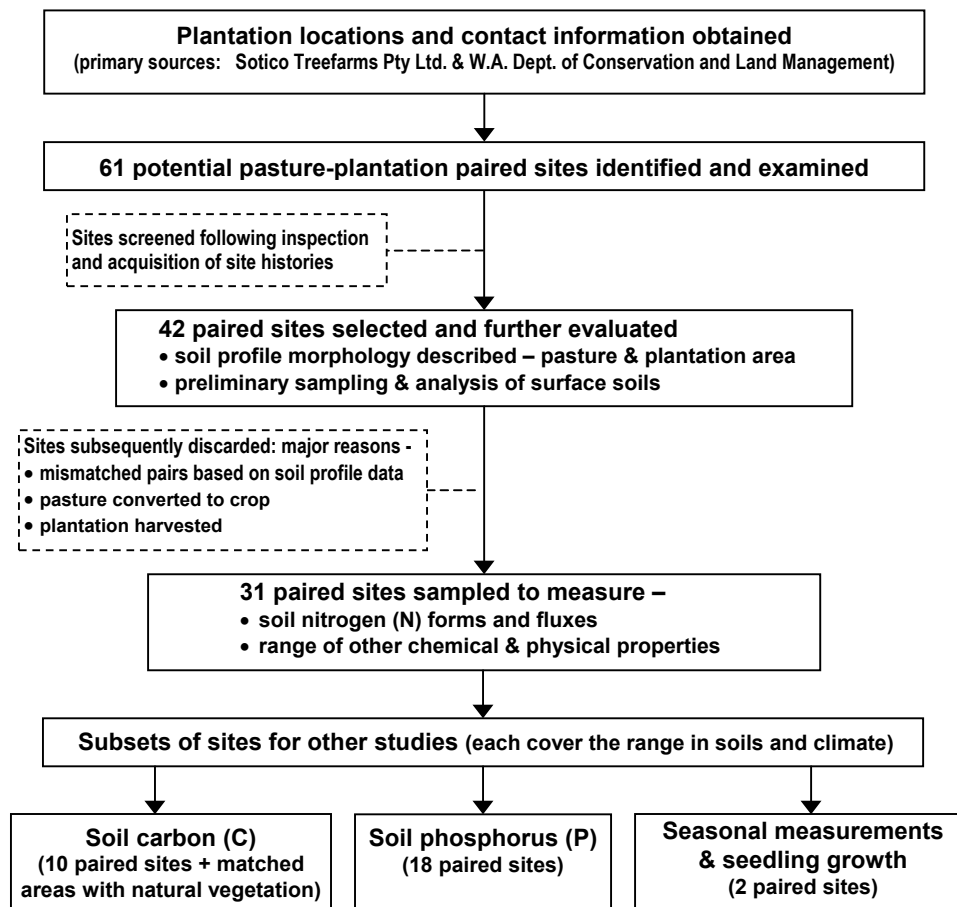


Figure 1. Sequence in screening paired pasture-plantation sites and selecting subsets for various measures of soil properties.

Average long-term rainfall ranges from 538 mm at the O’Connell site east of Collie to 1434 mm at Flanagan’s south of Manjimup (Table 1). The long-term average for summer evaporation ranges from 519 mm near Manjimup to 694 mm east of Collie. Rainfall declines inland from the west coast and from south-west to north-east along the south coast, while evaporation generally increases from south to north (Figure 2).

The sites were further evaluated by describing the morphological properties of soil profiles to 1 m, and classifying soils. Intact soil cores were obtained at each site using a split core barrel driven into the ground with a pneumatic hammer. A single core was sampled from a central position in each of the pasture and plantation area, with additional cores being taken at some sites if there was concern about disturbance or spatial variation. For each profile, soil horizons were identified, morphological characteristics described and soils classified according to three systems: the FAO-UNESCO classification (Food and Agriculture Organization of the United Nations, 1990); the Northcote Key and classification (Northcote *et al.* 1975; Northcote, 1979), and; the more recent Australian classification (Isbell, 1996). Additional information obtained at each site included site position (by GPS), topography and aspect. The detailed soil morphological description was used to rate the similarity of pasture and plantation soils at each site. One rating was based on comparison of profiles and a second on similarity of the surface soil (the zone of primary interest in this project).



Plate 1. Paired sampling sites with low productivity plantations in the low rainfall zone east of Collie (a, b) and with high productivity stands in the high rainfall zone near Northcliffe (c), Walpole (d) and Pemberton (e, f).

Comparison of the morphological characteristics of soil profiles at the 42 sites showed that the degree of similarity between pasture and plantation plots was high at 24 sites, moderate at 13 sites and low at 4 sites (Table 2). The profiles at 1 site differed between the pasture and plantation soils. A further rating based on the upper 30 cm, the zone of most importance in this study, showed that all but 8 sites were well matched. This assessment was used to exclude several sites from the subsequent sampling of surface soils to measure forms of soil C, N and P (Figure 1).

Preliminary analysis of surface soil

The 42 potential sites were further evaluated by analyses of surface soils from the adjacent plantation and pasture areas. At each site, surface soils were sampled from four contiguous plots

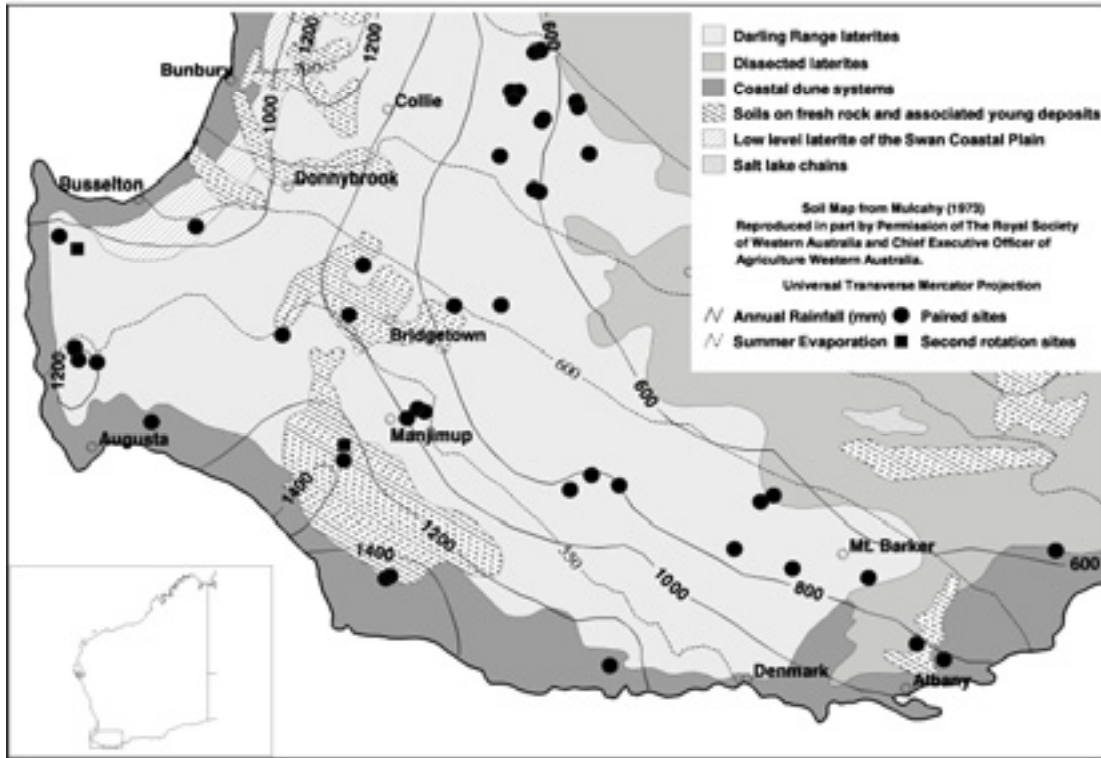


Figure 2. Location of the 42 paired pasture-plantation sites and second rotation experiments in relation to broad soil groups, long-term average annual rainfall (solid lines) and average summer (Dec, Jan, Feb) evaporation (dashed lines). Climate estimates are from the climate analysis model of Hutchinson (1990). [Map compiled by G.E.Donald, CSIRO Animal Production, Floreat, WA]

(each 6m by 10 m) in each of the plantation and pasture areas. The plots were positioned 20 to 25 m from the plantation edge, the distance depending primarily on site topography and aspect. Six soil cores (0-10 cm) were bulked from each plot for analysis. Concentrations of total nitrogen (N) and total phosphorus (P) were measured to assess whether differences in total N and P reflected fertiliser history of a paired pasture/plantation site. Concentrations of N and P in soils were determined with an auto-analyser following Kjeldahl digestion. As the pasture areas continue to receive regular dressings of P fertiliser and to produce larger quantities of N-rich organic residues, it is expected that soil from the plantation areas will have lower concentrations of total N and P than the paired-pasture soil. Differences between the pasture and plantation areas will also depend on the extent to which N and P are leached below the 10 cm depth.

Soil profiles: chemical properties and nutrient stores

Soil profiles were comprehensively sampled to a depth of 1 m at two sites with contrasting climate, soil and tree growth. Sites were at Gibbs plantation (low rainfall, siliceous sand) east of Collie, and at Moltoni's plantation (high rainfall, sandy apedal yellow duplex soil) near Pemberton. They were subsequently used for a series of other detailed studies (see below). The aim was to quantify the distribution of organic carbon and major nutrients, and estimate total nutrient stores. The distribution of nutrients in the profile will indicate the relative contribution of surface soils, the zone of focus of our studies, to plant nutrient supply.

Table 1. Location, soil type, tree planting year and estimated annual rainfall at the paired plantation/pasture sites identified and sampled in south-western Australia.

Site name	Location	Planting Year	Topography	Aspect	Annual Rainfall (mm) ⁽¹⁾	Summer Evaporation (mm) ⁽²⁾
Allison	Perillup	1990	Flat, very broad rise	-	776	572
Andrews	Albany	1988	Gentle lower slope	E	865	572
Anning	Walpole	1990	Moderate mid-slope in hilly terrain	N	1291	531
Ayers-H	Greenbushes	1989	Gentle upper slope below laterite outcrops	WNW	983	581
Browne	Bridgetown	1990	Very gently sloping crest	E	1016	565
Bush	Mt. Barker	1990	Very gentle lower slope	SSW	725	581
Clarke-B	Darkan	1990	Very gently sloping broad valley floor	NNE	603	694
Clarke-DH	Darkan	1990	Gentle mid-slope	E	593	687
Crosby	Quindinup	1989	Moderate mid-slope	E	775	579
Decke-DH	Manjimup	1987	Very broad flattish crest	S	985	548
Decke-L	Manjimup	1987	Very gentle lower slope	E	985	548
East	Manjimup	1989	Moderate upper slope in hilly landscape	E	1023	543
Flanagan-A	Northcliffe	1989	Crest of broad low ridge	-	1417	524
Flanagan-B	Northcliffe	1989	Gentle upper slope on broad low rise	N	1434	524
Geary	Yallingup	1989	Moderate mid-slope in undulating landscape	WNW	1028	574
Gibbs	Bowellling	1989 ⁽³⁾	V. gentle slope crossed by low gravel spurs	S	721	658
Hall-A	Kendenup West	1990	Gentle slope – ferrug. gravel & quartz stone	S	645	593
Hall-B	Kendenup West	1990	Flat	-	661	590
Hartridge	Augusta	1989	Flat	-	1087	538
Jefferies-A	Duranillin	1990	Smooth gentle mid-slope below laterite	W	644	655
Jefferies-B	Duranillin	1990	Mid-slope below laterite ridge	NE	655	653
Lamberti	Witchcliffe	1988	Broad gentle mid-slope near laterite outcrops	NNE	1199	547
Lindsay	Nannup	1989	Moderate lower slope in hilly terrain	W	998	556
Lodge	Boyup Brook	1990	Gentle lower slope	N	649	603
Lubcke-A	Darkan	1984	Gentle lower slope	SSE	701	682
Lubcke-B	Darkan	1987	Gentle lower slope	W	697	682
Lubcke-C	Darkan	1990	Gentle upper slope	NNE	715	681
Lynch	Mt. Barker	1989	Gentle mid-slope	SSW	739	574
Mattinson	Napier	1989	Narrow valley floor	W	881	570
Moltoni	Pemberton	1988	Very gentle broad upper slope on crest	SW	1358	519
Noakes	Witchcliffe	1989	Gentle upper slope in rolling landscape	S	1208	553
O'Connell	Duranillin	1990	Flat	-	538	686
Oates	Busselton	1988	Very extensive flat	-	926	596
Parker	Boyup Brook	1990	Gentle lower slope	WSW	632	614
Patmore-A	Quindinup	1991	Flat crest of broad very low sandy rise	-	836	569
Patmore-B	Quindinup	1991	Moderate slope in hilly terrain below laterite	W	833	568
Robinson	Witchcliffe	1988	Flat	-	1226	545
South-H	Darkan	1990	Gentle lower slope	NE	667	688
South-L	Darkan	1990	Moderate mid-slope below laterite outcrops	E	680	691
Walker	Green Range	1990	Gentle upper slope near crest of low dune	SW	574	626
Wunnenburg-A	Darkan	1989	Gentle lower slope.	NW	645	677
Wunnenburg-B	Darkan	1989	Flat, very broad rise	-	645	677

⁽¹⁾ Average annual rainfall estimated from historical rainfall data using the climate analysis model of Hutchinson (1990).

⁽²⁾ Long-term average pan evaporation for summer (December, January and February) estimated from historical records using the climate analysis model of Hutchinson (1990).

⁽³⁾ Replanted after failure of 1985 planting

Table 2. Classification of soil under pasture and rating of the similarity between pasture and plantation areas in profile and surface soil characteristics at paired sites in south-western Australia.

Site name	SOIL CLASSIFICATION SYSTEM ⁽¹⁾			Similarity of Pasture & Plantation Soils ⁽²⁾	
	FAO-UNESCO	Isbell (1996)	Northcote (1979)	Profile	Surface
Allison	Ferric Acrisol	Yellow Kandosol	Dy5.5 (Sandy Apedal Yellow-mottled Duplex Soil)	1	1
Andrews	Ferric Acrisol	Yellow Chromosol	Dy5.8 (Sandy Apedal Yellow-mottled Duplex Soil)	1	1
Anning	Ferric Acrisol	Yellow Chromosol	Dy5.5 (Sandy Apedal Yellow-mottled Duplex Soil)	1	1
Ayers-H	Xanthic Ferralsol	Red Ferrosol	Gn2.1 (Red Massive Earth)	1	1
Browne	Ferric Acrisol	Yellow Kandosol	Dy5.5 (Sandy Apedal Yellow-mottled Duplex Soil)	1	1
Bush	Haplic Podzol	Aeric Podosol	Uc2.34 (Bleached Sand with Pan)	2	1
Clarke-B	Ferric Acrisol	Yellow Chromosol	Dy5.8 (Sandy Apedal Yellow-mottled Duplex Soil)	1	1
Clarke-DH	Ferric Acrisol	Yellow Chromosol	Dy5.6 (Sandy Apedal Yellow-mottled Duplex Soil)	1	1
Crosby	Ferric Acrisol	Grey Chromosol	Dy5.7 (Sandy Apedal Yellow-mottled Duplex Soil)	2	1
Decke-DH	Haplic Arenosol	Clastic Rudosol	Uc1.22 (Siliceous Sand - gravelly)	1	2
Decke-L	Ferric Acrisol	Yellow Chromosol	Dy5.8 (Sandy Apedal Yellow-mottled Duplex Soil)	1	1
East	Haplic Arenosol	Clastic Rudosol	Uc1.22 (Siliceous Sand - gravelly)	2	1
Flanagan-A	Xanthic Ferralsol	Yellow Kandosol	Gn1.8 (Sandy Yellow-mottled Gradational Soil)	1	1
Flanagan-B	Ferric Acrisol	Yellow Chromosol	Dy5.5 (Sandy Apedal Yellow-mottled Duplex Soil)	2	1
Geary	Haplic Arenosol	Clastic Rudosol	Uc1.22 (Siliceous Sand - gravelly)	3	1
Gibbs	Haplic Arenosol	Arenic Rudosol	Uc1.21 (Siliceous Sand)	1	1
Hall-A	Ferric Acrisol	Yellow Chromosol	Dy5.8 (Sandy Apedal Yellow-mottled Duplex Soil)	1	1
Hall-B	Haplic Arenosol	Clastic Rudosol	Uc1.21 (Siliceous Sand - gravelly)	1	1
Hartridge	Gleyic Arenosol	Arenic Rudosol	Uc1.21 (Siliceous Sand)	2	1
Jefferies-A	Haplic Arenosol	Arenic Rudosol	Uc1.21 (Siliceous Sand - gravelly)	1	1
Jefferies-B	Haplic Arenosol	Arenic Rudosol	Uc1.22 (Siliceous Sand)	1	1
Lamberti	Haplic Acrisol	Yellow Kandosol	Dy4.5 (Sandy Apedal Yellow Duplex Soil)	2	1
Lindsay	?Dystric	Red Kandosol	Dr4.5 (Sandy Apedal Red Duplex Soil)	2	1
Lodge	Haplic Acrisol	Yellow Chromosol	Dy4.4 (Sandy Pedal Yellow Duplex Soil)	2	3
Lubcke-A	Rhodic Ferralsol	Red Ferrosol	Gn2.11 (Red Massive Earth)	1	1
Lubcke-B	Haplic Acrisol	?Yellow	Dy4.5 (Sandy Apedal Yellow Duplex Soil)	2	2
Lubcke-C	Haplic Arenosol	Clastic Rudosol	Uc1.22 (Siliceous Sand - gravelly)	2	1
Lynch	Ferric Acrisol	Yellow Chromosol	Dy5.5 (Sandy Apedal Yellow-mottled Duplex Soil)	2	2
Mattinson	Haplic Arenosol	Arenic Rudosol	Uc1.21 (Siliceous Sand)	1	1
Moltoni	Ferric Acrisol	Yellow Chromosol	Dy5.6 (Sandy Apedal Yellow-mottled Duplex Soil)	1	1
Noakes	Haplic Acrisol	Grey Chromosol	Dy4.5 (Sandy Apedal Yellow Duplex Soil)	2	2
O'Connell	Ferric Acrisol	Yellow Kandosol	Dy5.8 (Sandy Apedal Yellow-mottled Duplex Soil)	1	1
Oates	Ferric Acrisol	Grey Kandosol	Dy5.6 (Sandy Apedal Yellow-mottled Duplex Soil)	3	1
Parker	Ferric Acrisol	Yellow Kandosol	Dy5.6 (Sandy Apedal Yellow-mottled Duplex Soil)	3	2
Patmore-A	Haplic Arenosol	Arenic Rudosol	Uc1.21 (Siliceous Sand)	1	1
Patmore-B	Haplic Arenosol	Clastic Rudosol	Uc1.21 (Siliceous Sand - gravelly)	1	1
Robinson	Ferric Acrisol	Yellow Chromosol	Dy5.5 (Sandy Apedal Yellow-mottled Duplex Soil)	1	1
South-H	Xanthic Ferralsol	Red Kandosol	Gn1.2 (Sandy Yellow-mottled Gradational Soil)	1	1
South-L	Xanthic Ferralsol	Yellow Kandosol	Gn1.2 (Sandy Yellow Gradational Soil)	2	2
Walker	Haplic Arenosol	Arenic Rudosol	Uc1.21 (Siliceous Sand)	1	1
Wunnenburg-A	Ferric Acrisol	Yellow Chromosol	Dy5.8 (Sandy Apedal Yellow-mottled Duplex Soil)	Poor	Poor

⁽¹⁾ Soils in plantation and pasture areas were classified using one international (FAO-UNESCO) and two Australian systems.

⁽²⁾ Degree of similarity between pasture and plantation soils was ranked as: 1 = good, 2 = moderate, 3 = low.

At each site, three pits to 1 m depth were dug in each of the pasture and plantation areas. Steel cores were used to take samples at the 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 (Moltoni) or 70-90 (Gibbs) cm depths. Two cores taken 30 cm apart in each pit were bulked to make up samples at each depth. Samples were dried, sieved and the < 2 mm fractions analysed to determine concentrations of total organic carbon, pH, total N and P, Colwell-extractable P, and exchangeable Ca, Mg, K and Na. Total weights of the < 2 and > 2 mm fractions were used to calculate soil gravel content, soil bulk density, and the weight of the < 2 mm on an areal basis to calculate amounts of nutrients to 1 m.

Organic carbon was determined using the Walkley-Black dichromate oxidation technique (see 3.1.2.1). pH was measured in a water suspension (1: 5 soil:solution) after shaking for 1 h at 20°C. Concentrations of total N and P were determined using automated colorimetric procedures following digestion of soil in $\text{H}_2\text{SO}_4/\text{H}_2\text{O}_2$ at 360°C. In the Colwell P method (Colwell, 1963), 1 g soil was shaken in 100 ml extracting solution (0.5M NaHCO_3 at pH 8.5) for 16 hours at 20°C and, following filtration, the concentration of P determined in the acidified filtrate. Exchangeable Ca, Mg, K and Na were measured by shaking 5 g soil in 100 ml 1M NH_4Cl for 1 h at 20°C, filtering the extract, and determining concentrations of the cations in the filtrate by atomic absorption spectrometry.

3.1.2 Measurements of carbon, nitrogen, phosphorus and other properties in surface soil

These studies represent the major component of the project. Concentrations of different forms and supply rates of N, and a range of other properties, were measured in 0-10 and 10-20 cm depth samples from 31 paired sites. Forms of C and P were measured in samples from subsets of these sites (Figure 1). Soil samples were generally obtained from the same plot location as the preliminary sampling position (see 3.1.1). Six soil samples from each depth were bulked for each of four contiguous plots (each 6 m by 10 m) in each of the plantation and pasture areas. Soil measurements relying on microbial activity (microbial biomass C, respired C and N mineralization indices) and requiring sieving of fresh soil used the < 5 mm soil fraction. Soils were held at field moisture or adjusted to -25 kPa matric potential. All other analyses were on air-dried samples of the < 2 mm fraction, which is the fraction most commonly used for routine soil analyses.

3.1.2.1 Carbon

The quantity of soil carbon (C), or soil organic matter (SOM) is simple to measure, but often relatively insensitive to changes in SOM quality under different land-use management regimes (eg. Buschbacher *et al.* 1988, Reiners *et al.* 1994, Veldkamp 1994). Therefore, our study has also focussed on measures of labile and microbially-available forms of SOM.

A subset of 10 paired sites with a wide range of soil types (Table 3) were used to investigate the effect of land-use management regime on total organic matter, availability of C to microbial degradation, and permanganate oxidisable fractions. Sites were chosen so that, in addition to sampling of the adjacent pasture and plantation areas, a nearby area of native vegetation (unmanaged) with matching soils could also be sampled. This provided a contrast between three land-use management regimes at each of the sites. The four bulked 0-10 cm samples were each sieved to remove gravel, and analysed individually. Details of the four procedures used to quantify soil C follow.

Table 3. Selected soil (0-10 cm) and management history characteristics of each of the sites selected for C studies.

Site	Soil type	Surface texture	Water content at -25 kPa (%)	pH	Years since conversion ^A	
					N.V. to Past.	Past. to Plant.
Andrews	Yellow duplex	loamy fine sand	18.5	5.12	10	10
Anning	Yellow duplex	gravelly clayey sand	27.6	6.01	48	8
Ayers	Red earth	gravelly sandy clay loam	32.6	5.90	29	9
Gibbs	Siliceous sand	grey sand	11.2	5.71	31	9
Hall B	Siliceous sand	coarse sand	16.6	5.59	43	8
Hartridge	Siliceous sand	grey sand	21.1	5.36	30	9
Jefferies B	Siliceous sand	pale yellow sand	7.3	5.96	31	8
Moltoni	Yellow duplex	gravelly sandy loam	28.3	5.91	18	10
Patmore B	Siliceous sand	gravelly sandy loam	25.4	6.30	20	7
Robinson	Yellow duplex	gravelly sandy loam	34.2	5.84	42	10

^A N.V.: Native Vegetation, Past.: Pasture, Plant.: Plantation.

Total organic C

Total organic carbon determination on the < 2mm soil fraction was based on the Walkley-Black dichromate oxidation technique (Walkley 1947).

Permanganate oxidisable C

Organic matter oxidised by potassium permanganate of varying strengths has shown promise in chemical characterisation of labile C. The original description of the permanganate oxidisable C method (Loginow *et al.* 1987) used three concentrations of permanganate (33, 167, and 333 mM MnO_4^-). Other authors (eg. Blair *et al.* 1995) have defined a carbon management index based on a single concentration of permanganate (333 mM). We followed the procedure of Blair *et al.* (1995), but used 3 concentrations of MnO_4^- , and a pre-wetting step to ensure that the soil and permanganate solution were intimately mixed. Labile C fractions, LC_{33} , LC_{167} and LC_{333} were calculated as carbon oxidised by 33, 167 and 333 mM MnO_4^- respectively, and expressed as a proportion of total organic C.

Respiration in optimum temperature and moisture conditions

We investigated the microbial degradation of soil organic matter, as microbial availability is the basis of organic matter turnover and hence governs nutrient storage and cycling in soil. Field fresh soil (< 5 mm) was packed into PVC cores (44 mm inner diameter, 60 mm height) at field bulk density. Soil was equilibrated at -25 kPa matric potential, and each core was placed in a separate 500 mL air-tight glass jar with a metal lid. Respiration was measured as CO_2 trapped in 10 mL of 2 N KOH, which was initially replaced weekly, then fortnightly for the last 2 measurements. Carbonate in the KOH traps was measured by comparing the conductivity of the solution with a range of standards. Respiration chambers were aerated regularly to ensure non-limiting oxygen supply.

Microbial biomass

The chloroform fumigation-extraction method of Sparling and West (1988) was used to determine microbial biomass, but an extraction ratio of 1:6 was used instead of 1:5. Microbial C was calculated as the difference between C extracted from fumigated and unfumigated samples, divided by a k_{EC} factor of 0.3, which was the average for a group of Western Australian soils investigated by Sparling and Zhu (1993).

Statistical Analyses

The effect of land-use management on soil organic matter properties was investigated by regressing soil organic matter values (pooled over the 4 replicate samples) against an independent soil property (clay+silt percentage) and comparing differences between land-use history on regression lines.

3.1.2.2 Nitrogen

Legumes in improved pastures have contributed to enrichment of soil organic matter relative to that present under natural vegetation. Establishment of eucalypt plantations on these pasture soils will lead to further changes in the nature of soil organic matter pools due to a decrease in nutrient-rich legume residues and an increase in lignified litter from the plantation eucalypts. These changes have the potential to affect nutrient availability in soil for uptake by plants. This could occur because changes in the nature of soil organic matter can affect its rate of decomposition and the rate at which it releases nutrients. Of particular importance in this regard is nitrogen supply, which often limits growth of plantation forests. Rate of mineralization of organically bound nitrogen depends on the quality of soil organic matter as well as soil environmental factors, principally soil moisture and soil temperature. Soil factors important in determining potential rate of N mineralization are organic matter content and composition, total nitrogen store, particle size distribution and soil water retention properties. At least some of these factors may change in response to land use changes. Thus, where eucalypt plantations are established in areas previously under agriculture, soil factors that are important in regulating nitrogen supply rates may also be affected. Depending on the time scale of these changes, productivity of the current or future rotations of tree crops may be influenced.

The objective of this part of the project was to evaluate and quantify changes in soil nitrogen supply in relation to the change in land use from pasture to plantation. Four approaches were used:

- (i) undisturbed intact soil cores from paired pasture and plantation soils were incubated in the laboratory under constant conditions of soil temperature and moisture to determine an N mineralization index for each paired site.
- (ii) unincubated soils collected at the same time as the intact cores were incubated under anaerobic conditions to determine potentially mineralizable N.
- (iii) long-term laboratory incubations of pasture and plantation soils were used to evaluate changes in the size and decomposition rate of potential nitrogen supplying pools in the soil.
- (iv) actual seasonal rates of N mineralization were quantified in the field at two contrasting sites using sequential *in situ* soil coring over a 12-month period. This last approach is described in section 3.1.3.

Index of N mineralization.

Intact soil cores were collected from each of 31 paired pasture and plantation sites during late winter/spring when soil was close to field capacity. In order to manage the work, sampling was spread over two years. Fifteen sites were sampled over a 2-month period in 1997, and 16 sites over a 3-month period in 1998. At each site, 6 pairs of steel tubes, 44mm diameter, were driven into the soil to a depth of 20 cm in each of 4 replicate plots in both the pasture and plantation. The cores were removed, cooled and returned to the laboratory in insulated boxes. Soil in one core from each pair was removed from the tube and separated into 0-10cm and 10-20cm depths. Soil from the 6

cores within each plot were bulked and sieved, and the < 5 mm fraction was analysed for mineral N content (extraction in 1M KCl and mineral N determination by automated colorimetry). The second set of cores from each pair was incubated at 20°C for 28 days before being extracted in a similar way for determination of mineral N content. The difference in mineral N between the freshly collected soil cores and those incubated for 28 days was calculated and used as an index of N mineralization for each pasture-plantation pair.

Potentially mineralizable N

This second index of mineralization was determined on all unincubated samples obtained by bulking soils from the initial set of 6 cores for each plot. 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.

Long-term laboratory incubations

Soils (< 5 mm fraction) sampled from 28 of the paired sites during the spring of 1997 and 1998 were incubated using a multiple micro-lysimeter system with 4 replicate lysimeters for each tree and pasture pair (Plate 2). The base of each micro-lysimeter consisted of a polycarbonate membrane with a 0.4 µm pore size able to withstand a bubble pressure of > 25 kPa. Each micro-lysimeter was filled with approximately 40g to 50g of soil so that the bulk density of soil in the micro-lysimeters was similar to that of the field soil. A fibre- glass filter was placed on top of the soil to prevent disturbance during addition of leaching solutions.

The micro-lysimeters were incubated at 20°C for 13 months in a constant temperature room. Each lysimeter was leached periodically with 240 mL of a solution containing 0.01 M CaCl₂ and 0.01 M KCl. Incubation periods between leaching varied from 10 days initially to more than 2 months by the end of the experiment. Soil moisture was equilibrated by applying 25 kPa pressure to the micro-lysimeter head-space for 40 h following each leaching cycle. Leachates were analysed for NH₄-N and NO₃-N by automated colorimetry using a Lachat micro-bore flow injection analyser.

Soil N mineralization results from pasture and tree areas were analysed separately. For each land-use type, cumulative mineral N production was related to time of incubation for each of the 28 sites by fitting the model:

$$N_t = N_{li} \cdot (1 - e^{-kl \cdot t}) + N_{ri} \cdot (1 - e^{-kr \cdot t}) \quad (1)$$

N_t is the cumulative amount of mineral produced at time t , N_{li} is the labile pool of mineralizable N at site i , N_{ri} is the resistant pool of mineralizable N at site i , and kl and kr are the decay rate constants for these pools. Single pairs of rate constants were determined for each of the sets of tree and pasture sites, while there were separate labile and resistant pools for each of the individual tree and pasture sites.

3.1.2.3 Phosphorus

Measurement of forms and fluxes of soil P that are related to plant available P is more problematic than the measures of soil nitrogen supply. Although significant amounts of P are held in organic forms and microbial activity is an important determinant of P supply, much of the P released into the soil solution reacts and is bound by mineral surfaces. P supply in soil is therefore very dependant on the mineralogy, and particularly the area of charged mineral surfaces. P is strongly bound to clay and to iron or aluminium oxides.

When P fertilizer is applied to soils, most of it dissolves fairly rapidly. Initially there are a complex series of precipitation reactions but as the P diffuses from the initial reaction zone, adsorption onto the outside of soil particles becomes dominant. While the P remains on the outside of soil particles, it can be rapidly removed and is considered to be 'effective' in the supply of P to plant roots. Nevertheless, there is a large variation between soils in the effectiveness of P fertilizers. This arises because of differences in the amount and surface area of particles that can adsorb P. If a soil has a large adsorption surface area, large amounts of P must be added before there is much increase in the P concentration in solution. That is, the soil has strong buffering for P. Much more P must be added to such a soil than to one with fewer adsorbing particles to get a comparable uptake of P by plants. The effectiveness of P fertilizers therefore decreases as the P buffering increases.

With increasing time after application, P slowly diffuses into the interior of soil clay minerals and iron and aluminium oxides. When this happens, it can only slowly move back to the surface of these minerals, and thence to the soil solution. Hence, applied fertilizer becomes less effective with time and additional P is required to produce the same plant growth response. The rate of these changes is rapid at first. Effectiveness of P applied in fertilizer might drop to somewhere between 40 and 60 per cent of that of freshly applied P after a year of reaction. However, the rate of change slowly decreases and further change becomes very slow after four to five years. As a result, regular annual applications of fertilizer over several years can build up a large reserve of P. If applications are then stopped, it can take many years before the status of the soil has declined far enough for deficiency to reappear (Barrow 1980b). Most of the sites used for plantations have a long history of P application.

The complexity of P chemistry in soils has led to many approaches aimed at identifying indices that are best related to P uptake by plants. These include procedures that have been developed to measure various forms of P in soils (eg. Hedley *et al.*, 1982), and others to examine the relative importance of intensity, quantity and capacity factors to plant P availability (eg. Dalal and Hallsworth, 1976). Intensity refers to the P concentration in soil solution, quantity to the amounts that can be extracted (related to plant availability), and capacity to the ability of soils to replenish P removed from solution. We have explored both of these approaches.

Initially we tested the feasibility of using the sequential fractionation procedure of Hedley *et al.* (1982) to measure the effect of land-use change (pasture to plantation) on concentrations of various inorganic and organic forms in soils. The procedure was evaluated with soils from the paired site on Ayers' property near Greenbushes. It was time consuming and laborious, and prone to cumulative errors associated with sequential use and recovery of residue soil for subsequent extractions. Based on the initial data, we also questioned whether the results from the large number of paired sites would be interpretable in view of the limited duration of land-use change and the wide array of soil types. The procedure may be more applicable to studies of changes where there are longer histories of land-use differences or management practices involving large changes to soil conditions such as soil organic matter. For example, Cross and Schlesinger (1995) used this fractionation procedure in examining the pedogenesis of soils of different weathering over time.

We therefore focused on a second approach of examining measures of the intensity, quantity and capacity factors of soil P supply that are related to plant availability. This involved several extraction methods run in parallel and determining the P released into solution by extractants of varying strength. A number of these procedures are used routinely by soil testing services to estimate fertilizer requirements of agricultural and forest species (Rayment, 1993). A second series of analyses was used to measure P-sorption properties, including estimates of intensity and the P buffering capacity of the soils.

For these measurements, bulked surface soils (0-10 cm, < 2 mm) from pasture and plantation areas at a subset of 18 paired sites covering the range in soil types were analysed. Details of analytical procedures are outlined below.



Plate 2. Multiple micro-lysimeter system used to determine cumulative mineral-N production in pasture and plantation soils.

Extraction methods

The extraction procedures in increasing order of strength were –

- CaCl_2 extraction – estimates of P using this mild extraction procedure were determined as part of the P equilibration procedure outlined below.
- Olsen P - P was extracted using a 0.5M NaHCO_3 solution at pH 8.5 and shaking 5 g soil in 100 mL solution for 30 minutes (Olsen *et al.*, 1954). Concentration of P in the filtered extract was determined with a UV-Visible Spectrophotometer based on the method of Murphy and Riley (1962).
- Colwell P - P was extracted using a 0.5M NaHCO_3 solution at pH 8.5 and shaking 1 g soil in 100 mL solution for 16 hours (Colwell, 1963). Concentrations of P in extracts were determined in the same way as for Olsen P.
- Bray P - P was extracted with 0.03M NH_4F 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 extracts were determined in the same way as for Olsen P.
- Total P – concentrations of P were determined using an automated colorimetric method on a Lachat Flow Injection Autoanalyser following digestion of soil in $\text{H}_2\text{SO}_4/\text{H}_2\text{O}_2$ at 360°C.

Equilibration method

Dilute solutions containing different concentrations of P were mixed with soils to measure how much P was removed from, or released into, solution (i.e. P sorbed or desorbed). Plotting sorption against solution concentration gives a measurement of the P buffering, which is proportional to the ratio of P sorbed to P in solution. These sorption curves also provide an estimate of the solution concentration at which P is neither sorbed nor desorbed. This "null point" concentration is a useful measure of the "intensity" factor of soil P supply. A further measure is obtained by extrapolating sorption curves back to zero concentration. Formally, this value (referred to as q) is the amount of P that could be desorbed if the concentration could be held at zero, and if the equation applied over that range. Finally, by measuring the changes in the positions of the sorption curves through time we can see how these properties would vary through time.

These measurements are also of value in assessing the possibility of leaching of P. In most soils, P is retained on the solid phase and there is little in the soil solution. Losses through leaching are unlikely. The exceptions are those soils with very low P buffering. These are very sandy soils and

leaching of P can occur, especially in high rainfall areas. To evaluate the potential for leaching, a measure of the ratio of solution P to sorbed P, or the reciprocal of P buffer capacity, is particularly useful.

To quantify sorption-desorption curves, soils (<2 mm fraction) were gently mixed in 0.01M CaCl₂ solutions containing a range in concentration of P. Soils were mixed with solutions (ratio 1:10) for periods of 1 hour, 1 day or 1 week at 20°C. P concentrations were determined in filtered extracts by the manual colorimetric procedure based on the method of Murphy and Riley (1962). At least 18 extractions were required for each soil. From this, the change in concentration was calculated and hence the amount of phosphate sorbed or desorbed.

The relation between sorption S and solution concentration c is normally a curve and for low P soils can be described by a function such as $S = k c^b$. Such curves can be represented as straight lines with a slope of k if S is plotted against c^b . When some desorption of P occurs, there is an intercept and the equation becomes:

$$S = a_i c^{b_i} - q_i \quad (2)$$

where a , q and b are parameters with the subscript i indicating 1h, 1 d or 1 week. That is, this equation permits separate values to be allocated to the a and q parameters for each of the periods used, but with a common value for b .

A second equation fitted to the data was:

$$S = a c^{b_1} t^{b_2} - q t^{b_3} \quad (3)$$

where t is the time in hours. This equation had two fewer parameters and allows for interpolation through time. Thus values for 1 day were constrained by the values for 1 h and 1 week. Both these equations involve the principle that sorption and desorption are symmetrical and that a smooth line can be drawn through sorption and desorption points. The second equation involves the principle that both sorption and desorption increase through time and the increases are described by a function of similar form. However, the two functions are permitted to be different. Consequently, when S is zero, and hence neither sorption nor desorption occur, the resulting value for concentration can vary with period. Both equations were fitted by noting that they are simultaneous with the equation that related the change in solution concentration to sorption. The criterion for best fit was that the sums of squares for the difference between observed and predicted concentrations be minimized.

A measure of the P buffering capacity of the soils was obtained from the fitted curves. This is measured by the slope of the sorption curve and, by convention, a period of 1 day was chosen to compare the soils. Consideration of the equations shows that the slope (dS/dc) varies with concentration. A convention has developed that the slope be measured over the concentration range of 0.25 to 0.35 $\mu\text{g mL}^{-1}$. This value, which can be calculated from the equation as $a 24^{b_2} (0.35^{b_1} - 0.25^{b_1})$, is known as the "Ozanne and Shaw value" (Ozanne and Shaw, 1968). This has been used as the measure of P buffer capacity in this study.

3.1.2.4 Relationships among soil and climate variables

In addition to the measures of soil C, N and P outlined above, a range of other chemical properties were measured on soils (0-10 and 10-20 cm, < 2 mm fraction) from the 31 paired sites sampled for N mineralization measurements. These included properties likely to help explain variation in forms and flux rates of C, N and P, and others that may influence or be affected by tree growth and nutrient uptake. Chemical properties determined were pH, bicarbonate-extractable P (Colwell method), and concentrations of exchangeable Ca, Mg and K. These procedures have been outlined above (3.1.1). Measurements of the physical properties of the soils included bulk density, gravel content, water-holding capacity at 25 kPa pressure, and particle size distribution.

This broad range of soil properties was used to examine relationships among soil and climatic variables across sites using multiple regression procedures.

3.1.3 Seasonal variation in N and C measures

At two sites with contrasting soil and climate (Gibbs and Moltoni), seasonal rate of N mineralization was quantified by sequential in-situ soil coring. The site near Pemberton (Moltoni) is a fertile yellow duplex soil and the site east of Collie (Gibbs), a siliceous sand. Annual average rainfall is estimated to be 1360 mm at Moltoni's and 730 mm at Gibbs. The areas to be regularly sampled were fenced to prevent disturbance and contamination of cores by grazing animals. The pasture was regularly mown to maintain a height similar to the surrounding grazed areas (Plate 3).



Plate 3. Fenced sampling plots in pasture at the Moltoni paired site

Four replicate plots were established within the tree and pasture areas at each site for regular field sampling. Field incubations were conducted each 4 weeks using the *in situ* coring technique (Raison *et al.* 1987). At the commencement of each sampling period, 12 steel tubes (44mm dia.) were driven into the soil to 20 cm at each plot. Six of the soil cores were withdrawn immediately and returned to the laboratory for analysis. The remainder were covered with plastic caps and allowed to incubate for 4 weeks under field conditions and then returned to the laboratory for analysis. Immediately following sampling, soil cores were placed in cooled insulated containers before transport to the laboratory where they were stored at 4°C prior to preparation and analysis. Soil cores were divided into two depths (0-10 and 10-20 cm), sieved through a 5mm screen to remove large roots and gravel and the six cores of each type within each plot were bulked for analysis of ammonium and nitrate. Mineral N was extracted from 50 g moist weight of soil with 50 ml of 1M KCl after end-on-

end shaking for 1 hour. Monthly net N mineralization rates were calculated from the difference in mineral N content of incubated and unincubated soil core samples. Potentially mineralizable N was determined on unincubated soil samples as described above.

On four sampling occasions during the year (May, July, October, January), microbial biomass C was determined on freshly collected soil from the cores returned immediately to the laboratory. The procedure for measuring microbial C is as outlined in above (3.1.2.1), except that determinations were carried out with soils at field moisture.

3.1.4 Plant bioassay

A number of the measures of C, N and P are, individually or in combination, widely used as indices of the capacity of soils to supply nutrients for plant growth. Some are used in routine soil analysis programs to predict fertilizer requirements for growth of pastures, crops and trees. Their use for predictive purposes is generally in combination with other information such as the previous history of cropping and fertiliser use. Extensive research has been done to evaluate extraction procedures on the basis of how well soil measures are related to the growth of plants, or the responsiveness of plants to nutrient application.

The emphasis in the current project has been to evaluate the impact of land-use change on a number of soil properties related to plant availability of nutrients. Less emphasis has been given to plant studies. However, bioassay experiments were established at 2 paired sites using intact soil cores. The aim was to evaluate differences between pasture and plantation soils in their effects on seedling growth and nutrient uptake, and the response of seedlings to applied N and P.

Experimental details –

The study was conducted in a period conducive to rapid seedling growth (Nov.'98 to March'99).

Sites: Experiments were established at the two sites where other measurements were made of soil profile characteristics (3.1.1) and seasonal variation in N mineralization (3.1.3). The site near Pemberton (Moltoni) is a fertile yellow duplex soil and the site east of Collie (Gibbs) a siliceous sand.

Experiment design: A split-plot design was chosen in which there were three replicate blocks of each land-use type (pasture, plantation) as main plots, and factorial combinations of three P rates and three (Gibbs) or two (Moltoni) N rates as subplots. All undisturbed soil cores representing subplots of a single main plot were taken from one of three different positions in each of the pasture and plantation areas.



Plate 4. Soil cores from pasture (back) and plantation (front) areas being repositioned and buried in the pasture site.

Undisturbed soil cores: Sets of 9 (Gibbs) or 6 (Moltoni) soil cores (15 cm diam., 42 cm long) were taken from three positions in each of the pasture and plantation areas. Cores were moved to a single pit within a fenced pasture area and reburied (Plate 4).

Nutrient treatments: Phosphorus treatments applied as potassium dihydrogen phosphate at the time of planting (Plate 5a) were 0, 15 and 90 kg P ha⁻¹ at Gibbs site and 0, 30 and 180 kg P ha⁻¹ at Moltoni's. Nitrogen treatments applied as urea in 3 doses were 0, 40 and 240 kg N ha⁻¹ at Gibbs and 0 and 240 kg N ha⁻¹ at Moltoni. A basal dressing of potassium sulphate was also applied to each core on 3 occasions

Planting and maintenance: A single *E. globulus* seedling was planted in each core in early November 1998. Seedlings were watered regularly to avoid drought and sprayed with insecticide twice. Plant growth after 3 months is shown in Plate 5b.

Measurement and analysis: Seedling height and stem diameter were measured on eight occasions. Trees were harvested on 9th March, 1999 and tops sorted into leaf, branch, stem-wood, stem-bark. Samples were dried, weighed and ground for analysis. Concentrations of N and P in each fraction were determined with an auto-analyser following Kjeldahl digestion. Effects of land-use type and nutrient treatments on growth and N and P content of plant tops were evaluated for each site by analysis of variance.



Plate 5. Field bioassay at Gibbs site: (a) applying nutrients at planting (b) growth shortly before harvest

3.1.5 Plantation productivity and nutrient uptake

This component of the project aims to –

- (i) estimate stand productivity at the paired sites and evaluate this in relation to climate and soil characteristics
- (ii) estimate nutrient concentrations in aboveground biomass and the likely return of nutrients to soils in slash at each site when plantations are harvested.

Tree measurements

Tree stem dimensions were measured at the 31 paired sites used to measure N mineralization and other soil properties. Four measurement plots (average 165 m² each) were marked out in each stand in the area in which soils were sampled. Tree heights were measured with an electronic clinometer ('Hypsometer') and diameters were measured at 1.3 m above the ground. This information was used to calculate the stem conical volume of each stand. The mean annual increment (MAI) in volume over bark (m³ ha⁻¹ year⁻¹) was determined from current total volume and age of the plantation.

Dry matter production

Stem conical volume is well related to above-ground tree biomass and the biomass of individual tree components (i.e. stem-bark, stem-wood, canopy) for *E. globulus* growing in plantations across the range of climatic conditions in south-western Australia. In related studies, we have developed relationships based on results from destructive sampling of trees associated with the slash management experiments (3.2) combined with data from the study of Hingston *et al.* (1998) for trees up to age 9 years sampled from six sites. A relationship for stem-bark was used to predict bark biomass on an areal basis from measured stem volume.

Bark sampling and analysis

Estimates of tree nutrient composition focussed on determining the concentration and amount of nutrients in stem bark. At the time of tree measurements, a composite sample of stem bark was obtained for each of the four measurement plots at each site. A wad punch was used to take a single bark disk to the depth of the cambium from each tree. Samples were taken at a height of 1.3 m and

bulked for an average of 10 trees in each plot. The bark samples were dried, weighed and ground for analysis. Mean disk weight was calculated to provide an index of bark thickness for each site. Concentrations of N and P in each fraction were determined with an auto-analyser following Kjeldahl digestion. Concentrations of Ca, Mg, K and Na were determined by atomic absorption spectrometry. Concentrations were used to determine total stores in stem-bark, and the mean annual rate of accumulation of nutrients in bark at each site.

3.2 Inter-rotation Harvest Residue Experiments

Research into second rotation site management was commenced prior to the current project and is still continuing. It was initiated following allocation of *Industry Statement Funds* to the CSIRO Centre for Mediterranean Agricultural Research (CCMAR) to investigate the impact of trees on soil fertility. We have established extensive field experiments at two sites with contrasting soils to evaluate effects of silvicultural treatments applied in the inter-rotation period on soil nutrient supply processes and tree growth. The experiments reported here are examining the impact of harvest residue management treatments. This research is continuing with funding from the Australian Centre for International Agricultural Research (ACIAR).

Results from these studies were recently reported to a workshop of the Centre for International Forestry Research (CIFOR) on “Site Management and Productivity in Tropical Plantation Forests: Impact on soils and options for management over successive rotations”. The workshop was held in Kerala, India in December 1999. Sections of our paper (O’Connell *et al.*, 2000) presented to this meeting are incorporated into this section of the current report. Additional results on the impact of harvest residue treatments on forms of P in soils, a component specific to the current project, are also presented.

Objectives and approach

The objectives of the research were to:

- (i) develop methodologies to manage soil fertility and maintain high productivity
- (ii) determine nutritional requirements for growth of trees in second-rotation plantations

The impact on soil fertility and tree growth of site management practices during the inter-rotation period following stand harvest is being evaluated using a series of designed experiments. The focus in this report is on management of harvest residues and its impact on soil organic matter, soil nutrient status, nutrient flux rates and tree growth in the four years following harvest of the first rotation of *E. globulus* plantations.

Location and site description

The research is being conducted at two second-rotation *E. globulus* plantation sites in south-western Australia (see Figure 2 for locations). The plantations were established on farmland previously used for conventional agriculture. The two sites, near Busselton (lat. 33° 45’S, long. 115° 07’E) and Manjimup (lat. 34° 20’S, long. 116° 00’E), fall within the main climatic range where the majority of eucalypt plantations are established (Table 4). The site near Manjimup is on relatively fertile karri forest soil (red earth - Ferralsol). The site near Busselton is on a low-fertility soil (grey sand over laterite - Podzol). General chemical properties of surface soils at each site are listed in Table 5.

Table 4. Climatic data at Manjimup and Busselton.

Location	Annual rainfall (mm)	Mean daily max. temperature (°C)		Mean daily min. temperature (°C)		Cloudy days (yr ⁻¹)	Clear days (yr ⁻¹)	Mean annual RH (9 am) (%)
		Jan.	July	Jan.	July			
Manjimup	1023	27.1	14.2	13.0	6.4	145	64	56
Busselton	825	28.5	16.3	13.8	7.5	101	97	72

Table 5. Soil chemical properties at the two experimental sites at time of application of harvest residue treatments.

Site/ Depth (cm)	pH	Organic C (g kg ⁻¹)	Labile C (g kg ⁻¹)	Total N (g kg ⁻¹)	Total P (g kg ⁻¹)	Bray P (mg kg ⁻¹)	Cations (cmol kg ⁻¹)		
							Ca	Mg	K
Red earth									
0-5	5.81	55.3	17.1	2.5	0.45	104	2.50	0.54	0.42
5-10	5.60	43.5	12.1	1.9	0.35	90	1.32	0.24	0.23
10-20	6.02	30.5	8.3	1.1	0.20	35	2.05	0.24	0.15
Grey sand									
0-5	5.13	45.6	14.3	1.8	0.10	3.5	1.99	0.59	0.18
5-10	4.77	33.8	12.1	1.2	0.06	1.8	1.18	0.33	0.12
10-20	4.76	22.4	7.2	0.6	0.04	1.8	0.77	0.17	0.06

The first rotation stand of *E. globulus* at the Manjimup site was established in 1986 at a spacing of 4 x 2 m. At the time of harvest in August 1994, above-ground biomass of the stand totalled 275 t ha⁻¹, with 170 and 24 t ha⁻¹ removed in harvested bole wood and associated stem bark, respectively. At Busselton, the first rotation of *E. globulus* was established in 1987 and harvested in May 1995. Productivity at this site was lower than at the Manjimup site with total above-ground biomass accumulation of the stand being approximately 98 t ha⁻¹ at the time of harvest. About 59 t ha⁻¹ was removed from the site in harvested bole wood and 8 t ha⁻¹ in bark.

Both sites were replanted with seedlings during winter in July-August 1995 at a density of 1250 stems ha⁻¹. There was no prior cultivation of the soil. A single spot application of compound NPS fertilizer (Agras 18:8:16, N:P:S) was applied at a rate of 130 g adjacent to each seedling. Weeds were controlled by hand cultivation and by the use of glyphosate herbicide in the first two years after planting.

Experimental design

At each site, four experiments were established to investigate impact of organic matter amendment (harvest residue management), inter-row cover crops (five agricultural legumes), and the responses to added N and P fertilizers at different rates. Only the harvest residue management studies are discussed in detail in this paper.

A randomized block design was used, with six treatments randomized within each of four replicate blocks. Treatment plots were 18 m x 18 m, with 40 trees per plot. Harvest residue management treatments were-

- 1) (BL₀) No slash — all litter and slash material removed

- 2) (BL₂) Single slash — uniformly redistributed
- 3) (BL₃) Double slash — addition of slash from the 'no slash' (BL₀) treatment
- 4) (B) Burn — (BL₂ with retained slash burnt)
- 5) (BL₂ + fertilizer) — broadcast (50 kg P ha⁻¹ as triple superphosphate and 45 kg K ha⁻¹ as K₂SO₄)
- 6) (BL₂ + fertilizer + legume) — broadcast P and K fertilizer with cover crop of vetch (*Vicia sativa*)

Results from the first four treatments are discussed here.

Experimental methods

Soils were sampled annually in December each year to assess the impact of treatments on soil chemical properties over time, with the exception that at Busselton the first sampling was conducted in June 1995. Additionally, samples were collected on the burn plots (B) at each site immediately after the residues had been burnt to assess the direct effects of fire. At each sampling time, nine steel tubes, diam. 44 mm, were driven into the soil to a depth of 20 cm at randomised locations within each plot. Soils were separated into three depths (0-5, 5-10, 10-20 cm) and the nine cores within each plot were bulked, air dried and sieved through 2mm. Soils were analysed for pH, organic C, cations and Bray-extractable P (for procedures see 3.1.1). Labile organic C was determined by partial oxidation with 333mM permanganate as outlined by Blair *et al.* (1995). Additionally, at two sampling times (before and 18 months after planting) we determined concentrations of a range of different P forms in surface soils from the four main slash treatments. P forms determined by independent extractions include CaCl₂-extractable P, and the labile or moderately labile forms of inorganic (Pi) and organic (Po) P extracted by bicarbonate (Bic) or hydroxide (NaOH) solutions.

Labile nitrogen status and rate of N mineralization were assessed by the in situ coring technique (Raison *et al.* 1987). Field incubations were conducted every 4 weeks. At the commencement of each sampling period, 18 steel tubes (44mm diam.) were driven into the soil to 20 cm at each plot. Nine of the soil cores were withdrawn immediately and returned to the laboratory for analysis and the remainder were covered with plastic caps and allowed to incubate for 4 weeks under field conditions and then returned to the laboratory for analysis. Details of sample preparation and mineral N analysis are given in section 3.1.3. Potentially mineralizable N was determined on all unincubated soil samples by the anaerobic incubation method of Keeney and Bremner (1966).

Tree growth was assessed periodically by measuring tree diameter and height within a central measuring plot containing 18 trees. Biomass was determined by relating tree volume to weight using allometric relationships derived from destructively harvested sample trees. These sample trees were also used to determine allocation of biomass between various tree components. LAI was determined from allometric functions relating leaf area to stem basal area at the crown base.

4. Results

4.1 Paired Plantation-Pasture Study

4.1.1 Paired site description and preliminary soil survey

Site characteristics

Paired sites were distributed across the region in which *E. globulus* is grown in south-western Australia and were representative of the broad range of climatic conditions and soil types (Figure 2, Tables 1, 2). By retaining a large number of sites for many of our studies, the impact of any mismatching at specific sites in determining effects of land-use change was reduced.

Soil types included red or yellow duplex, red earths, podzols, siliceous sands and sandy gradational soils. Attempts to obtain a stratification of sites where both sandy and heavier textured loams were represented across the climatic spectrum were unsuccessful because (i) landforms and soil types change with the rainfall pattern (Figure 2) and (ii) restrictions on the soil types used for the original plantings. This confounding of the variation in climate and soil type is illustrated by the relationship between the percentage sand and rainfall for 31 sites used for subsequent measurement (Figure 3). This associated variation in the two factors is important to the interpretation of variation among sites in the soil chemical properties described below.

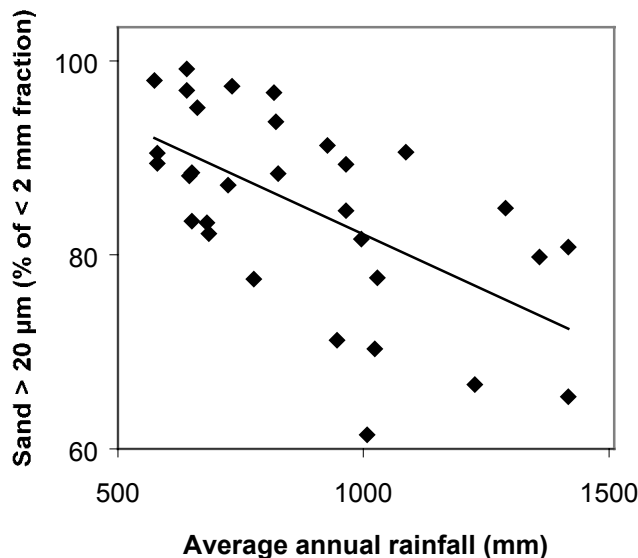


Figure 3. Proportion of sand in surface (0-10 cm) soil in relation to annual rainfall for 31 paired sites.

Average annual input of fertiliser is generally higher in the high rainfall zone, but largely due to greater input of N and K fertilisers. The inorganic forms of these elements not taken up by plants are readily leached from surface soils and were therefore not considered. There was no significant trend in rate of P application across the climatic gradient. P was applied predominantly as superphosphate. The average annual rate of P applied to pasture across 31 sites was 14 kg P ha⁻¹ year⁻¹. Difference in broadcast-applied P between pasture and plantation areas for the period since plantations were established averaged 124 kg P ha⁻¹. Calcium (Ca) and sulphur (S) are also applied in superphosphate. While S is likely to be leached, Ca may be retained on exchange sites in soils and affect the balance of cations. Based on the amounts of P applied, the additional amount of Ca applied to pasture since adjacent plantations were established was about 220 kg Ca ha⁻¹.

Preliminary survey of soil N and P

Concentrations of total P and N were higher in pasture soils than plantation soils at many of the sites, but the relative differences were variable (Figure 4). Among the 42 paired-sites initially sampled, 28 had smaller amounts of total P in plantation soil than in pasture soils. The levels of total P in these plantation soils ranged from 50 to 90% of those in pasture soils. There were 12 sites where the levels of total P in plantation soils were similar to the paired pasture soil (90-110% of pasture level) and 2 sites with more total P in plantation soils than pasture soils (110-120% of pasture levels). For total N, plantation soils from 21 paired-sites had at least 10% less total N than in pasture soil. There were 17 sites with similar levels of total N in plantation and pasture soils (90-110% of total N in pasture soil), and 4 plantation sites with more total N than pasture soils (110-120% of total N in pasture soils).

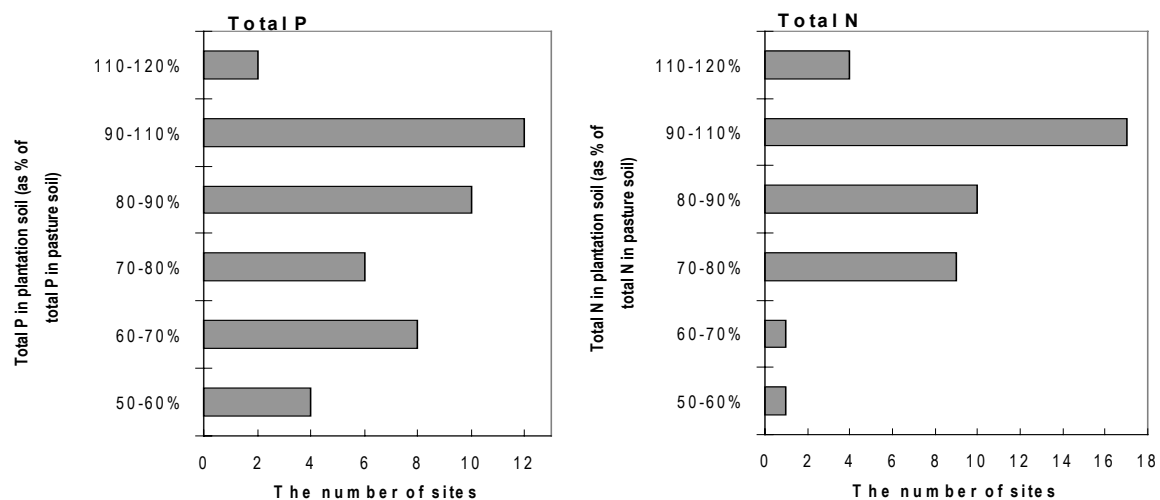


Figure 4. Amounts of total P and N in plantation soil as a percentage of P and N in pasture soil at the 42 paired sites.

Soil Profile Chemical Properties and Nutrient Stores

Concentrations, amounts and distributions of nutrients in soil profiles differed between the low rainfall sandy site (Gibbs) and the high rainfall loam site (Moltoni). At the sandy site, there were marked gradients down the profiles in concentrations of total N and P (Figure 5), bicarbonate-extractable P and exchangeable Ca, Mg and K associated with a similar trend in organic C. Differences in N and P concentrations between pasture and plantation areas were consistent with results of the preliminary survey and related to higher organic C in pasture soils. Soil pH varied between profiles and there was no consistent trend. At the loam site, there were also strong gradients in concentrations down the profile, particularly for organic C, total N and P (Figure 5) and extractable P. However, the decrease is less marked in the top 30 - 40 cm, and variability is higher, than on the sandy site. This may be explained by greater soil disturbance at the time of clearing of the tall forest, and deeper cultivation associated with two potato crops. One profile was omitted from the pasture estimates, as Ca and Mg concentrations were 2 – 3 times greater than in the other two profiles. This may have resulted from an ash-bed, as a charcoal layer was seen adjacent to the area sampled. Concentrations of N and P in this profile were comparable to the other profiles.

Concentrations of organic C, total N and exchangeable Ca and Mg in the surface 0 – 10 cm soil were comparable at the two sites, but were higher at lower depths in the loam soil. Concentrations of total and extractable P were much higher in the loam soils, particularly in surface soils. The loam soil contained about 12% gravel (> 2 mm fraction) in the surface 20 cm, increasing to 20 to 30% at depth. The sandy soil contained less than 1% gravel.

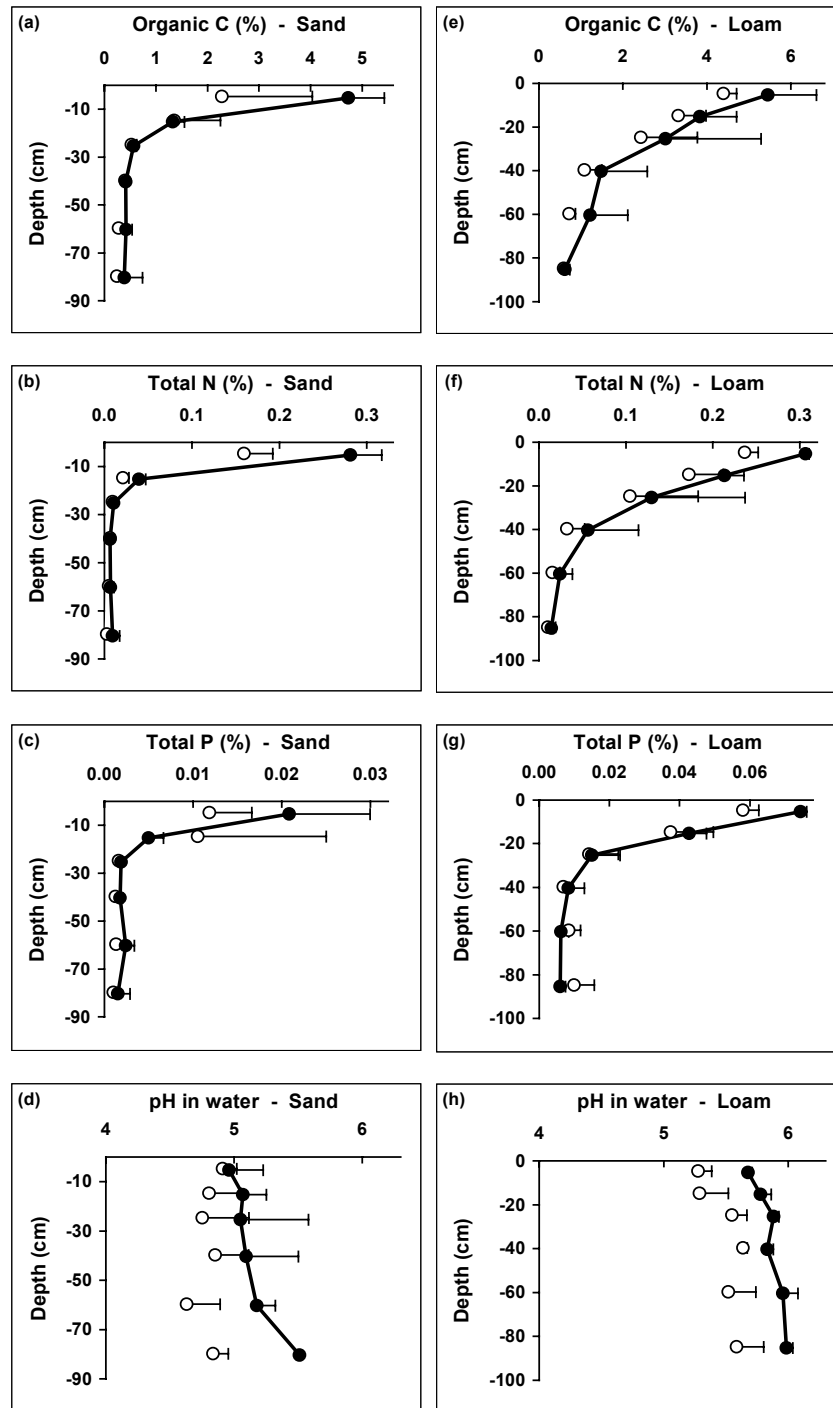


Figure 5. Variation in pH and concentrations of total N, P and organic C in soil profiles from the pasture (closed symbols) and plantation (open symbols) areas at the Gibbs sand site (a-d) and Moltoni loam site (e-f). Bars are the sd of the means of three profiles.

There are large differences between sites, and in some cases between pasture and tree areas, in the amounts of total and extractable nutrients stored in the surface metre of soil (Table 6). Amounts of total P are four times greater, and total N, Colwell-extractable P and exchangeable K two to three times greater in the loam soil than in the sand. Stores of exchangeable Ca and Mg are not substantially different between sites, although a higher proportion of these elements, as well as N and K, are held in the surface 20 cm of the sand. The proportion of extractable P held in the surface soil is higher in the loam (91%) than in the sand (55%). Amounts of N, P and Ca are comparable in soils from the pasture and plantation areas of the loam site. However, for the sandy profile, amounts of N, extractable P and exchangeable Ca and Mg are higher in the pasture soil than under the trees.

Table 6. Amounts (kg ha^{-1}) of total and extractable nutrients in soil profiles at the Gibbs (sand) and Moltoni (loam) sites. Values in parentheses are the percentages of nutrients in the surface 20 cm.

Site	Land-use	Total N	Total P	Colwell P	Exchangeable Cations		
					Ca	Mg	K
Gibbs Sand (0 - 90 cm)							
	Plantation	2710 (78)	430 (68)	28 (59)	1158 (62)	164 (75)	93 (59)
	Pasture	4738 (79)	537 (57)	101 (52)	1611 (70)	447 (50)	82 (74)
Moltoni Loam (0 - 100 cm)							
	Plantation	7029 (64)	2057 (51)	175 (91)	1858 (18)	356 (15)	217 (33)
	Pasture	8210 (64)	1785 (67)	183 (92)	1728 (43)	170 (47)	353 (31)

4.1.2 Measurements of carbon, nitrogen, phosphorus and other properties in surface soil

4.1.2.1 Carbon

Total organic carbon

Sites in this study had a wide range of total organic carbon (TOC) in the less than 2mm fraction (17 to 90 mg g⁻¹, see Figure 6). There was a strong relationship with the silt+clay content ($r^2 = 0.68$, $P < 0.001$), but there were no significant effects of land-use history on total organic carbon levels.

Soil C:N and C:P ratios

Site management had a marked significant effect on C:N and C:P ratios (Figure 7 - significant difference assessed as non-overlap of 95% confidence intervals). Ratios under managed conditions

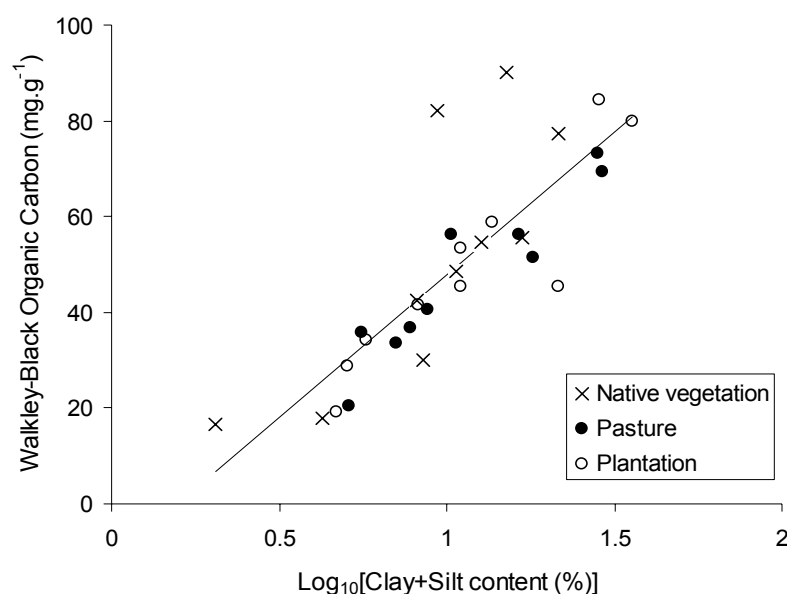


Figure 6. Total soil organic carbon concentration in relation to silt+clay content in surface (0-10 cm) soil. Silt + clay content was log transformed to linearise the relationship.

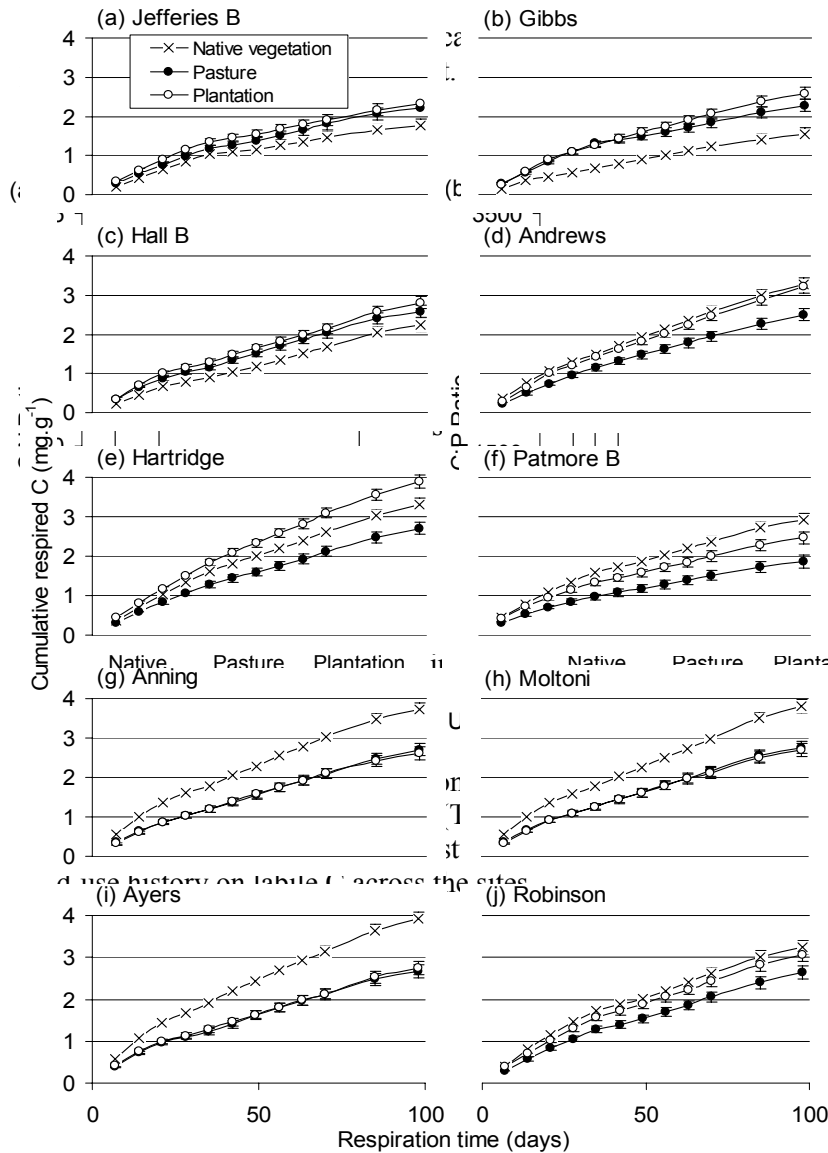


Figure 8. Respired CO_2 ($\pm$ standard error) under optimal moisture and temperature conditions for 10 sites under three management histories.

C:P (b) ratios. Error bars show 95% confidence intervals on the individual samples.

by on cumulative amounts

It and clay content (Figure red from the sandier soils, rest silt and clay contents. in regression.

length of the oxidiser, with very values in the native vegetation re were no significant effects of

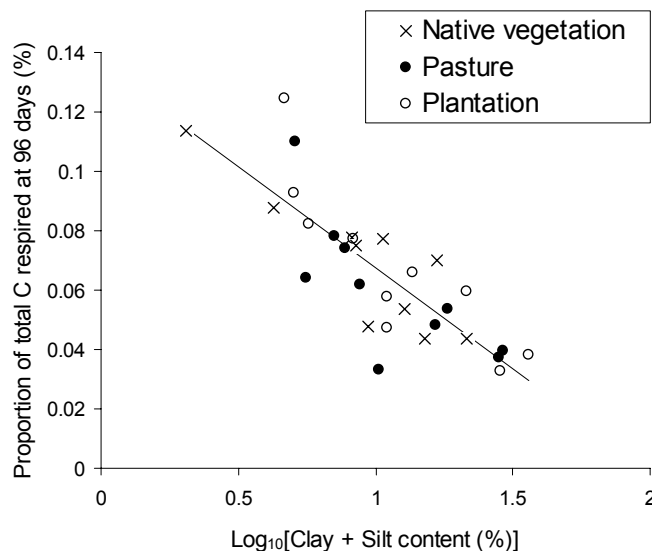


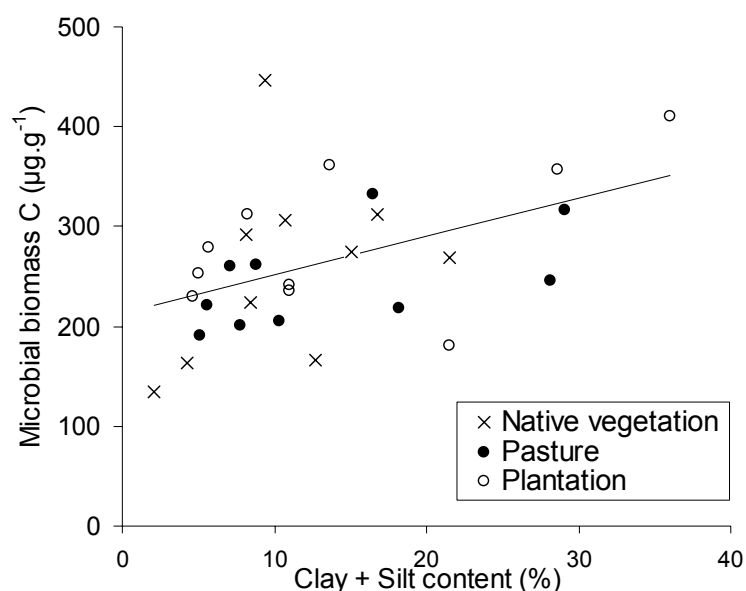
Figure 9. Relationship between proportion of C respired and clay+silt content of surface (0-10 cm) soil. The clay+silt content was log-transformed to linearise the data.

Table 7. Minimum, maximum and mean values (mg g^{-1}) for the Labile C fractions of soil from each of the land-use histories.

Land use history	LC ₃₃			LC ₁₆₇			LC ₃₃₃		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Native vegetation	1.6	13.7	6.9	2.9	23.4	12.1	2.9	25.9	13.4
Pasture	2.2	9.0	5.8	3.8	16.8	10.4	4.7	18.9	12.0
Plantation	2.1	10.9	6.1	3.7	19.4	10.8	4.3	22.4	12.7

Microbial biomass C

Microbial biomass carbon values ranged between 134 and 447 $\mu\text{g g}^{-1}$, with a weak relationship to texture ($y = 3.83x + 213$, $r^2 = 0.20$, Figure 10). There were no significant effects of land use history on microbial biomass levels, nor did the effect of site significantly influence the regression between texture and microbial biomass.

**Figure 10. Relationship between microbial biomass C and clay+silt content for each land-use type.**

4.1.2.2 Nitrogen

Indices of N mineralization.

Average concentrations of total soil N, and the range of concentrations across all sites, were similar in soils from pasture and plantation areas in surface (0-10 cm) and sub-surface (10-20 cm) samples (Table 8). However, the proportion of total soil N potentially available through N mineralization in 0-10 cm soil differed between the land-use types, with smaller proportions associated with plantation sites (Figure 11). Over all sites, the average amount of potentially mineralizable N in plantation soil was about 20% less than in pasture soil (Table 8). Although there was a large variation about the mean values, as reflected by the range in potentially mineralizable N for each vegetation type (Table 8), the overall trend for lower values associated with plantation compared to pasture plots was generally consistent over the range of soils and climatic regions sampled (Figure 12).

Table 8. Variation in soil characteristics of intact core samples (0-10 and 10-20 cm) from 31 paired plantation and pasture sites over a range of soil types and climatic environments.

Soil Characteristics	Pasture			Plantation		
	Mean	Min.	Max.	Mean	Min.	Max.
(a) 0-10 cm						
Total soil N (%)	0.27	0.07	0.64	0.27	0.07	0.72
Soil moisture when sampled (%)	26.3	10.7	54.4	20.3	6.1	41.7
Potentially available N ($\mu\text{g g}^{-1}$)	43.7	24.5	65.5	34.7	14.1	69.1
N Mineralization index ($\mu\text{g g}^{-1}28\text{d}^{-1}$)	30.2	10.1	62.9	17.9	7.4	43.3
(b) 10-20 cm						
Total soil N (%)	0.09	0.02	0.23	0.09	0.02	0.23
Soil moisture when sampled (%)	16.6	7.1	39.4	13.0	3.1	37.1
Potentially available N ($\mu\text{g g}^{-1}$)	6.4	1.7	17.1	7.2	2.9	21.0
N Mineralization index ($\mu\text{g g}^{-1}28\text{d}^{-1}$)	2.9	1.3	6.1	3.0	0.9	7.6

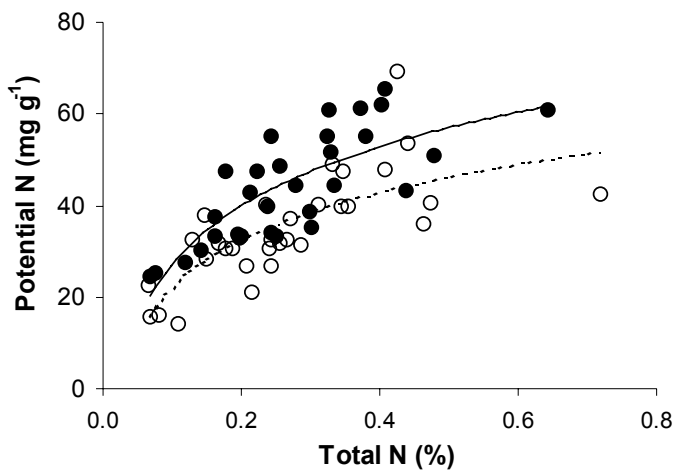


Figure 11. Relationship between N potentially available for N mineralization (anaerobic incubation) and total soil N for pasture (closed symbols) and plantation (open symbols) sites.

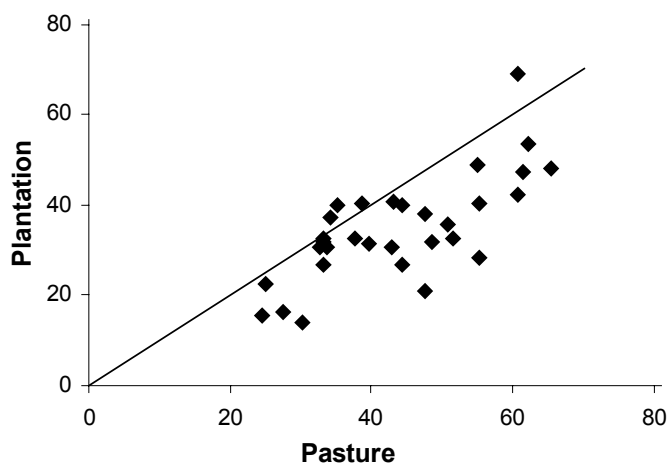


Figure 12. Relationship of N potentially available for N mineralization ($\mu\text{gN g}^{-1}$ soil) in plantation and pasture soils (0-10cm) determined as ammonium produced during by anaerobic incubation of soil at 40°C for 7 days. The line represents the 1:1 ratio.

Lower concentrations of potentially available N in plantation plots in 0-10 cm soils were also associated with lower rates of N mineralization as determined by the N mineralization index (Table 8). Mean values of the index were about 40% lower in plantation soils compared with pasture soils.

Again, there was a large variation between plantations and pasture in the magnitude of the N mineralization index (Figure 13). However, in surface soil, the N mineralization index of plantation plots was greater than on pasture plots at only 3 of the 31 sites, indicating a broad general trend of reduced N mineralization in soil under the eucalypt plantations.



Figure 13. Relationship of N mineralization index ($\mu\text{g N g}^{-1} \text{ soil } 28 \text{ d}^{-1}$) in plantation and pasture soils (0-10cm) determined by incubation of undisturbed soil cores in the laboratory at 20°C .

Soil moisture under plantations was generally lower than in soil under pasture, and this could have affected N mineralization. Average surface soil moisture was 25% lower under trees than under pasture (Table 8) and this was a generally consistent trend over all sites.

Long term laboratory incubations

The fitted model (equation 1) provided a good description of the cumulative mineral N production across all sites and explained more than 99% of the variation in data sums of squares for both pasture and plantation sites (Figure 14).

Pool sizes varied widely between the different sites (Figure 15; Table 9), possibly reflecting differences in fertility over the range of sites and soil types sampled. However, there was no

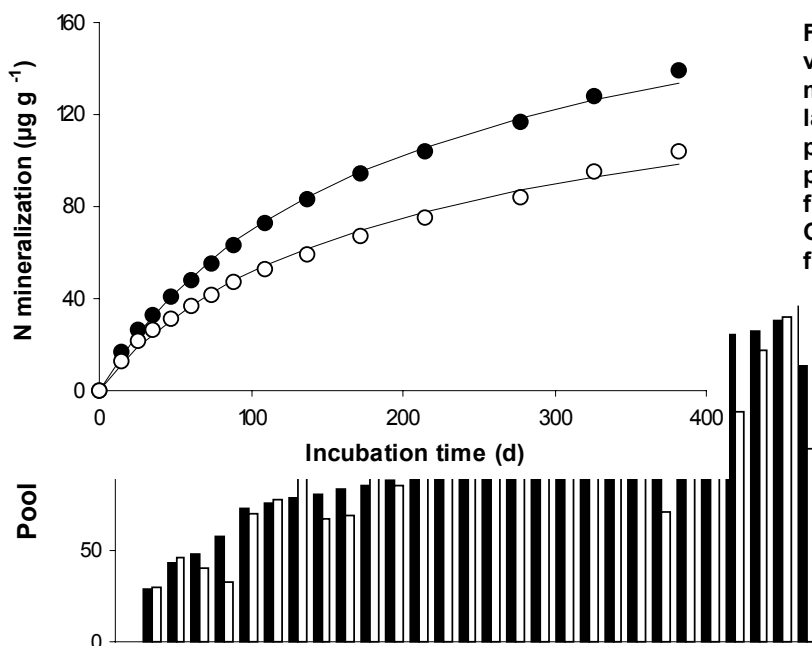


Figure 14. Time course of variation in cumulative N mineralization during laboratory incubation of pasture (closed symbols) and plantation (open symbols) soil from the Ayers site near Greenbushes. Fitted lines are from equation 1.

pasture paired sites determined by fitting equation 1 (sect. 3.1.2.2) to cumulative N mineralized in long-term laboratory incubations.

consistent pattern of difference between mineralizable soil N pool sizes in plantation and pasture soils (Figure 15). Likewise the rate constants of mineral N production from the two soil organic matter pools, and the half-lives of these pools, were similar for the two vegetation types (Table 9). Part of the variation in the magnitude of the mineralizable pool of N in soil organic matter was related to soil texture. Pool sizes increased with increasing amounts of fine fractions (silt plus clay) in soil for both plantation and pasture sites (Figure 16).

Table 9. Variation in soil mineralizable N pool sizes, with associated rate constants and half-lives, determined by fitting equation 1 to cumulative N mineralized in long-term laboratory incubations of soil from 28 paired pasture and plantation sites.

Soil N mineralization Characteristics	Pasture			Plantation		
	Mean	Min.	Max.	Mean	Min.	Max.
Labile pool ($\mu\text{g g}^{-1}$)	17.0	0.0	42.2	16.7	1.8	45.8
Resistant pool ($\mu\text{g g}^{-1}$)	89.1	19.0	182.2	83.7	22.1	161.8
Total pool ($\mu\text{g g}^{-1}$)	106.1	28.7	182.2	100.4	29.8	186.7
Labile rate (d^{-1})	0.0185			0.0165		
Resistant rate (d^{-1})	0.0034			0.0036		
Labile half life (d)	42			37		
Resistant half life (d)	193			204		

4.1.2.3 Phosphorus

Large amounts of phosphorus have been applied to most of the 18 sites in this study since they were cleared for agriculture (Figure 17). Total application exceeded $1000 \text{ kg P ha}^{-1}$ in one case where the difference in application between the pasture and the plantation pairs was also very large. As this was against a very high base, the large difference does not necessarily mean that plants growing on the plantation soil would be deficient in P.

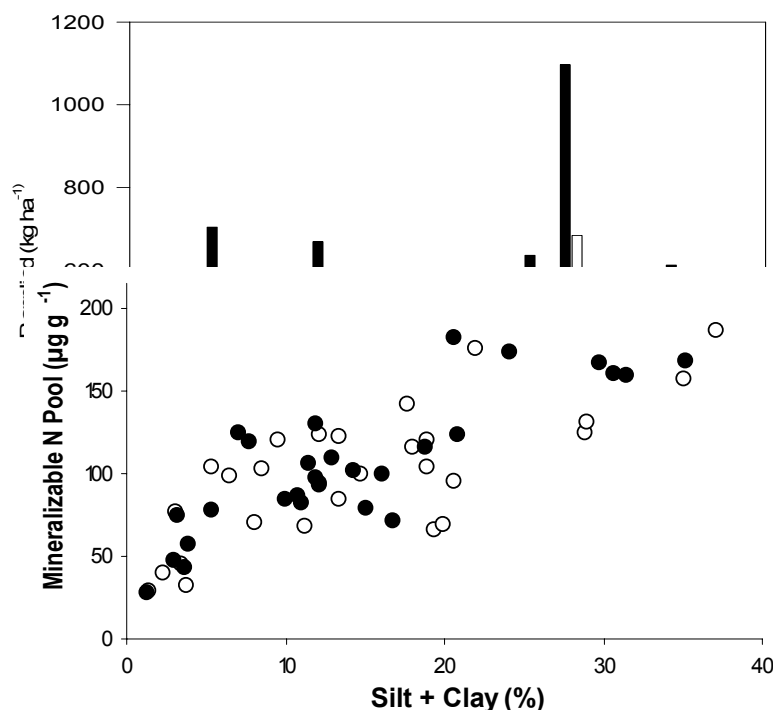


Figure 17. P applications from farmers records for 18 sites. Filled bar represents the pasture sites, open bars the plantations.

Figure 16. Variation in total mineralizable N pools across 28 plantation and pasture paired sites in relation to soil texture for pasture (closed symbols) and tree (open symbols) soils.

Extractions of different strength

Concentrations of total P were generally lower in plantation soils than in pasture soils, although there was considerable variation in differences among sites (Figure 18). There was also a large variation in total P across the 18 paired sites (range 0.004 – 0.07%). In terms of amounts of P in 0–10 cm soils, pasture soils had on average 45 kg ha⁻¹ more P than plantation soils. Accounting for the age difference between plantations, this was equivalent to an induced difference of 5.3 kg P ha⁻¹ year⁻¹. This compares with an estimated annual application of P on the pasture sites averaging 15 kg ha⁻¹.

One possible reason for the low recovery of added P is that leaching loss of P occurred on some soils. If this were so, losses can be expected to be greatest on the soils of lowest buffering for P. Hence on these soils we would expect the smallest difference between pasture and plantation sites. A measure of the leaching potential is given by the inverse of the P buffer capacity, that is, a measure of the proportion of added P remaining in solution. Plotting the difference in total P between pasture and plantation soils against this measure shows that three of the soils with a small difference in total P had a very low P buffering, suggesting leaching losses were likely (Figure 19). This possibility is supported by other data from the P equilibration study (see below). The three sites were siliceous sands where pastures had received about 76 kg P ha⁻¹ since the trees were planted. There was a large range in differences in total P for the remainder of the sites, although the reciprocal of the buffer capacity was much smaller and leaching losses unlikely (Figure 19).

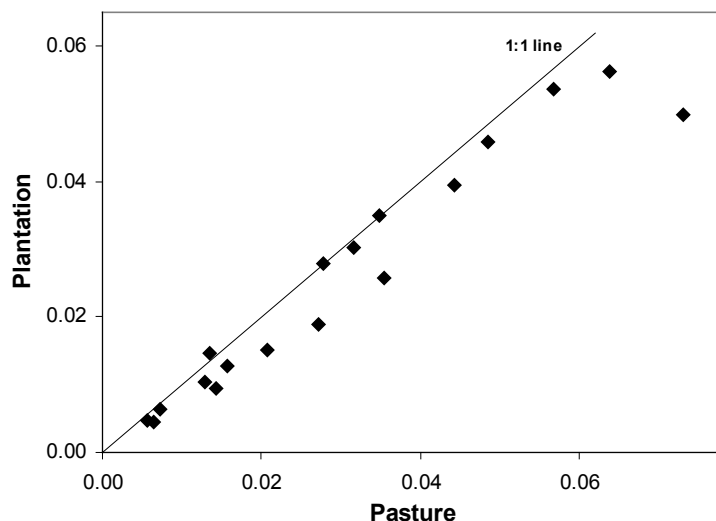


Figure 18. Relationship between total P (%) in pasture and plantation soils (0–10 cm) for 18 paired sites. The 1:1 line represents values where total P in pasture soils would be the same as in plantation soils.

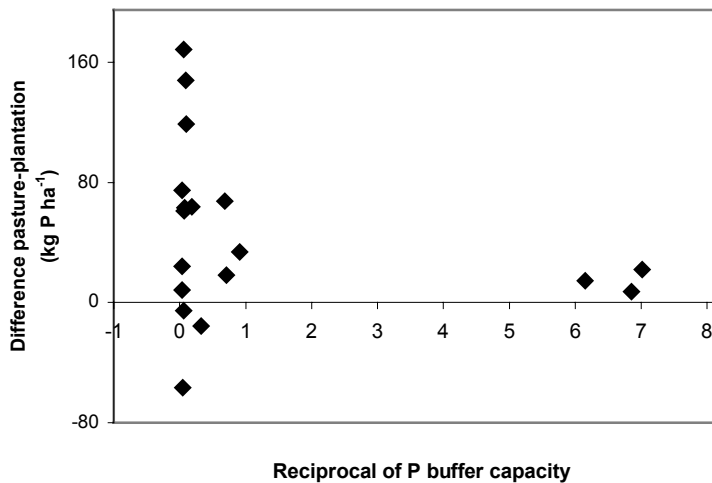


Figure 19. Difference between pasture and plantation soils (0-10 cm) in amounts of total P plotted against the reciprocal of a measure of P buffering capacity.

Concentrations of P extracted by common soil test reagents also showed considerable variation across sites (Figure 20). Concentrations were higher in pasture soils at most sites, a notable exception being the Moltoni site that also had the highest extractable-P values. Although absolute differences in concentrations between pasture and plantation were greatest for the strongest extracting solution, relative differences were not markedly different between the various reagents. Mean differences between pasture and plantation soils ($\mu\text{g g}^{-1}$) for the 18 paired sites were: Olsen 5.3, Colwell 13.0, and Bray 25.3. Concentrations were lower in plantation than in pasture soils by an average of about 40% for each of the extraction procedures.

Correlations among the various measures of extracted P, other soil properties and rainfall are shown in Table 10 for the pasture soils. Similar correlations among properties were observed for the plantation soils. The P extractions of different strength are well correlated with each other, the poorest relationship being between the mildest (Olsen) and strongest (total P) extractions. The P extraction measures are positively correlated with estimates of desorbable P and the P buffer capacity determined in the P equilibration study (see below). However, these relationships, and the positive correlations with annual rainfall, gravel, silt + clay content, total C and N and exchangeable K, are strongest with total and Bray-extractable P and decline with the milder extracting solutions (Table 10). For exchangeable Mg the correlations become increasingly negative as the strength of extracting solutions decreases.

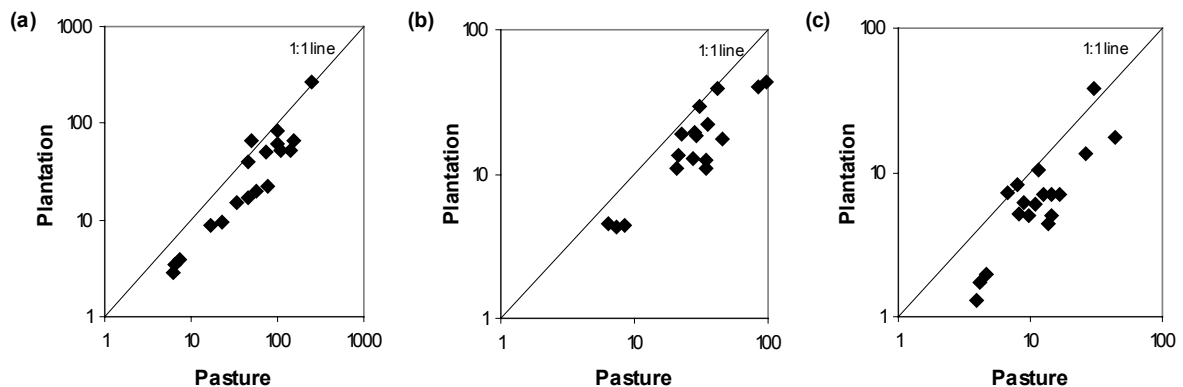


Figure 20. Relationships between concentrations ($\mu\text{g P g}^{-1}$ soil) of extractable P in pasture and plantation soils (0-10 cm) determined using (a) Bray, (b) Colwell, and (c) Olsen extraction procedures. Concentrations are plotted on the logarithmic scale and the 1:1 lines represent values where P in pasture soils would be the same as in plantation soils.

Table 10. Correlations between measures of soil P, other soil properties and rainfall for pasture soils at 18 sites

Soil property	Correlation coefficients							
Total P	1.00							
Bray-extractable P	0.85	1.00						
Colwell-extractable P	0.70	0.91	1.00					
Olsen-extractable P	0.47	0.76	0.95	1.00				
Desorbable P (q 24h)	0.88	0.73	0.71	0.55	1.00			
P buffer capacity	0.83	0.64	0.43	0.20	0.79	1.00		
P previously applied	0.41	0.52	0.55	0.49	0.48	0.25	1.00	
Rainfall	0.80	0.82	0.78	0.62	0.84	0.67	0.50	
Gravel % (>2 mm)	0.63	0.28	0.11	-0.11	0.59	0.67	-0.13	
Silt + clay %	0.82	0.57	0.31	0.08	0.70	0.94	0.14	
Bulk density	-0.47	-0.17	-0.08	0.04	-0.59	-0.67	0.07	
Total C	0.73	0.43	0.24	0.04	0.74	0.88	0.05	
Total N	0.80	0.48	0.33	0.13	0.81	0.88	0.14	
Exchangeable Ca	0.46	0.23	0.00	-0.18	0.47	0.55	0.11	
Exchangeable Mg	-0.06	-0.32	-0.45	-0.56	-0.05	0.30	-0.45	
Exchangeable K	0.78	0.61	0.42	0.18	0.71	0.71	0.12	
pH	-0.03	-0.02	-0.02	-0.01	0.17	0.13	0.21	
	Total P	Bray P	Colwell P	Olsen P	Desorb. P	Buffer cap.	Applied P	

Equilibration studies

P sorption curves fitted by equations 2 and 3 (3.1.2.3) to pasture and plantation soils at each of the 18 sites were used to estimate 'null point' concentrations (measure of P intensity), desorbable P and P buffer capacity. An example for pasture soils with 24-hour mixing time at the Jefferies-B site is illustrated in Figure 21a. The lower part of the graph is expanded in Figure 21b to show the 3 parameters measured.

In fitting both sorption functions (equations 2 & 3), the b_1 and the q parameters are correlated. That is, increasing one and decreasing the other can produce similar values for the residual sums of squares. In order to constrain the values for q (the desorbable P measure) and therefore obtain values that were more readily compared, the value of b_1 was fixed at 0.35. Other studies have shown this to be a common value for Western Australian soils (N.J. Barrow, unpublished data). If sorption is then plotted against $c^{0.35}$, the plots are linearised and this gives a visual indication of the extrapolation involved in estimating q . Plots of sorption functions for the Anning site are shown in Figure 22.

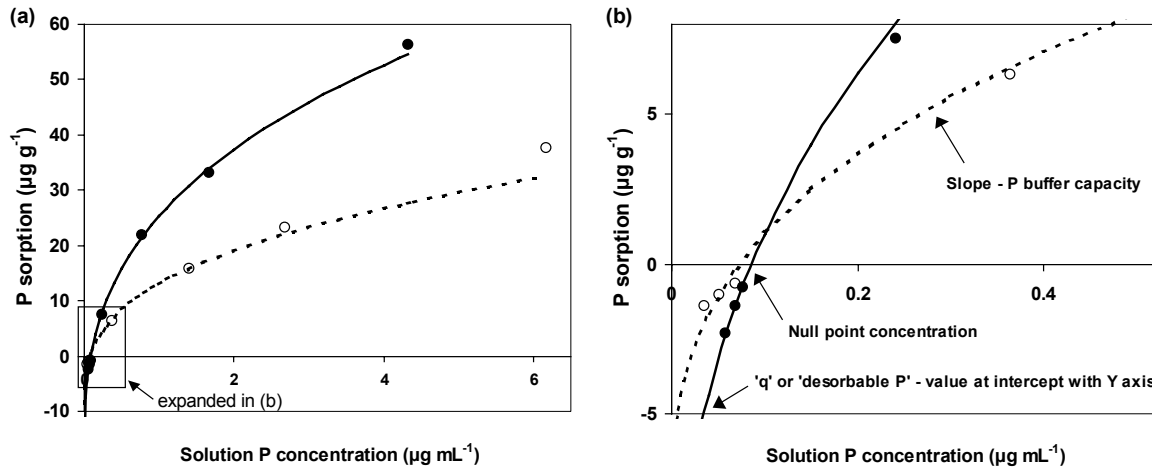


Figure 21. P sorption curves (equation 2, sect. 3.1.2.3) fitted to 24-hour equilibration values for pasture (closed symbols) and plantation (open symbols) soils from the Jefferies-B site. Fitted curves are shown for (a) the complete data, and (b) the expanded lower part of the graph with parameters indicated.

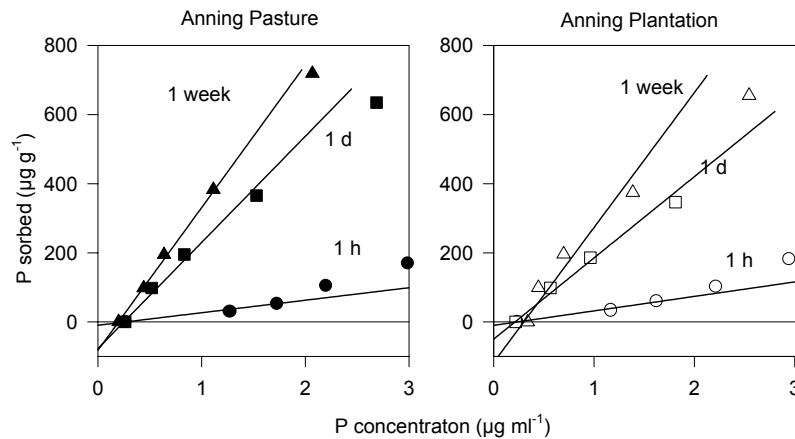


Figure 22. Plots of sorption curves for the pasture and the tree samples at Anning site. Values have been plotted against $c^{0.35}$ so that plots are linearised. Points indicate observations, lines indicate the fit of equation (3).

Values of a (slope of the lines: proportional to P buffer capacity) and q (desorbable P) were compared among sites and between the two land-use types. A small difference in a might be expected, with a tendency for the pasture sites to have a slightly lower value because repeated application of P slowly decreases a . However, over all the sites, a values, and therefore the measure of P buffer capacity, were little affected by land-use with the mean difference between the pasture and plantation pairs being very small.

It was expected that land-use change might have had a larger effect on values for q , because this measurement is likely to be sensitive to recent P history. Over all the sites, the difference between pasture and plantation soils was less distinct (Figure 23) than the differences in extractable P. For the heavier textured soils with higher desorbable P levels there was no consistent difference between the land-use types. However, on the sandy soils with lower P buffer capacities, concentrations of desorbable P were generally higher in pasture soils than in plantation soils (Figure 23).

The null point measure was also expected to be a sensitive measure of the P status of the soils. As the pasture sites had been fertilized more recently, it was thought that the null point values would be higher and that the decrease with time in the null point values would be more marked because the

soils would be further from equilibrium. The results showed that null points generally decreased with time of mixing, but that there was no consistent trend for the decrease to be more marked for the pasture soils. Overall, the mean difference in (log) null point values between the treatments was very small (Figure 24).

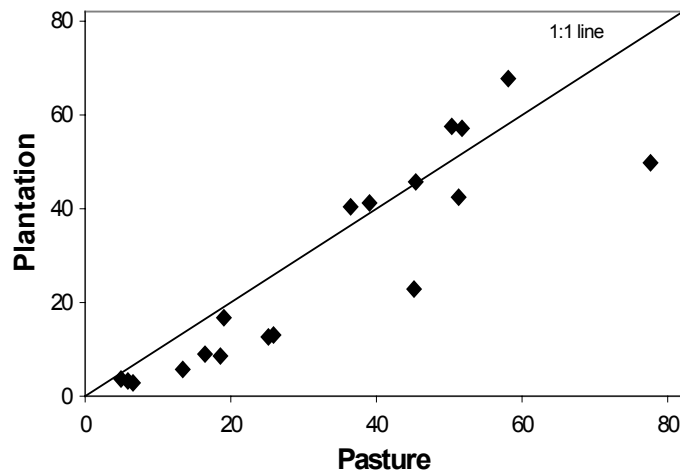


Figure 23. Relationship between concentrations of desorbable P (q_{24hr} as $\mu\text{g P g}^{-1}$ soil) in pasture and plantation soils (0-10 cm) at 18 paired sites. The 1:1 line represents values where P in pasture soils would be the same as in plantation soils.

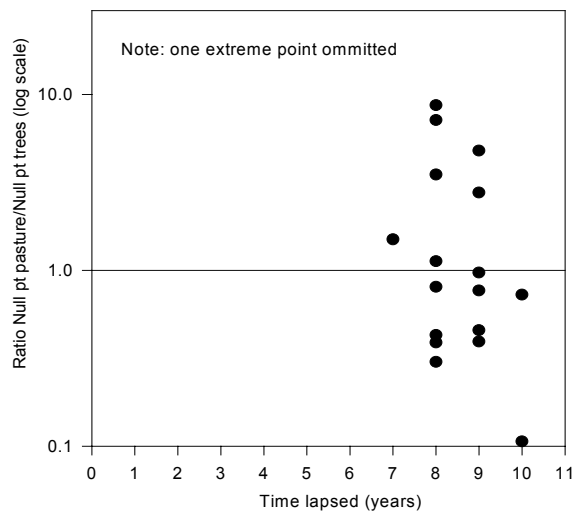


Figure 24. Ratio of the null point values for pasture and plantation soils plotted against the period lapsed between establishing the plantation and soil sampling. The average trend is close to zero. Because of the large range of values, a log scale has been used to represent the null points. The difference in log values is a ratio.

V large range of P sorption properties of these soils. For the soils with very low P buffering capacity the sorption curves were very flat and extrapolation was involved in the estimation of the null points, sometimes to unrealistic high values. Nevertheless, the figure illustrates the important principle that solution concentrations of P can be high in poorly buffered soils and hence they are prone to leaching loss.

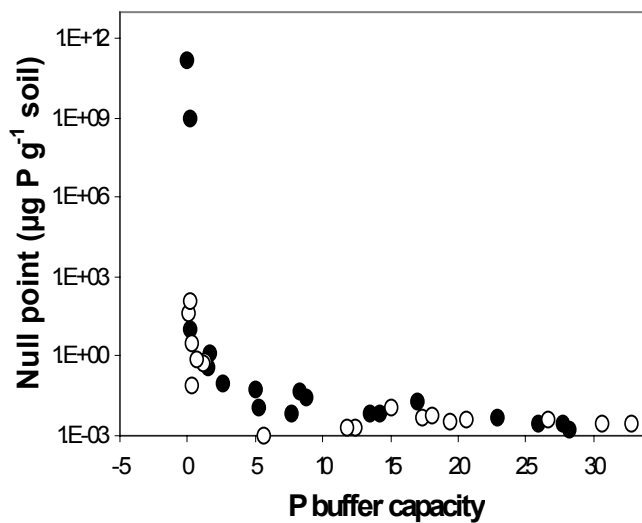


Figure 25. Plot of null point values against the buffering capacity of the soil as indicated by the Ozanne and Shaw value (the increase in sorption between concentrations of 0.25 and 0.35 $\mu\text{g P mL}^{-1}$ at 24 hr) for pasture (closed symbols) and plantation (open symbols) plots.

4.1.2.4 Relationships among soil and climate variables

Correlations among the broad range of surface soil chemical and physical properties and climate variables are shown for the surface (0-10 cm) pasture soils in Table 11. This incorporates data from the 31 paired sites for which the N studies were done. It therefore extends the information on some measures of C and P that were considered with smaller subsets of sites. The matrix illustrates the commonly observed high correlation between total organic C, total N and total P and also the correlation of a number of nutrient measures to soil physical characteristics. Correlations among properties in the plantation soils were similar, although on average marginally lower, than for the pasture soils.

Table 11. Correlation coefficients for climatic variables and surface (0-10 cm) soils properties for pastured land at 31 paired sites

Soil Climate Variable	Correlation Matrix- pasture soils (0-10 cm)														
Total C	1														
Micro. biomass	0.65	1													
Total N	0.98	0.71	1												
C: N ratio	-0.44	-0.52	-0.57	1											
Total P	0.81	0.54	0.85	-0.53	1										
Colwell extr. P	0.43	0.15	0.47	-0.34	0.69	1									
PH	0.26	0.20	0.24	0.09	0.17	0.06	1								
Exchang. Ca	0.62	0.47	0.58	-0.01	0.47	0.24	0.43	1							
Exchang. Mg	0.31	0.51	0.29	0.07	0.09	-0.19	0.16	0.56	1						
Exchang. K	0.66	0.61	0.66	-0.29	0.62	0.16	0.32	0.57	0.48	1					
Gravel % >2mm	0.72	0.54	0.67	-0.27	0.61	0.28	0.24	0.65	0.42	0.52	1				
Silt + Clay cont.	0.85	0.82	0.87	-0.52	0.80	0.31	0.24	0.55	0.41	0.80	0.67	1			
Bulk Density	-0.58	-0.76	-0.59	0.45	-0.40	-0.03	-0.09	-0.32	-0.54	-0.50	-0.43	-0.67	1		
Water hold. Cap.	0.61	0.89	0.67	-0.46	0.52	0.07	0.31	0.47	0.58	0.74	0.45	0.82	-0.81	1	
Ann. Rainfall	0.53	0.48	0.54	-0.35	0.54	0.28	0.37	0.28	0.20	0.66	0.20	0.64	-0.51	0.60	1
Summer Evap.	-0.53	-0.26	-0.53	0.29	-0.46	-0.34	-0.29	-0.25	-0.21	-0.44	-0.10	-0.44	0.52	-0.42	-0.80
	Tot C	Micr.B	TotN	C:N	TotP	ColP	pH	ExCa	ExMg	ExK	Gr>2	Si+Cl	BD	WHC	Rain

This data set was used in explaining variation among sites, and to evaluate differences in chemical properties between pasture and plantation soils. Mean, minimum and maximum values for, and proportional differences between, pasture and plantation soils are given in Table 12. Differences here are based on the combined means but are comparable to the average change calculated from proportional differences at each site. On average, pasture and plantation soils are comparable with regard to physical properties. There is also no difference in pH or in mean concentrations of total organic C, microbial biomass C and total N. However, soils under the plantations had substantially lower concentrations of total P (15%), Colwell-extractable P (37%) and exchangeable calcium (Ca; 28%) than pasture soils. In contrast, concentrations were higher in plantation soils for exchangeable magnesium (Mg; 29%) and exchangeable potassium (K; 21%) (Table 12).

Table 12. Mean, minimum and maximum values for surface (0-10 cm) soil properties in pasture and plantation areas at 31 paired sites. Relative differences are calculated from overall means.

Soil Property	Pasture			Plantation			Difference Past.-Plant. %
	Mean	Min.	Max.	Mean	Min.	Max.	
Organic C (%)	4.46	1.84	9.30	4.55	1.92	10.52	-2
Total N (%)	0.274	0.069	0.642	0.269	0.066	0.719	2
Total P (%)	0.0380	0.0056	0.1012	0.0327	0.0045	0.0967	15
C:N ratio	17.1	13.6	29.7	18.2	13.5	30.3	-6
Microbial Biomass C ($\mu\text{g g}^{-1}$)	311	101	630	307	93	595	1
Colwell P ($\mu\text{g g}^{-1}$)	42.3	8.2	113.0	29.1	6.6	106.2	37
Exchangeable Ca (cmol kg^{-1})	1.46	0.57	2.49	1.10	0.20	2.89	28
Exchangeable Mg (cmol kg^{-1})	0.27	0.14	0.52	0.35	0.15	0.72	-29
Exchangeable K (cmol kg^{-1})	0.16	0.05	0.40	0.19	0.07	0.46	-21
pH	4.88	4.37	5.44	4.95	4.41	5.46	-1
Silt +clay (% of <2 mm)	15.3	1.3	37.0	15.9	1.4	41.0	-4
Gravel % (>2mm fraction)	22.4	0.5	74.4	21.0	0.4	72.7	6
Bulk Density	1.07	0.72	1.35	1.04	0.65	1.29	3

Differences between pasture and plantation soils were explored using multiple linear regression analysis. A large proportion (80%) of the variation in total organic C across sites was accounted for by a model incorporating silt+clay content, amount of soil (gravel) and climate (Figure 26). There was no difference between pasture and plantation soils.

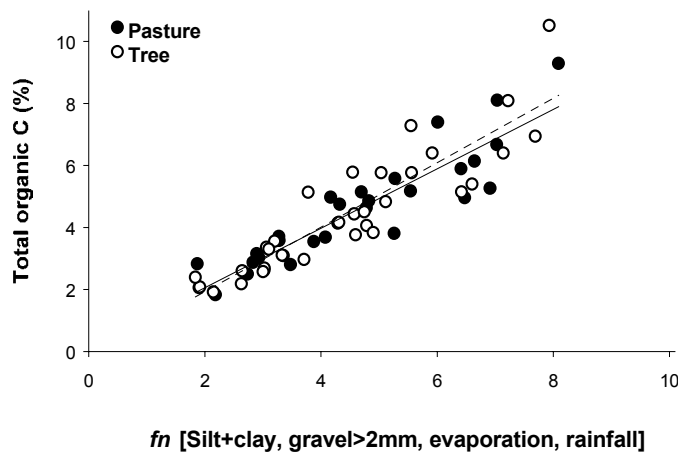


Figure 26. Total organic C in 0-10 cm soil in relation to a function incorporating texture, gravel and climate variables.

Microbial biomass C (measured in winter-spring when soils were near to field capacity moisture) was related to texture and the moisture content at sampling (64% accounted for). However, it was most strongly related in a model incorporating the measures of potentially mineralizable N, which explained 79% of the variance (Figure 27). The separation between pasture and plantation soils is related to the difference in potential N between land-use types (see 4.1.2.2).

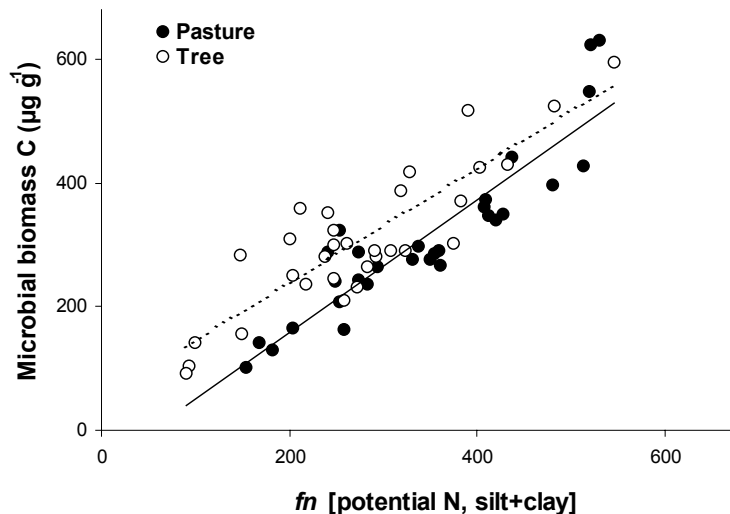


Figure 27. Microbial biomass C in 0-10 cm soil in relation to a function using texture, gravel and climate variables.

There was a large range (20-fold) in concentrations of total P in 0-10 cm soils across the sites (Table 12). Much of the variation (68%) could be related to silt and clay content, although inclusion of total organic C improved the model fit (73%). This model distinguished the two groups of soil (pasture and plantation) (Figure 28a). Pasture soils had significantly ($P < 0.05$) higher concentrations of total P than plantation soils, the difference being similar in absolute terms across the range of sites. A model incorporating the estimates of total P applied to pasture and plantation soils further improved the fit (81%) and extinguished the difference between pasture and plantation soils (Figure 28b). The amount of P in surface soil (<2 mm fraction) was calculated from P concentrations and the weight of soil per unit area and further regression models fitted. A model that included silt and clay, percent gravel and past P application accounted for 66% of the variance.

None of the regression models tested could explain a high proportion of the variation in Colwell-

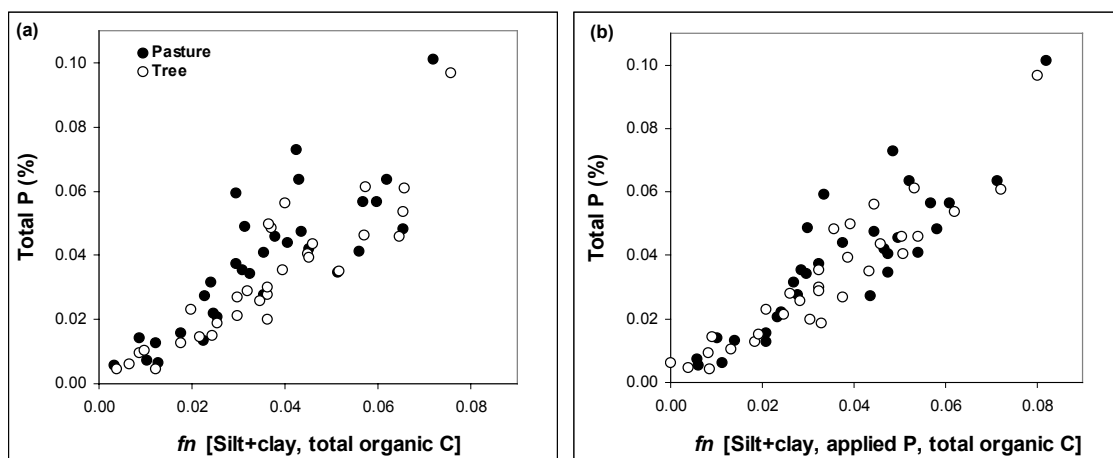


Figure 28. Relationships between (a) total soil P and a function of texture and organic C, and (b) total P and a function of texture, organic C and total previous application of P

extractable P. One significant function (29% accounted) used terms for texture and water-holding

capacity and the effect of land-use change was significant ($P < 0.05$). Again inclusion of a term accounting for the difference in past fertilizer application extinguished this difference between pasture and plantation soils.

Models fitted to concentrations of exchangeable cations explained less of the variation than those for C and P. Neither Ca nor Mg was strongly related to other soil properties. Nevertheless, there was a significant difference ($P < 0.01$) in concentrations of exchangeable Ca between pasture and plantation soils. For Mg, a significant linear regression model incorporating organic C accounted for just 26% of the variation, but showed plantation soils had significantly ($P < 0.01$) higher Mg concentrations than pasture soils. Inclusion of the amount of P applied improved the relationship (33%). Exchangeable K was most strongly related to percentage silt and clay (52% accounted for) with concentrations being higher ($P < 0.05$) in plantation than pasture soils but mostly on the heavier textured soils (Figure 29).

4.1.3 Seasonal variation in N and C measures

N mineralization.

N mineralization, estimated by sequential soil coring over a complete season showed a marked seasonal variation (Figure 30). At each of the experimental sites, rate of soil N mineralization was related to seasonal variation in soil environmental parameters, especially soil moisture. Highest rates of mineralization occurred in winter and spring when soils were moist and lowest rates in summer when little rain falls in this region and surface soils are dry.

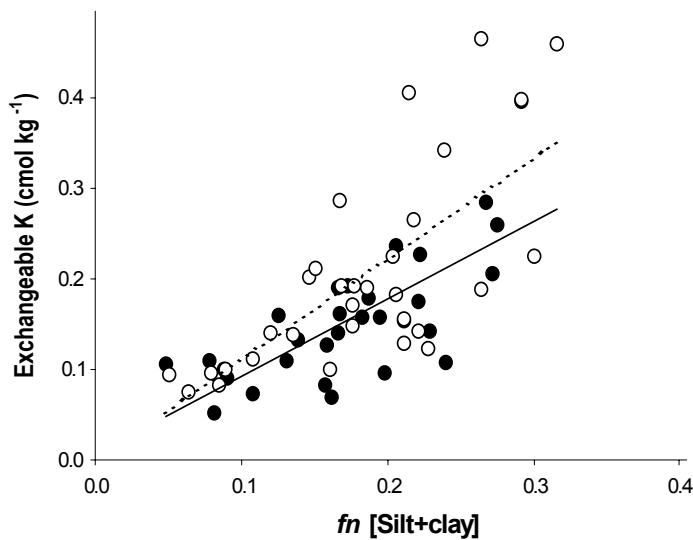


Figure 29. Relationship between concentrations of exchangeable K and a function of a measure of soil texture in 0-10 cm soil for pasture (closed symbols) and plantation (open symbols) plots.

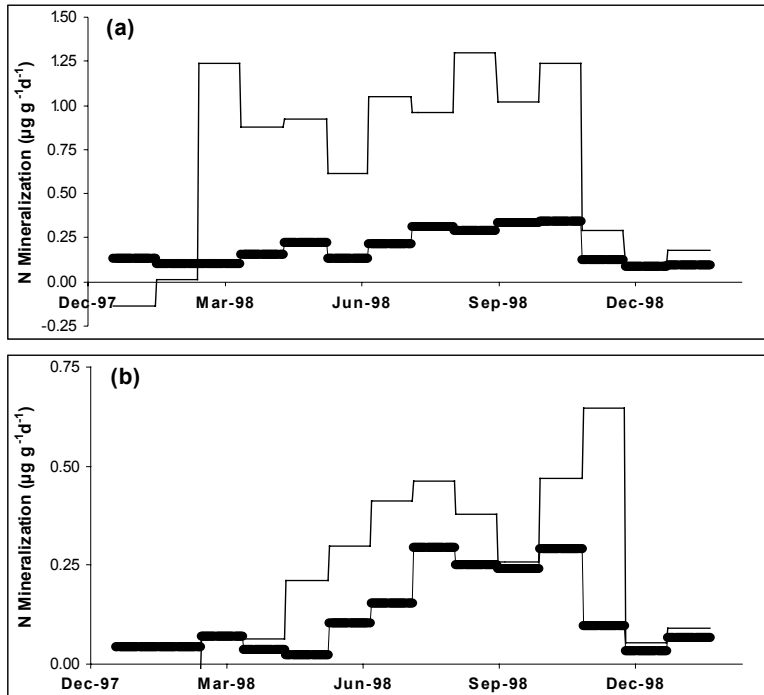


Figure 30. Seasonal variation in N mineralization in soil under pasture (fine line) and trees (bold line) at (a) the Moltoni and (b) the Gibbs sites.

Monthly net N mineralization rates, expressed per unit of potentially available N (Figure 31), increased with increasing soil moisture content at both experimental sites. At the Gibbs site, which has soil with a sandy texture and lower water-holding capacity than soil at the Moltoni site, N mineralization declined at very high moisture contents (>25%) under pasture. Under these saturated conditions, N mineralization is probably inhibited and N losses through denitrification may have occurred.

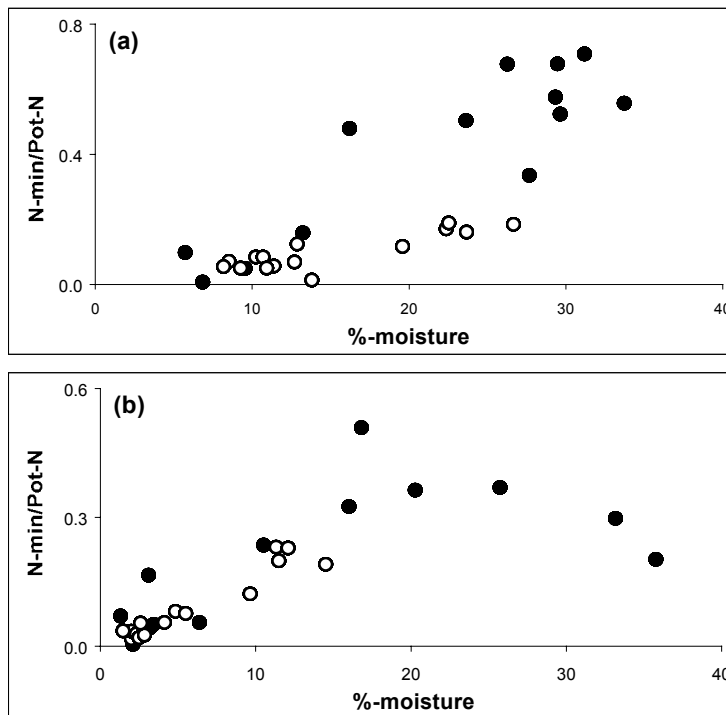


Figure 31. Normalized monthly net N mineralization ($\mu\text{g N g}^{-1}$ soil 28 d^{-1}) per unit ($\mu\text{g N g}^{-1}$ soil) of potentially available N in relation to soil moisture content at (a) the Moltoni and (b) the Gibbs sites for pasture (closed symbols) and plantation (open symbols) plots.

Microbial biomass

Microbial biomass determined in the surface 10 cm of soil on four occasions through the year at the two sites showed a strong seasonal pattern with maximum values in winter and spring. At the Moltoni site, measurements taken a year apart in winter gave comparable values.

4.1.4 Plant bioassay

Responses to nutrient treatments were apparent from about 2 months after planting, when differences in stem volume measurements had become established. At the Gibbs sandy site, dry weight of plant tops was significantly higher in pasture soil than in plantation soil after 4 months of growth (Figure 32a). There was a significant interaction between effects of N and P application on growth, but no difference (interactions ns) between pasture and plantation soil in the response to applied nutrients. This was despite the difference in measures of extractable P and N mineralization at this site (see 4.1.2, 4.1.3). Application of P without N depressed growth, possibly due to stimulation of microbial activity and immobilization of soil N.

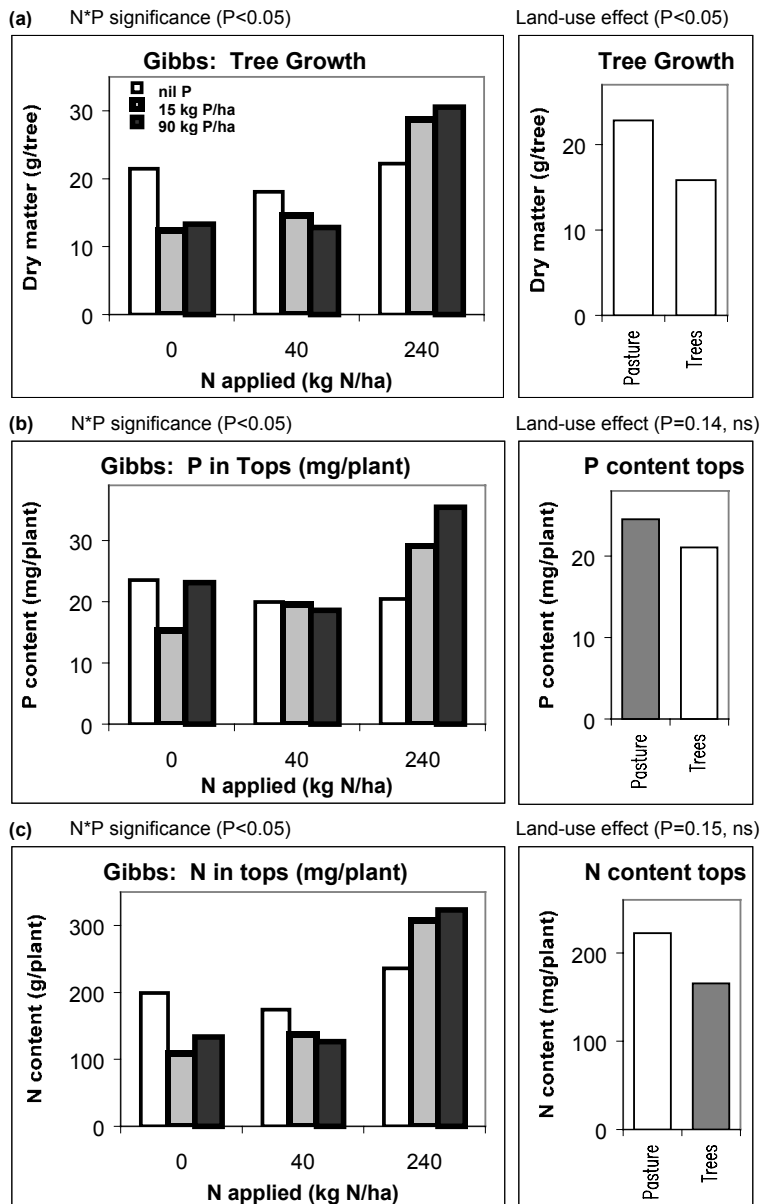


Figure 32. Effects of N and P application, and of land-use type (pasture and plantation) on dry matter and N and P content of 4-month old *E. globulus* seedlings at the Gibbs (sand) site.

Similar treatment effects were observed for N and P uptake into tops, except that pasture-plantation differences were not significant (Figure 32b,c). The magnitudes of treatment effects on uptake, particularly of P, were also different to dry matter production. Average P uptake was affected more by P application, and less by N application, than dry matter production. This was due to P application increasing, and N application decreasing, P concentrations in plant tops: changes in concentrations were greater in stems than in leaves (Figure 33). P concentrations in plants growing in pasture soils were not significantly different to those in plants from plantation soils.

In the loam soil at Moltoni's site, application of N increased growth, N concentrations in leaves and the N content of plant tops (Figure 34). However, there was no significant effect of P application or any difference between plants growing in cores from pasture or plantation areas. This lack of response to P treatment and to land-use type is consistent with the findings from the soil measurements. There were high concentrations of total and extractable P, and little difference between pasture and plantation areas, although the initial survey had suggested some differences in soil P at this site. The response to N application is surprising considering the high N mineralization rates in pasture soil recorded at this site (see 4.1.3), and indicates the high requirement of *E. globulus* at this early stage of growth.

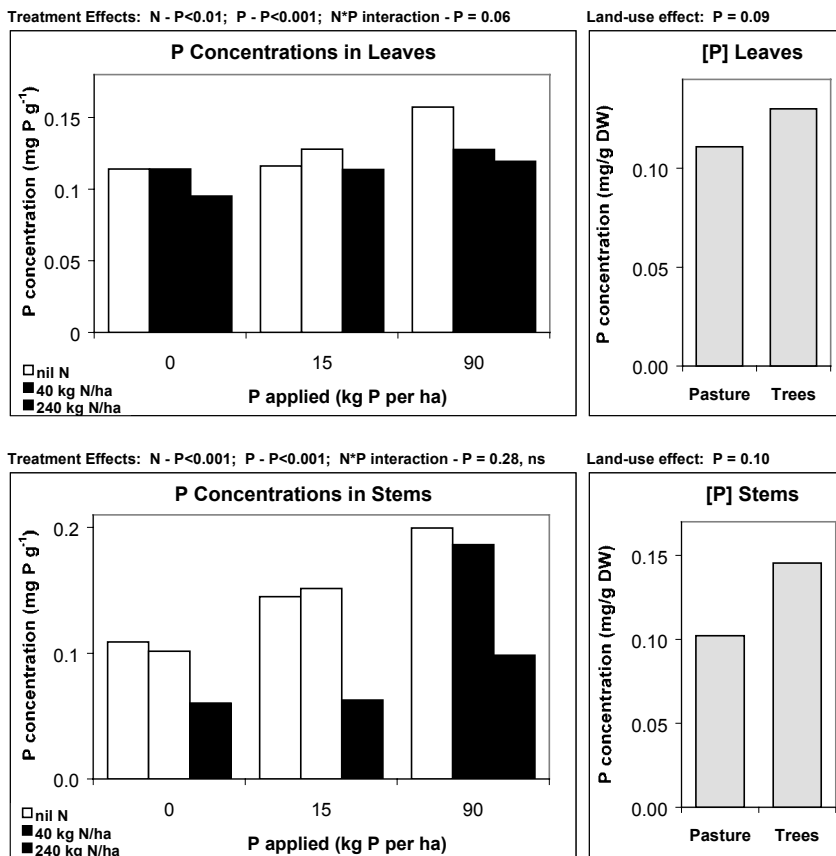


Figure 33. Effects of N and P application, and soil from different land-use areas (pasture and plantation) on P concentrations in leaves and stems of 4-month old *E. globulus* seedlings at the Gibbs (sand) site.

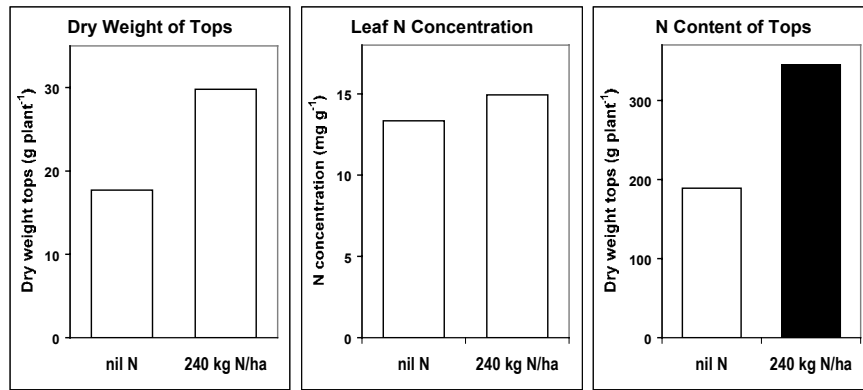


Figure 34. Effects of N application on top dry weight, foliar N concentrations and N uptake by seedlings growing on loam soil at Moltoni's site. Values are means for P treatment and land-use type.

4.1.5 Plantation productivity and nutrient uptake

Tree growth

Productivity of *E. globulus* across the 31 paired sites ranged from 4.3 to 51 m³ ha⁻¹ yr⁻¹ (mean annual increment [MAI] in stem conical volume over bark). Growth was strongly related to the long-term average rainfall (Figure 35) with 86% of the variance being accounted for by this function. Addition of summer evaporation or the various surface soil properties did not improve the relationship. However, when rainfall is omitted, productivity is related to total soil P ($r^2 = 0.51$). A significant amount of the variation (58%) could be explained in a regression model incorporating total soil P and textural properties (silt+clay, % gravel).

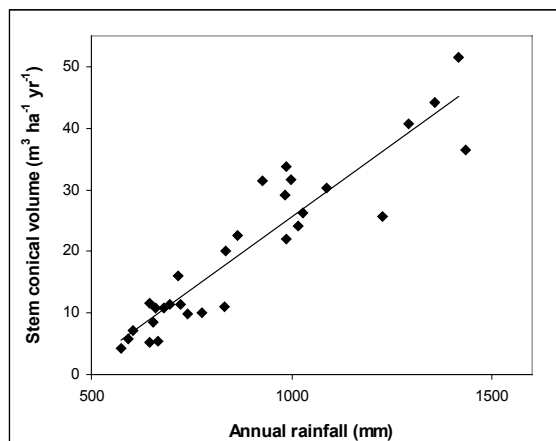


Figure 35. Annual increase in stem volume in relation to long-term average rainfall for the 31 paired sites. Stands were aged between 8 and 12 years.

Stem volume at the two sites where N mineralisation rates were measured seasonally, and field bioassay studies were conducted, varied greatly in productivity. MAI's were 11.4 m³ ha⁻¹ yr⁻¹ for the 10-year-old stand at Gibbs (sand), and 44.1 m³ ha⁻¹ yr⁻¹ for the 11-year-old stand at Moltoni (loam).

Nutrient composition of bark

Concentrations of total N, P, Ca, Mg and K in bark varied markedly between sites. Nevertheless this variation was not generally related to measures of bark weight per unit area (used to indicate thickness or density), which varied by a factor of 2.4 across sites. Concentrations of N, Ca and K were positively correlated with tree size (as measured by MAI's), while Mg concentrations decreased with increasing tree size. Bark P concentrations were not correlated with tree size, but tended to decrease with increasing concentrations of total soil P. In general, variations in concentration of nutrients other than P were not well related to any of the soil properties.

The range in amounts of N, Ca and K in stem-bark across sites was greater relatively than the range in stem volume (Table 13), due to the increase in concentrations of these nutrients with tree size.

Annual rainfall accounted for a high proportion of the variation in bark content of each nutrient, as it did for stem volume. For the five nutrients measured, between 74% and 85% of the variance could be accounted for by regression models that used annual rainfall and one or two site or soil parameters. Relationships for bark N and Ca are shown in Figure 36. Bark contains about one-third of the total Ca in aboveground tree components, but a smaller proportion of N and P (Table 13). Amounts of N and P in bark represent a small proportion of the total stores in soil. However, bark contains significant amounts of Ca, Mg and K in relation to the amount of exchangeable forms in the surface soil (Table 13). Nutrient content of the surface 10 cm of soil generally accounts for a major proportion of the total in the soil profile to 1 m (cf. Table 6)

Table 13. Summary of stand volume, and nutrient content of bark and surface soils (0-10 cm, < 2 mm), at the 31 paired sites.

	Mean	Min	Max	% of total A/G *
<u>Stand age & productivity</u>				
Stand age (years)	9.8	8	12	
Stem volume ($\text{m}^3 \text{ha}^{-1}$)	204	39	515	
<u>Nutrients in stem bark (kg ha^{-1})</u>				
N	22.1	2.9	63.3	9
P	3.7	0.7	11.2	10
Ca	186	23	488	35
Mg	26.7	5.2	75.7	
K	33.3	5.2	129.7	
<u>Nutrients in 0-10 cm soil (kg ha^{-1})</u>				
Total N	1911	691	3977	
Total P	226	54	548	
Extractable P (Colwell)	22	7	103	
Exchangeable Ca	337	81	869	
Exchangeable Mg	66	27	146	
Exchangeable K	59	31	149	

* Based on data from O'Connell and Grove (1999)

4.2 Inter-rotation Harvest Residue Experiments

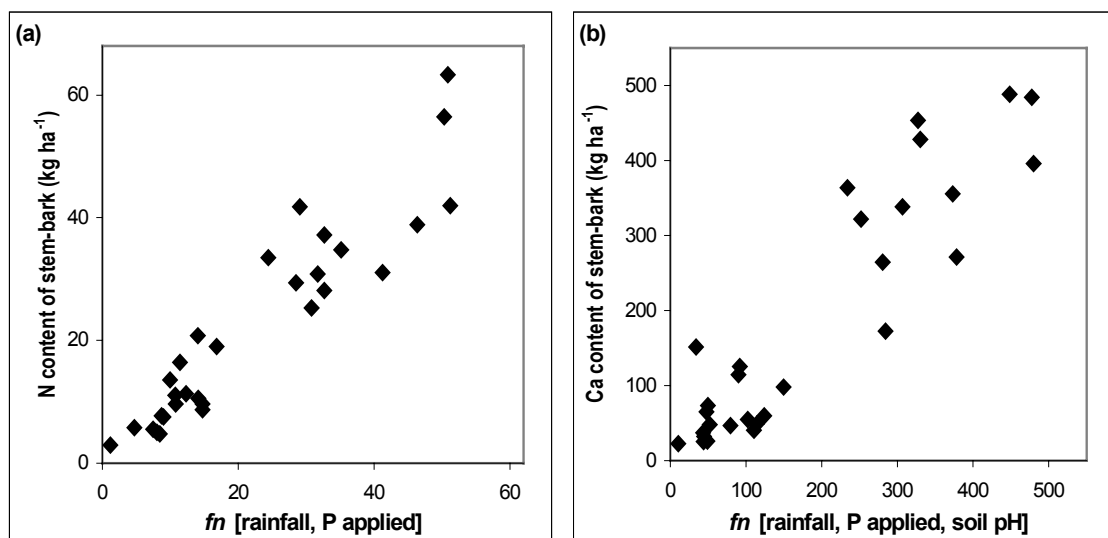


Figure 36. Bark content of (a) N in relation to a function of annual rainfall and total P previously applied in fertiliser, and (b) Ca in relation to a function of annual rainfall, total P previously applied, and pH of surface soil under plantations.

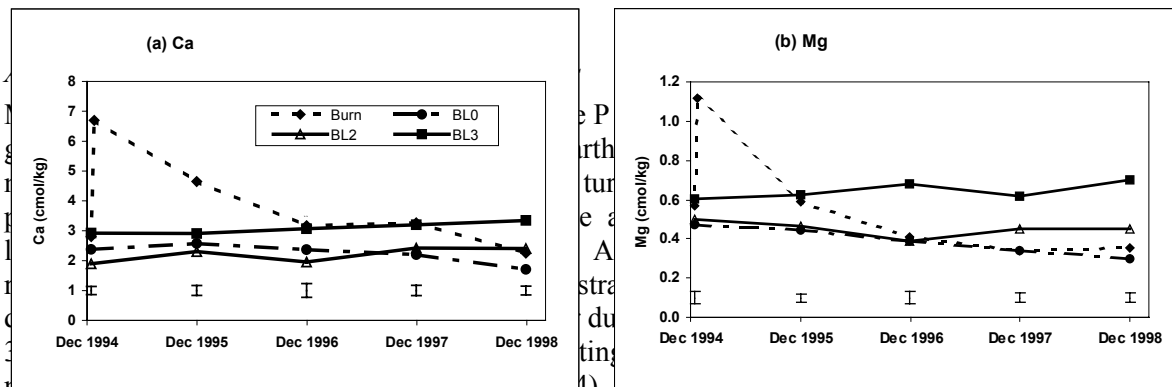


Figure 37. Variation in (a) Ca and (b) Mg concentration in surface (0-5 cm) soil at the red earth site in relation to harvest residue management treatments and time since harvest.

	Dry weight (t ha ⁻¹)	N (kg ha ⁻¹)	P (kg ha ⁻¹)	Ca (kg ha ⁻¹)	Mg (kg ha ⁻¹)	K (kg ha ⁻¹)
Red earth						
Leaves	21.5	259	15	315	30	96
*Wood, bark & miscellaneous	29.6	88	8	282	29	86
Total	51.1	347	23	597	59	182
Grey sand						
Leaves	13.0	138	9	188	18	56
Wood, bark & miscellaneous	18.3	81	7	200	18	55
Total	31.3	219	16	388	36	111

* Wood residues < 3cm diameter. At the red earth a further 30 t ha⁻¹ of larger wood residues (> 3 cm diameter) was present on the soil surface following harvesting.

Impact of harvest residue management on soil stores of nutrients

Changes in soil chemical properties have been monitored annually since December 1994 (red earth site) and June 1995 (grey sand site), with the most recent results available for December 1998 at both sites. Changes in soil nutrient status appear to result from three processes, namely (i) immediate effects of fire in the burn treatment, (ii) longer term impacts due to addition of harvest residues to the soil surface, and (iii) longer term changes in soil which appear to be largely independent of applied treatments.

Burning harvest residues significantly increased soil pH, cation concentrations and labile P (grey sand site only) in surface (0-5 cm) soil due to the addition of ash. There was little impact of fire on lower soil horizons. Many of the observed changes were large with increases of up to more than 1 unit in pH, more than 100% in some cation concentrations (Figure 37, 38), and greater proportional change in labile P. However, all these effects were relatively short lived, with soil properties returning to near pre-burn levels within one to two years after treatment.

The main long-term impacts on soil nutrient status of harvest residue management relate largely to

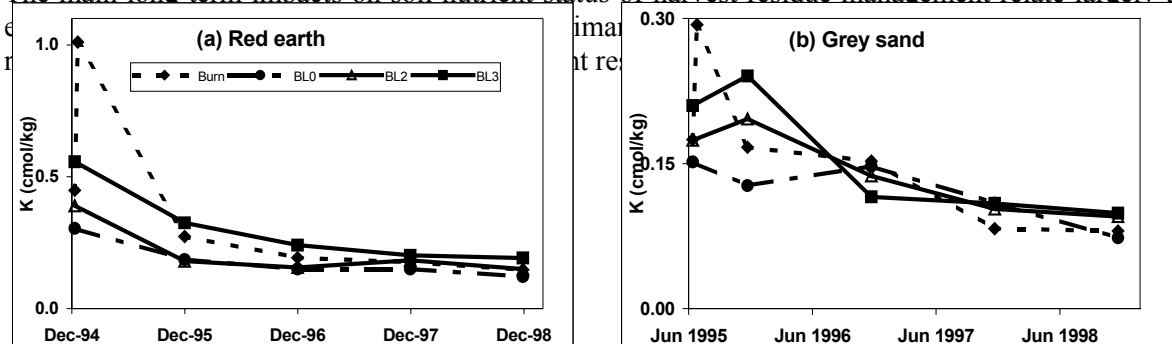


Figure 38. Variation in exchangeable K at (a) the red earth and (b) the grey sand site in surface soil (0-5 cm) in relation to harvest residue treatments and time since harvest.

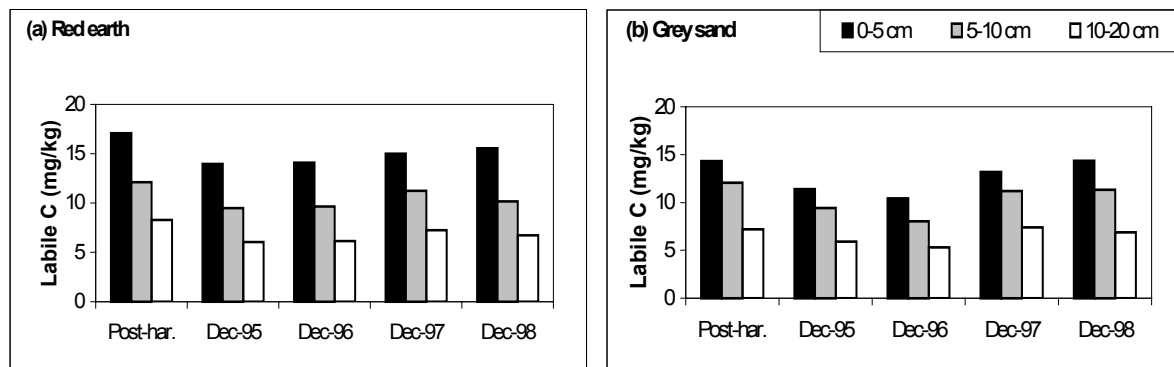


Figure 39. Variation in concentrations of labile soil C with time since stand harvest (July 1994 at the red earth site and April 1995 at the grey sand site).

concentrations of exchangeable Ca and Mg (Figure 37) and at the red earth site significantly increased exchangeable K (Figure 38). Again, these effects were largely confined to the upper 5 cm of the soil profile. Despite the large amounts of residues added, there appears to have been limited impact on soil C status. At the grey sand site there was no significant effect of harvest residue management on soil organic C concentrations for any of the treatments at any soil depth. In surface soil (0-5 cm) at the red earth site there were significant treatment effects ($P < 0.05$) on soil organic C levels during the last two of the five sampling periods (3.5 and 4.5 years after stand harvest). At these times the BL₃ treatment, which had received about 160 t ha⁻¹ added residues, contained organic C levels in 0-5 cm soil which were 20-25% greater than in the other three treatments. There were no significant treatment effects at other depths.

Changes in soil chemical status that appear to be related to time since stand harvest, rather than to the treatments applied were evident for several elements. In particular soil exchangeable K concentrations declined in all treatments during successive sampling periods (Figure 38) at both sites. The decrease in K concentrations was greatest in surface soil (2.1 to 2.8 fold), intermediate in 5-10 cm soil (1.8 to 2.1 fold) and least in 10-20 cm soil (1.2 to 1.6 fold) over the period of the experiment. Likewise, labile C concentrations were not affected by harvest residue treatments but they did vary significantly with time since stand harvest at both sites (Figure 39). In the first one to two years after harvest, labile C concentrations decreased and in subsequent years gradually increased again to approach levels similar to those in immediate post-harvest soil samples.

There was evidence of change in some forms of P with time since stand harvest. Total P in the surface (0-5 cm) soil at the red earth site was 6-fold higher than at the grey sand site. Concentrations of the forms of P measured [CaCl₂-extractable P, labile or moderately labile forms of inorganic (Pi) and organic (Po), and P extracted by bicarbonate (Bic) or hydroxide (NaOH) solutions] did not differ significantly among slash treatments at the red earth site. However, at the grey sand site, concentrations of bicarbonate-extractable forms in soil were higher in double slash than in the zero slash treatments. Concentrations of Pi forms were generally higher, and Po lower, at the grey sand site than at the red earth site (Figure 40). CaCl₂-extractable P at the grey sand site and NaOH-Po at both sites decreased significantly with time after harvest.

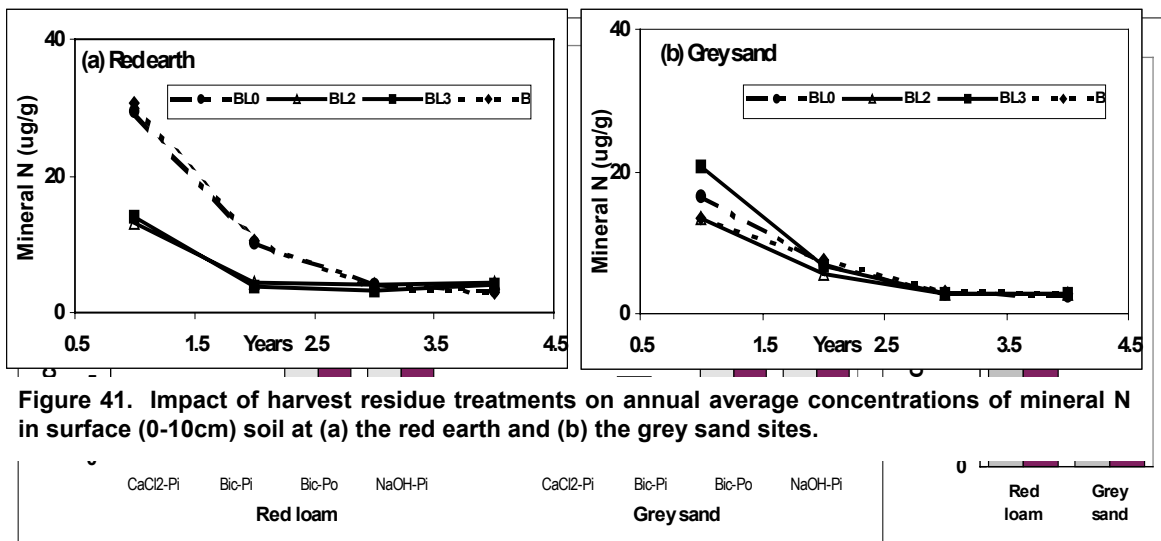


Figure 40. Temporal variation in labile soil phosphorus fractions (mean over all slash management treatments). (a) Pi and Bic-Po forms (b) NaOH-Po form

Impact of slash treatments on mineral nitrogen flux rates

Harvest residue management had a significant impact on the dynamics of soil mineral N. High concentrations of mineral N were present in soil immediately following harvest (Figure 41). These pools declined in subsequent years, probably largely through leaching of nitrate below the root zone. At the more highly textured red earth site, mineral N pools were significantly higher where residues had been removed (BL₀ and B treatments). At the sandy site the opposite was the case – highest mineral N concentrations in soil after harvest were associated with the highest level of residue retention (BL₃ treatment).

Both the measured rates (Figure 42) and potential (Figure 43) for N mineralization in surface soil (0–10 cm) were significantly affected by harvest residue treatments. At both sites cumulative annual rates of N mineralization were significantly higher on high residue (BL₃) treatments compared to low residue treatments in the third and fourth years of measurement. At the red earth site treatment BL₂ followed similar trends. For these treatments the cumulative annual rates of N mineralization also appear to be increasing over time. Annual rates of mineralization per unit weight of soil were generally higher in the more highly textured and fertile red earth soil than in the grey sand.

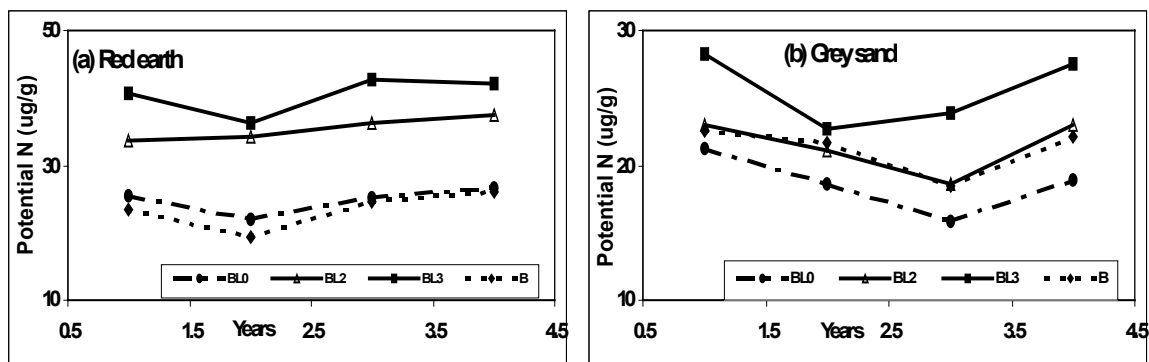


Figure 43. Impact of harvest residue treatments on mean annual potential rates of N mineralization in surface (0–10cm) soil at (a) the red earth and (b) the grey sand sites. Potential for N mineralization is estimated as the ammonium produced after anaerobic incubation at 40°C for 7 days.

Annual average rates of potential for N mineralization in soil (anaerobic incubation) showed similar treatment effects to the measured rates of mineralization. High residue treatments resulted in significantly higher concentrations of potentially mineralizable N at both sites during each measurement period. As with mineralization rates, potential for N mineralization was systematically higher in the red earth soil compared to the grey sand.

Impact of harvest residue management on tree growth

Responses in tree growth to harvest residue treatments were limited at the two experimental sites (Figure 44). At the red earth site, growth rates during the first year after planting were significantly greater ($P < 0.05$) on the highest residue plots (BL_3) compared with other treatments. However in subsequent years growth on treatments BL_0 and BL_2 increased relative to BL_3 (Figure 45a) and the significance of growth differences between residue treatments declined. In years 2, 3 and 4 after planting there were no significant differences in growth amongst the applied treatments.

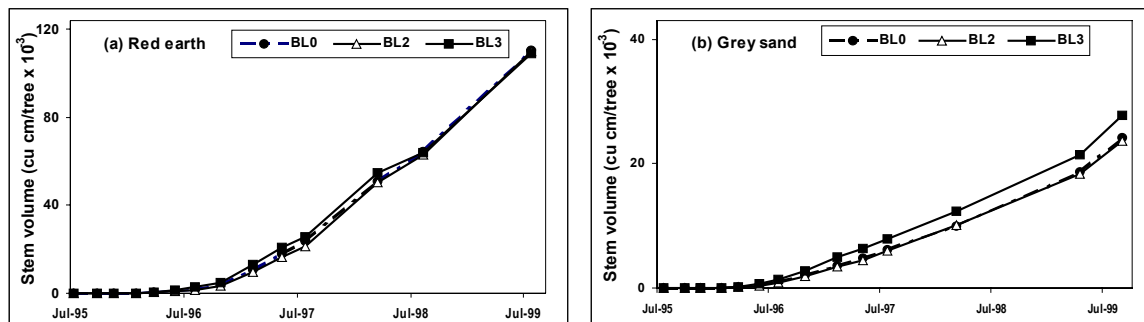


Figure 44. Impact of harvest residue treatments on mean tree conical volume at (a) the red earth and (b) the grey sand sites.

At the grey sand site there was a significant difference in tree growth between residue treatments during the first year after planting with highest growth where residues had been removed. This trend was reversed by the end of the first year (Figure 45b) with greater relative growth rates for treatments with highest amounts of retained harvest residues. However, although growth on the high residue treatment BL_3 was greater than on other treatments during the last three years of measurement, these differences were generally not statistically significant.

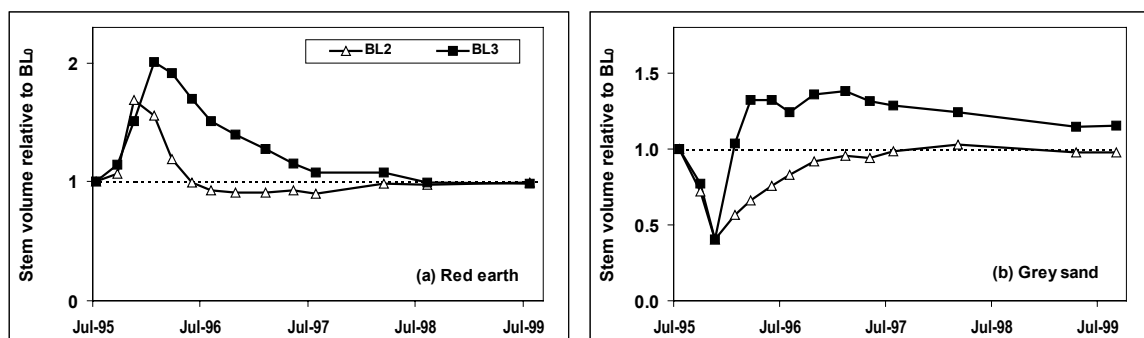


Figure 45. Growth on BL_2 and BL_3 treatments relative to BL_0 over the 4-year measurement period since planting at (a) the red earth and (b) the grey sand sites.

Leaf area index differed markedly between sites, reflecting differences in soil nutrient status, water availability and tree growth rates. At each site leaf area increased rapidly in the second year of growth, reaching a plateau between 3.5 to 3.7 at the red earth site and 1.2 to 1.4 at the grey sand site. Over most of the growth period there was no significant systematic difference in LAI between the applied harvest residue treatments.

5. Discussion

The paired-site approach has been extensively used to study effects on soil properties of changes to land-use (Conteh and Blair, 1998; Whitebread *et al.*, 1998)). In sampling paired sites, replicate measurements in each of the paired areas represents internal replication, which presents a problem in statistically testing land-use effects for individual sites. The strengths in our approach have been to take adequate steps to ensure reasonable matching of land-use types, together with the sampling of a large number of sites. Measurements of soil physical properties, which will not be affected by land-use change, give us confidence that there is no systematic difference in intrinsic properties between pasture and plantation soils (Table 12). Our study primarily focused on the 0-10 cm soil depth. Analysis of soil profiles sampled to 1 m showed that a high proportion of total nutrient stores are in this surface layer (Table 6).

The paired site approach has most commonly been used to examine effects of changes from natural vegetation to agricultural systems, with the period following change often being several decades. Where soils are inherently infertile, measurement of changes to soil nutrient properties with conversion of land from natural vegetation to agricultural has the advantage of low initial base levels. In our study, significant changes to properties related to land-use were measured against a relatively high initial fertility level (regularly fertilized legume pastures) and in a short time frame (6 - 11 years).

Impact of land-use change on surface soil properties

(i) Carbon

There was no difference in total organic C between pasture and plantation soils measured across the 31 paired sites (Figure 26), or between the 3 land-use types (pasture-plantation-native vegetation) at 10 sites (Figure 6). A high proportion of the variation in organic C across sites could be explained by a function that included terms for texture, gravel content and rainfall, factors which can be expected to strongly influence the productivity of the original vegetation and pasture. Other studies with fewer sites have shown variable effects of afforestation on soil C. Bashkin and Binkley (1998) also found that there was no net change in total soil C pools 10-13 years after establishing *Eucalyptus saligna* plantations on ex-sugar cane fields in Hawaii. However, Condon and Newman (1998) observed decreases in total organic carbon of 20 and 40% in 10-17 year-old coniferous plantations growing on land converted from grassland in New Zealand. They attributed this to a lack of organic matter input to soil in the plantation. Our study was constrained in evaluating changes to the C balance by being restricted to the < 2 mm fraction of the 0-10 cm soil. We did observe less fine root material in plantation soil than in pasture soil, but this difference may have been offset by higher quantities of litter retained under the trees. Additionally, soil moisture was consistently lower under the plantation than under the pasture sward, so that conditions for decomposition of organic matter were also poorer.

Rates of respiration were not related to fertility of the soil as measured by C:N and C:P ratios, as the native vegetation soils had significantly higher C:N and C:P ratios and similar or higher rates of respiration. The absolute cumulative respired C at 96 days (range: 1.55 – 3.94 mg g⁻¹) compared well with published figures for a similar study conducted by Bauhus *et al.* (1993), who found cumulative respiration figures of 0.86 to 1.89 mg g⁻¹ at 25°C for 151 days for a single soil type with different residue burning treatments. Respiration rates were approximately linear after about 30 days, and did not appear to approach a plateau up to 96 days (Figure 8), even in soils with a relatively high proportion of respired C (*cf.* Figure 9). This indicated that respiration rates may have been limited by a factor other than substrate chemical composition, such as rate of diffusion of O₂ or organic compounds to the site of microbial activity, or a nutrient limitation. Nutrient limitation is unlikely to have caused the observed linearity, as nutrients released as organic matter decomposes could then be expected to increase microbial populations and the rate of respiration. There was no significant difference in respiration rates between plantation and pasture soils for this limited number of sites. It is possible that the higher respiration in native vegetation at three sites may be an artefact caused by differences in the distribution of C within the 10 cm depth: organic matter may be more concentrated at the surface in the uncultivated soils and experience different environmental conditions to organic matter in cultivated soils. This possibility requires further investigation. We are currently sampling soil profiles and surface litter at these sites to provide a more comprehensive evaluation of land-use effects on the amounts and forms of soil C.

Another indicator of labile soil C was organic C respired during the 96 day incubation as a proportion of total C. Although there was no difference between the land-use types, this measure clearly showed that sandy soils had higher relative levels of C utilization (up to 12%) than heavier textured soils (down to 4%) (Figure 9). Greater physical accessibility in the more open-textured soils may be an important factor influencing respiration rates.

Carbon respired over the 96 day period was a lower proportion of total organic C than that oxidised by 33 mM MnO₄⁻. Labile C oxidised by 33 mM MnO₄⁻ accounted for 10.3 to 14.7% of total organic C, about half that of that oxidised by 333 mM MnO₄⁻. Although the LC₃₃ and LC₁₆₇ fractions gave better discrimination between sites than LC₃₃₃ (Table 7), there was no significant difference between land-use types. The 333 mM MnO₄⁻ oxidisable C measure has commonly been used for measuring labile C (eg. Blair *et al.*, 1995, Conteh *et al.*, 1998), but our results suggest that other fractions (with lower oxidising strengths) may be better correlated with the labile pool of C. Bell *et al.* (1998) also found that carbon oxidised by weaker permanganate concentrations (33 mM MnO₄⁻) was better correlated with a measure of soil physical stability.

Microbial biomass is generally considered to be a highly labile form of SOM, and accounted for approximately 0.5% of total C in these soils. For the 10 sites, microbial biomass C was weakly related to soil texture, and addition of land management history or site factors had no significant effect on the regression.

(ii) Nitrogen

There was a wide range (approximately 10-fold) in the concentration of total soil nitrogen associated with the variation in soil types and climate. Over all sites there was no difference in the average concentration of total N between pasture and plantation soil (Table 8). This might be expected, as total soil N represents a relatively large nutrient pool that responds slowly to management-induced changes. However, relative differences in total N between pasture and tree soils shows a distinct trend in relation to soil texture (Figure 46). This indicates that on sandy soils with low organic matter content, concentrations of total N are lower on plantation soils than on pasture soils. It is not clear whether this is due to continuing accretion of N on the pasture soil, loss of N under plantations or to a combination of both factors.

There was also a large range in the mineralizable pools of N determined by sequential leaching of soil in long-term laboratory incubations. In contrast to total N, however, there was no systematic difference between tree and pasture soils in the size or decay rate of these pools. There was a smaller range (3 to 5-fold) in the amounts of potentially available N in surface soil for both tree and pasture soils as determined by short-term anaerobic incubation. The variation in this measure of soil N was partly related to differences in soil texture across the range of sites sampled (Figure 47).

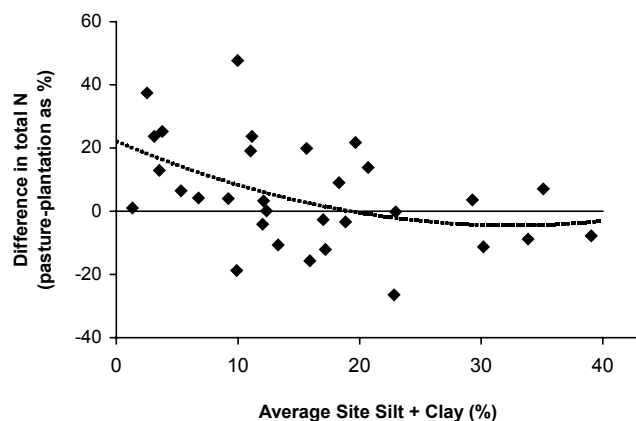


Figure 46. Relationship between the proportional difference in total soil N (pasture - plantation as % of site mean) and soil texture for 31 paired sites.

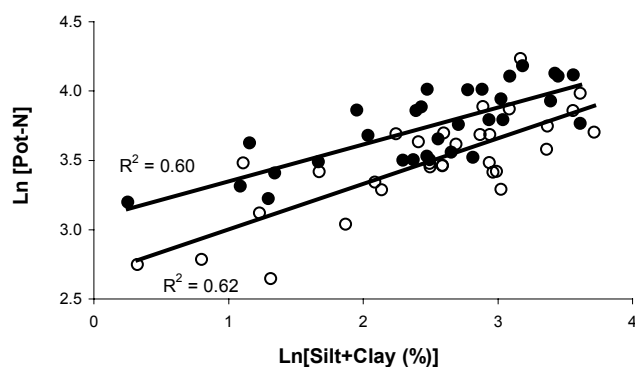


Figure 47. Variation in potentially mineralizable N (anaerobic incubation) in relation to soil texture in surface soil (0-10cm) across the 31 paired pasture (closed symbols) and plantation (open symbols) sites.

Higher concentrations of potentially available N occur in soils having greater amounts of silt and clay. In contrast to the other measures of soil N, amounts of potentially mineralizable N were more strongly influenced by land use change, with lower concentrations in surface soil associated with the plantations relative to pasture plots. These differences were reflected in the index of N mineralization, determined as the amount of mineral N produced during incubation of intact soil cores at optimum moisture content. Although the index was highly variable, the generally lower values obtained from tree plots compared to pasture indicates that the potential supply rate of mineral N may be reduced under trees. This, together with the pattern of lower soil moisture content observed in surface soil under trees, suggests that annual rates of N mineralization will be reduced when farmland is planted to eucalypts. These results support our initial hypothesis that the soil supply of N for plant growth will be reduced where plantations replace pastures due to the reduction in input of readily degradable nitrogen-rich residues.

Differences in relative mineralization rates measured at one time could be exacerbated by differences in soil moisture under trees and pasture during autumn and spring. Soil under trees will wet up more slowly than under pasture due to canopy interception of early winter rainfall. In spring when pastures senesce, perennial roots of tree crops will continue to utilize moisture and dry out

surface soils. These factors could reduce the period during which surface soils have moisture levels that are optimal for microbial activity, and thus for mineralization of organically bound soil N.

The reduction in annual net N mineralization rates in soil when plantation crops are established on pasture indicated by the above measures is supported by the limited seasonal estimates made at two of the paired sites. At the more fertile Moltoni site, annual N mineralization was 4-fold lower under trees than under pasture. Similarly, there was a 2-fold difference in annual mineralization rate at the drier, less fertile Gibbs sites. The magnitude of the difference in N mineralization between trees and pasture plots at these two sites cannot be used as general measures of the effect on N supply of trees planted on pasture land because they rely on the similarity of the paired sites prior to plantation establishment. The measures were also only made over one season, and could have been affected by the specific rainfall pattern experienced during that period. Nevertheless, these data, together with the estimates of potentially available N and the index of N mineralization described above, all suggest that N supply rates of pasture soils are likely to decline when the land is planted to successive crops of eucalypts. Plantation managers will need to take account of this and implement management strategies to maintain adequate N nutrition to sustain tree growth in future rotations. Practices used in the inter-rotation period can have large effects on N losses, soil N mineralization rates, and therefore N supply for growth of successive plantations. Retention of harvest residues is one practice that will favour the maintenance of soil N on plantation sites (see below).

(iii) Phosphorus

Concentrations of total and extractable forms of P were lower in plantation soils than in pasture soils at most sites. The differences in total soil P could be explained largely by the difference in P fertilizer application that has occurred since plantations were established. There was also a trend towards larger differences in total P in the heavier textured soils (Figure 28), which may partly be explained by a greater propensity for leaching of P in the sandy soils. This likelihood is supported by the small differences in soil P (Figure 19) and the higher soil solution P (indicated by null point values; Figure 25) in poorly P buffered soils.

Differences between pasture and plantation areas in the amount of P in surface soil were on average about 50 kg P ha⁻¹. This compares with an average of about 124 kg more P applied to pasture than to plantation soils since the plantations were established. At the 10-20 cm depth there was a mean difference of only 3 kg of P, indicating that P was retained near the surface at most sites. Therefore, the difference between pasture and plantation areas in the amount of P in surface soil is, on average, about 40% of the difference in P applied to the two land-use types. A balance in these amounts would not be expected, as no account is taken of the export of P associated with crop and animal production, or of the accumulation of P within the trees. Export from the sites in farm produce is difficult to estimate and we have not attempted to quantify this. Nevertheless, the amounts are likely to be greater than those accumulated in the aboveground components of *E. globulus* stands. In a high productivity 8 year-old *E. globulus* stand (MAI about 40 m³ ha⁻¹ yr⁻¹) near Manjimup, about 56 kg P was estimated to be in aboveground components, with about half of this retained on the site after harvest (O'Connell and Grove, 1999).

The total P determination represents the strongest of the extraction methods. Effects of land-use change on soil P were also discernable with the weaker extractions using solutions of sodium bicarbonate (Olsen and Colwell) or acid-fluoride (Bray). These extraction procedures are commonly used in soil testing laboratories for identifying deficient soils and estimating plant fertiliser requirements (Rayment, 1993). Measurements from the 18 paired sites showed that for each of the 3 extraction methods, P concentrations were about 40% lower in plantation soils than in pasture soils (Figure 20). This is a greater proportional difference than was found for total soil P (15%, Table 12). However these extractable P concentrations were generally less well related to physical and chemical properties than total soil P, particularly for the milder extractants (Table 10). Consequently, relationships developed through multiple linear regressions to explain variation in

extractable P measures across sites accounted for a lower proportion of the variation (59 – 70%; results not shown) than for total P (81%; Figure 28). In contrast to total P, inclusion of amounts of P previously applied in fertiliser did not generally improve the relationships or account for the difference between pasture and plantation soils at the 18 sites. The exception to this was for Colwell-extractable P measured at the 31 sites. The higher correlations between soil properties and P determined by stronger extractions (Table 10) is probably due to the greater removal of native P, which is likely to be related to variation in intrinsic soil characteristics.

The large differences in concentrations of extractable forms of P between pasture and plantation soils in the present study would be caused largely by differences in the input of recently applied P coupled with the transformations of P that will vary among soils. Agricultural research in this region has shown that the relative effectiveness of applied P, measured against plant response to freshly applied P, can decrease by 30-60% within a year (Bolland and Bowden, 1986). Bolland (1992) also showed that discontinuing P application to a relatively infertile soil caused decreases in extractable P of about 50% within 1-3 years. However the rate of these changes declines with time and the cumulative effect of many years of P application can build up large reserves of P. Many sites used for plantations have had a long history of P application and it may take many years before the status of soil has declined far enough for deficiency to reappear (Barrow, 1980b). At present, we do not know when and on which soils the onset of P deficiencies will begin to impair plantation growth. It is also difficult to say to what extent the differences between pasture and plantation soils are due to the continuing increases in P concentrations in pasture soils or to declining concentrations in soils under plantations.

The P equilibration studies provided estimates of the P buffering capacity of soils, null point concentrations (concentration at which there is no net sorption) and desorbable P. These measures are relatively well predicted from functions which each relied on at least 15 data points (range in P solutions and equilibration time). Our expectation was that the change in land-use with continuing P application only to the pasture soils could affect the buffering capacity of soils (ie. lower buffering as increasing P is applied). However, if this is the case, it was not detectable against the background variability in matched land-use pairs across sites.

Estimates of desorbable P showed that concentrations were generally high in pasture than under plantations for sandy soils that have a low P buffering capacity. There was no consistent pattern for heavier-textured soils. The null point values varied widely across sites but again there was no consistent difference between pasture and plantation soils. It may be that this measure is too sensitive to the background natural variability encountered in soils to be useful in discerning changes to soil P supply of significance for plant growth. However, this requires further investigation.

(iv) Cations

A marked change was detected in the concentrations and balance between cations in the surface 10 cm soil caused by the difference in land use over a period of only 6-11 years. There was no measurable effect of land-use change on soil pH despite the lower concentrations of exchangeable Ca and higher concentrations of Mg and K in plantation soils (Table 12). Acidification of soils in plantation forests has been reported in some situations (see Noble and Randle, 1998). In the current study, lower exchangeable Ca concentrations in plantation soils could be expected to be associated with lower soil pH. If there has been an effect, it is possible that it has been matched by a similar change in pasture soils, where there is a greater potential for acidification caused by leaching of NO_3 and export of farm produce (Helyar and Porter, 1989).

The possibility that higher Ca concentrations in pasture soils was caused by input of Ca in fertilizers, mainly as superphosphate, to pastures and not to plantation soils since trees were planted was investigated. The difference in application would be approximately 220 kg Ca ha⁻¹ based on

average differences in P application to pasture and plantation soils. This compares with an average difference of 122 kg ha⁻¹ of exchangeable Ca in 0-10 cm soils. However, in contrast to soil phosphorus, past fertiliser did not significantly account for the variation in exchangeable Ca in surface soils. This may be explained by leaching of Ca, which will vary according to soil characteristics. This factor is less important in the case of soil P. It is also possible that several processes are interacting, masking any effects of input by fertilizer. The processes that lead to acidity and base cation leaching in agricultural soils can be expected to cause greater loss of Ca from the surface of pasture than plantation soils at the paired sites. This is supported by our data showing higher mineralisation rates, higher amounts of NO₃ and higher soil moisture (greater potential for leaching losses) in pasture soils. Additionally export of Ca in farm products could also be expected to contribute to a lower Ca balance in pasture soils than in the trees, the opposite trend to that observed. Countering this, uptake and accumulation of Ca in the stand will act to reduce Ca levels in soils. Being a smooth barked species, *E. globulus* accumulates large amounts of Ca in the aboveground biomass (Lambert, 1981, Grove *et al.*, 1996). At a relatively high productivity site near Manjimup, we estimated there was about 1200 kg Ca ha⁻¹ in the aboveground components of an 8-year-old stand of *E. globulus*, of which about 423 kg was contained in stem bark. (Grove and O'Connell, 1995). Our estimates of the amount of Ca in stem bark across the 31 sites ranges from 23 – 488 kg ha⁻¹, indicating that well over 1 tonne of Ca would have accumulated in the trees on the more productive sites. These quantities are large relative to the amounts of exchangeable Ca stored in the surface metre of soil (see Table 6). This emphasises the importance of decomposition of high-Ca harvest residues following plantation harvest in offsetting the trend towards lower soil Ca concentrations under plantations, and in supplying Ca to subsequent tree crops.

The trend to higher K levels in plantation soils is also probably a net effect of various processes. Some K has been applied to 2/3rds of the pasture sites since trees were planted and none to the plantation. However, the potential for leaching will be less in plantation than in pasture soils, due to greater interception of rain by the stand canopy and the greater rooting depth under trees. Furthermore, significant amounts of K are recycled in eucalypt forests in stem flow and through-fall (O'Connell and Grove, 1996). O'Connell (1985) estimated that about 38 kg K ha⁻¹ yr⁻¹ reaches the forest floor in natural *E. diversicolor* forest in this way, but much smaller amounts of Mg and Ca by these processes. Thus, the higher K levels in plantation may be caused in part by a combination of recycling through trees and less leaching of soils due to interception of rain by the tree canopies.

As a result of the higher amounts of exchangeable Ca in pasture soils, and the lower amounts of exchangeable K and Mg, there are large differences in the cation balances between pasture and plantation soils. This is best illustrated by the large differences in Ca:Mg, and Ca:K ratios in surface soils. A model that included terms for soil physical characteristics, P applied in fertiliser, and land-use type best described variation in Ca:Mg ratios (Figure 48). This explained 65% of the variance

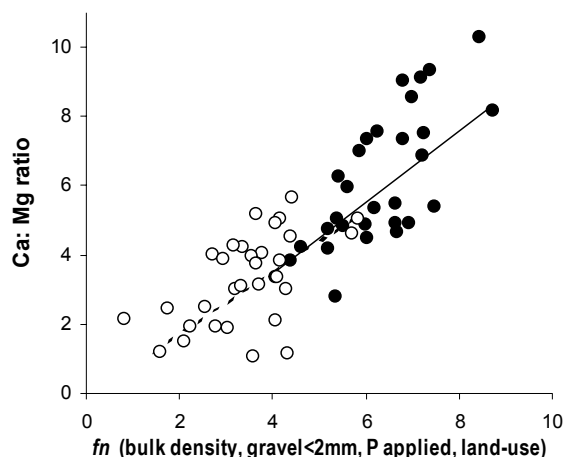


Figure 48. Ratio of exchangeable Ca/Mg in surface (0-10 cm) soil in relation to predicted values from a combined model for pasture (closed symbols) and plantation soils (open symbols) which includes terms for bulk density, gravel content and the amount of P previously applied to the land.

and shows a large separation in ratios between pasture and plantation soils. Although inclusion of P applied improved ($P < 0.001$) the relationship, it did not markedly reduce the effect of land-use. This suggests that Ca applied in fertiliser has influenced Ca:Mg ratios in soils, but that the effect of land-use change has also been influenced by other factors. This is consistent with the explanation for the changes to exchangeable Ca in soil described above. Variation in Ca:K ratios could not be explained as well by relationship to other soil characteristics. However, ratios were negatively correlated with the amount of silt and clay in soils, and a function accounting for the difference ($P < 0.001$) between pasture and plantation soils explained 35% of the variance. Ca:K ratios were on average 60% higher in pasture soils (21) than in plantation soils (13) across the 31 sites.

Improvements to the Mg and K status of plantation soils relative to pasture soils is beneficial for the supply of these essential nutrients to subsequent tree crops. However, the changes must also be assessed in relation to effects of harvesting and inter-rotation site practices before the full impact of plantations on the soil supply of these nutrients can be evaluated.

Land-use effects on plant growth

The primary focus of the project has been in evaluating changes in properties of surface soils, many of which are commonly used to indicate plant nutrient availability. Evaluating effects of the observed changes to soils on tree growth is an important step still to be addressed. Our measurements of seedling growth were restricted to two sites and the results rely on the similarity of pasture and plantation areas.

Results from the field bioassay were to a large extent consistent with expected responses, the notable exception being the lack of difference between land-use types in response to N and P application on the sandy soil (Gibbs). At the higher fertility site (Moltoni) the lack of response to P is consistent with the high concentrations of soil P in both pasture and plantation soils. Plants responded to N, even though the N status of the soil, assessed by various measures, is relatively high. However, the lack of a significant difference between pasture and plantation soils in the response to N was unexpected. It may be partly caused by the more favourable conditions for N mineralization in plantation soils when placed into the pasture environment.

At the Gibbs site, positive growth responses to N, and to P where N supply is adequate, is indicative of the relatively low fertility of this soil and the high nutrient requirement of the species in the early stages of growth. However, the lack of difference in response between pasture and plantation soil appears inconsistent with lower concentrations of extractable P and lower indices of N supply (N mineralization rate, potential N) in the plantation soil. Inability to discern differences in responses may be due to the relatively high variability in the experiment associated with use of intact soil (as opposed to bulking and obtaining more representative soil). However, it may also be due to differences in soils that are independent of the effects of land-use change. Growth was better on the pasture soil, and this was associated with higher organic C, a difference that is inconsistent with the finding for all sites of no difference in organic C levels between land-use types. We can only speculate that the better growth in pasture soil was associated with the higher organic matter status, possibly through greater buffering of soil water and nutrient supply. This emphasises the problems of relying on testing effects of land-use change at specific sites rather than examining broader trends with many sites.

Tree growth and bark nutrient composition

The good relationship between rainfall and growth is not unexpected, especially considering the extreme range in climate and soils. Inclusion of chemical soil properties did not improve the model fit, probably because variation in soil characteristics across sites was to some extent confounded with variation in rainfall (see Figure 3).

Nutrient concentrations in bark were generally not related to bark weight per unit area (i.e. per core). This was being used as a surrogate for thickness, which is observed to increase with tree size. It is likely that thickness is confounded with variation in bark density but this has not been examined.

Concentrations of N, Ca and K in bark were comparable to those reported for other smooth-barked eucalypts in Australia (Grove *et al.*, 1996). However, concentrations of P (range 0.017 - 0.063%) are generally higher than is reported for other eucalypts (0.005-0.026%, Grove *et al.*, 1996). This is probably explained by the younger age of trees and the elevated P status of the agricultural soils in our study.

The amounts of nutrients in bark vary greatly across sites, with a 22- to 25-fold variation in N, Ca and K, and a 15-fold variation in P and Mg (Table 13). Much of this variation is associated with productivity differences. Therefore, a similar scale of variation in nutrient composition can be expected for canopy tissues (foliage and branches), which is the other major component of residues left on the site following harvest. The likely impact of harvest residues on site nutrient capital will therefore vary markedly between sites.

A nutrient budget estimated for the relatively fertile red earth site following harvest of an 8-year-old *E. globulus* stand (O'Connell and Grove, 1999) showed that 40% of the P in aboveground material and smaller amounts of N (18%) and Ca (9%) were exported in stem-wood. Stem-bark contained less N and P, but substantially more Ca (4-fold higher) in stem-bark than in stem-wood, which emphasises the importance of debarking on site to minimize export of nutrients. On the basis of this budget, and assuming a similar distribution of nutrients in stands at the 31 paired sites, stem-bark retained on the site after harvesting would contain about 11% of the N, 17% of the P and 38% of the Ca in harvest residues.

Impacts of inter-rotation harvest residue management

The amounts of added residues and their nutrient contents were significant in relation to the stores in surface soils at both sites. For the single slash treatment, total C additions amounted to more than two thirds and one third of the soil-stored C in surface soil (0-10 cm) at the red earth and grey sand sites, respectively. When larger woody residues (> 3 cm) are considered, the amount of C in harvest residue additions to the red earth site exceeded that present in surface soil. Much of this material had decomposed by December 1998 (4.5 and 3.5 years after harvest of the red earth and grey sand sites, respectively). Surprisingly, the addition of these residues has resulted in very little change in soil-stored C over the period of the experiment. The treatment that received double the residue addition, also showed limited change in the pool of C in surface soil. At the red earth site, C stored in 0-10 cm soil increased during the 4-year measurement period by only about 2% from values found at the initial sampling 6 months after harvest. There was a small decline in C storage in 0-10 cm soil at the grey sand site during the same period. Several studies in the tropics have suggested that decay of eucalypt residues results in smaller contributions to soil organic matter than does turnover of residues from other species (Bernhard-Reversat 1987,1993; Wang *et al.* 1991; Bargali *et al.* 1993). The extent to which these conclusions apply to temperate forests is uncertain. Monitoring of soils in the current study will continue annually throughout the rotation and should provide important insights into dynamics of soil C in response to harvest residue management.

Burning of the harvest residues clearly impacts markedly on soil pH and the storage and availability of many of the nutrients. Increases in plant availability of the cations and P after fire is one of the most common responses found (Grove *et al.* 1986). In our study these effects tended to be relatively short lived, with most soil properties returning to their pre-fire levels within the first or second year after fire. Possibly of more importance is the long-term impact of residue burning on site N status (Raison *et al.* 1993), especially if fire is used repeatedly after harvesting short rotation plantation forests. We estimate that at the red earth site, N volatilization losses from burning harvest residues and associated surface soil organic matter, together with removal of N in harvested logs, probably

exceeded 500kg N ha⁻¹. Replacement of these amounts of N would not normally be possible within the time scale of one 10-year rotation.

Retention of harvest residues may also play an important role in moderating the fluxes of mineral N in the early stage of tree growth following harvest and re-establishment of the new plantation. In a laboratory study, Aggangan *et al.* (1999) found eucalypt litter to be an effective agent for immobilization of mineral N and hypothesised that eucalypt residues may act as an important buffer against N loss through leaching or other processes during periods of disturbance. At our sites there were large accumulations of mineral N in soil following harvest, probably because of the maintenance of conditions conducive to N mineralization and the limited uptake by a newly developing root system. At the red earth site much of this labile N was present as nitrate and would have been subject to leaching loss with the onset of winter rains. Accumulations of nitrate were lower where residues had been retained, probably as a result of N immobilization as suggested by Aggangan *et al.* (1999), with the concomitant reduced prospect of N loss through leaching. In the third and fourth years after seedling establishment N mineralization on single and double slash treatments increased above nil slash plots but at this time most of the mineralized N would have been taken up by the well established root systems. At the less fertile grey sand site, N mineralization tended to be higher where residues had been retained at all stages of stand development. The standing pool of mineral N was initially highest at the greatest level of residue retention, but in this case labile N was predominantly in the ammonium form and would have been less likely to be leached below the rooting zone.

Two soil changes which are unrelated to residue treatment, but which are of importance in relation to C storage and plantation nutrition are (i) the patterns of labile C variation (Figure 39) and (ii) the decline in soil K status at both sites following stand harvest (Figure 38). Worldwide, there is currently great interest in sequestration and storage of atmospheric CO₂ by alternative land use systems. The data presented here illustrate the difficulty in measuring changes in total soil C levels in response to land management, despite the large amounts of added residues and the robust experimental designs. Alternative measures of soil C status, such as the fraction of C oxidized by weak permanganate solution, may provide a more sensitive option for tracking changes in soil C in response to different land management options.

The decline over time in exchangeable soil K at both sites to about half the levels present in the first soil sampling following harvest is of interest, particularly as K concentrations were generally higher in plantation soils than pasture soils at the paired sites. However, baseline data was not available from the two sites prior to harvesting. The extent to which the decline following harvesting represents a general pattern across a wide range of plantation sites is uncertain, but warrants further examination. If such a trend exists more generally, and represents a decline from the original baseline, then greater attention to managing K nutrition in *E. globulus* plantations in second and subsequent rotations may be required in the future.

At the red earth site there was no impact of residue management on tree growth 4 years after planting. This site is at the upper end of soil fertility of the land utilized for plantations in south-western Australia. Growth rates on nil and double slash treatments were similar to those where high rates of N and P had been used in nutrient application rate experiments at this site (Figure 49a) indicating that nutrient limitations were not restricting growth on the harvest residue management experiments. Consequently, in the short term, harvest residue management is unlikely to impact on plantation growth on such sites. However, in the longer term, over a number of rotations, any management practice which affects nutrient status of the site, such as N loss associated with burning harvest residues discussed above, may adversely impact on site productivity. At the grey sand site, which has a lower natural fertility status than the red earth site, there was a trend towards higher growth associated with greatest application rates of harvest residues. However during the majority of measurement periods these differences were not statistically significant. At this site, there were

also large responses to added nutrients (Figure 49b). Greater retention of harvest residues is associated with significantly increased rates of soil N mineralization and this may partly explain the relative patterns of tree growth found at the grey sand site. Growth trends will be monitored throughout the rotation to assess whether slash residue management impacts significantly on productivity of the second rotation harvest. Our current results indicate that demonstrating statistically significant growth differences between the alternative options for managing slash materials may be difficult. Nevertheless, conservative harvest residue management will assist in maintenance of site nutrient capital and this, coupled with appropriate fertilizer regimes, will favour sustained plantation productivity in the long term.

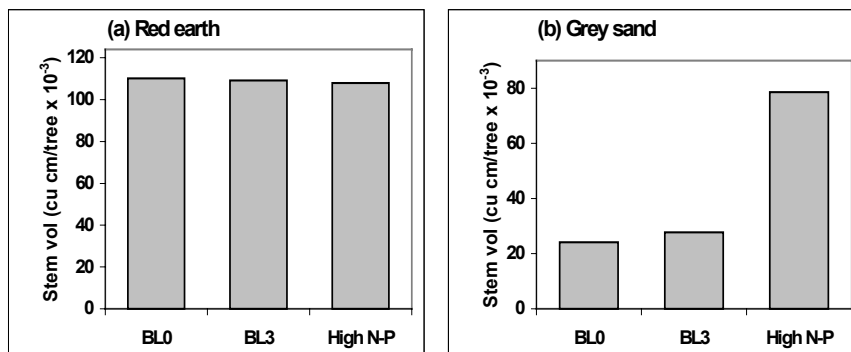


Figure 49 . Comparison of growth of 4-year old trees on harvest residue management treatments and treatments with high rates of applied N and P fertilizers at (a) the red earth and (b) the grey sand sites. BL₀ = no slash; BL₃ = double slash; High N-P = high fertiliser treatment in adjacent trials.

Conclusions

Changes in the management of agricultural soils through conversion of land from traditional farming systems to continuous tree cropping has resulted in significant changes to concentrations of some forms of N and P, and to concentrations and the balance of cations (Ca, Mg and K) in surface soils. While changes to some properties have appeared across the range of sites, others (e.g. total N, desorbable P) are only becoming evident on the sandy soils that are less well buffered. There were no detectable effects of land-use change on soil acidity, or on various measures of soil C. The observed changes have occurred within a relatively short time frame and were detectable despite being measured against a relatively high initial fertility level. They are consistent with our initial hypothesis that soil N and P supply for plant growth are likely to decline with changes in land management involving reduced input to soils of both P fertiliser and nutrient rich organic residues derived from legume-based pastures.

These findings emphasise the importance of introducing site management practices, particularly during the inter-rotation period, which conserve organic matter and nutrients and correct nutrient deficiencies so that the productivity of future rotations can be sustained. Our experiments in second rotation establishment have shown that retention of harvest residues has beneficial effects on mineral N dynamics and on concentrations of Ca, Mg and K in surface soils. Implementing practices which offset declining soil nutrient status will be critical to maintaining site fertility and productivity in the long-term, even though benefits to tree growth on some sites may not be apparent immediately.

6. Implications

- Conversion of land from conventional farming practices to continuous cropping with *E. globulus* is resulting in significant changes to a number of soil properties related to the plant availability of N, P, Ca, Mg and K. These changes are likely to result more from reduction in fertiliser and pasture residue inputs to soils rather than to effects of the tree crop per se.
- Changes to soil C (< 2 mm soil fraction) were not detected, although a more comprehensive analysis that includes the full soil profile is necessary to properly evaluate the effects of changed land use on C sequestration and turnover.
- Measures of an N mineralisation index, potential N mineralisation, total P and P extracted with solutions of different strengths were generally lower in plantation soils than in adjacent pasture soils that have a common past history. These changes are consistent with the effects of reduced P fertiliser input and change to the quality of organic residues in plantations that was hypothesised. If the observed trends continue, increased incidence of nutrient limitations to growth can be expected to impact on productivity unless corrective measures are taken.
- Although extractable P concentrations were lower in plantation soils than in pasture soils, no consistent differences in P buffer capacity or soil solution P could be detected. This may reflect the large bank of soil P accumulated under agriculture. Nevertheless the decline in soil tests that are commonly used to predict crop fertiliser requirements suggests that the incidence of P deficiencies will increase in second and subsequent rotations.
- The change to plantations has also resulted in lower concentrations of exchangeable Ca, and higher concentrations of exchangeable Mg and K in surface soils. Large amounts of these nutrients are held in aboveground dry matter, especially Ca that accumulates in bark. In the second rotation experiments, there were detectable increases in the concentrations of these elements in surface soil resulting from decomposition of retained slash materials. Evaluating the longer-term effects of tree cropping on these cations will need to take account of the recycling of these elements in slash residues. It was not possible in the current study to assess the net effect of changes in cation concentrations that occur during plantation growth and those resulting from decomposition of harvest residues.
- The changes to the properties of surface soils in plantations relative to conventionally managed pastures have developed over a short time span (6-11 years) and have been detectable against a relatively high initial fertility level. They are significant with regard to the expected longevity of this industry. This emphasises the need to adopt practices that conserve the organic and nutrient resources on site, and in a form least vulnerable to loss. Quantifying the impact that changes to soil chemical properties will have on the onset and extent of nutrient limitations to growth is beyond the scope of the present study.
- Second rotation plantations represent a small proportion of the total area planted to *E. globulus*. Information does not currently exist on changes to site productivity in second rotation plantations. Any losses in productivity will translate to larger losses in returns to growers due to fixed costs, particularly at establishment. Furthermore, sustaining the productivity of these tree crops is of increasing importance as the industry moves towards greater reliance on farmland plantations to meet woodchip export contracts. A stable resource supply is also required if there is to be a pulp-mill established in this region in the future.

- The impact of the changes to soil fertility on productivity of second and subsequent rotations will depend on the relative importance of nutrient and water constraints to growth. Soil water supply commonly limits growth in the mid to late stages of a rotation. Nutrient limitations are most likely in the early phase of plantation growth when high demand for nutrients is associated with the expansion of canopy tissues. This phase closely followed the change from conventional farming practices for first rotation tree crops, but this will not be the case for second and subsequent rotations. The impact of any decline in soil fertility on the yield from plantations at harvest will be more significant at sites where water limitations to growth are least.
- Site management following harvest and in establishing the subsequent tree crop has been shown to have a marked effect on soil nutrient supply. For example, burning of harvest residues was estimated to result in losses of N of about 500 kg ha⁻¹ in volatile forms from one site. Retention of harvest residues was shown to contribute to the maintenance of site nutrient capital by reducing the potential for loss of N at one site. Retention of residues also enhanced rates of N mineralisation three to four years after harvest when mineral N could be utilised by the developing stand, and increased concentrations of Ca, Mg and K in the surface 5 cm soil.
- Effects of harvest residues on site nutrient capital and the processes regulation nutrient fluxes will depend on the quantity of residues. Amounts of harvest materials, which consist of tree canopy tissues and stem-bark, are related to stand productivity measured as stem volume. We would therefore expect a large variation in amounts of organic matter and nutrients in residues returned to the soil surface following harvesting of stands across the sites studied, where MAI's ranged from 4.3 – 51 m³ ha⁻¹ yr⁻¹.
- Although harvest residue treatments have had only limited effects on tree growth at the two sites examined, practices that conserve harvest residues will help to maintain soil nutrient capital and favour sustained productivity in the long-term. This requires the development of operationally viable procedures to manage harvest residues during the preparation and replanting of sites.

7. Recommendations

This study shows there has been a decline in concentrations and fluxes of some nutrients in plantation soils relative to pasture soils that continue to be managed by conventional agricultural practices. At present there is no information on the impact of these changes on the productivity of second and subsequent rotations of *E. globulus*. Further investigation and monitoring is required to:

- Extend the current work to provide more comprehensive measurements of change (eg. soil carbon in litter and all soil fractions down the profile) and to include additional properties related to plant nutrient requirement.
- Evaluate effects of changes to soil nutrient supply on nutrient uptake and plant growth, and develop the capacity to predict and correct nutrient limitations based on climate, soil characteristics and past land-use history.
- Develop a system to monitor changes in productivity of successive rotations through permanent measure plots, incorporating procedures to monitor changes in soil properties over time. Interpretation of any productivity decline would require investigation of causative factors.
- Develop new studies to measure the impacts of plantations on soil fertility over a longer time frame than the present studies: these will integrate the changes induced from the initial conversion of farming land to plantations and the effects of harvesting and inter-rotation site management.
- Evaluate methods of harvest residue management at an operational level and develop cost effective practices that maintain soil fertility and are conducive to the establishment and growth of second rotation plantations.

8. References

- Aggangan, R.T., O'Connell, A.M., McGrath, J.F. and Dell, B. (1999). The effect of *Eucalyptus globulus* leaf litter on C and N mineralization in soils from pasture and native forest. *Soil Biology and Biochemistry*, **31**: 1481-1487.
- Bargali, S.S, Singh, S.P. and Singh, R.P. (1993). Patterns of weight loss and nutrient release from decomposing leaf litter in an age series of eucalypt plantations. *Soil Biology and Biochemistry*, **25**: 1731-1738.
- Barrow, N.J. (1980a). Differences amongst a wide-ranging collection of soils in the rate of reaction with phosphate. *Australian Journal of Soil Research*, **18**: 215-224.
- Barrow, N.J. (1980b). Evaluation and utilisation of residual phosphorus in soils. In 'The Role of Phosphorus in Agriculture' (Eds. F.E. Kasewnah, E.C. Sample and E.J. Kamprath). pp. 333-359. (American Society of Agronomy, Madison, Wis.)
- Bashkin, M.A. and Binkley, D. (1998). Changes in soil carbon following afforestation in Hawaii. *Ecology*, **79**: 828-833.
- Bauhus, J., Khanna, P.K., and Raison, R.J. (1993). The effect of fire on carbon and nitrogen mineralization and nitrification in an Australian forest soil. *Soil Biology and Biochemistry*, **31**: 621-639.
- Beadle, C.L. and Inions, G. (1990). Limits to growth of eucalypts and their biology of production. In: 'Prospects for Australian Forest Plantations', (Eds. J. Dargavel and N. Semple), pp. 183-193, Centre for Resource and Environmental Studies, Australian National University, Canberra.
- Bekunda, M.A., Smethurst, P.J., Khanna, P.K. and Willett, I.R. (1990). Effects of post-harvest residue management on labile soil phosphorous in a *Pinus radiata* plantation. *Forest Ecology and Management*, **38**: 13-25.
- Bell, M.J., Moody, P.W., Connolly, R.D., and Bridge, B.J. (1998). The role of active fractions of soil organic matter in physical and chemical fertility of Ferrosols. *Australian Journal of Soil Research*, **36**: 809-819.
- Bernhard-Reversat, F. (1987). Litter incorporation to soil organic matter in natural and planted tree stands in Senegal. *Pedobiologia*, **30**: 401-417.
- Bernhard-Reversat, F. (1993). Dynamics of litter and organic matter at the soil-litter interface in fast-growing tree plantations on sandy ferrallitic soil (Congo). *Acta Ecologica*, **14**: 179-195.
- Birk, E.M. (1992). Nitrogen availability in radiata pine plantations on former pasture sites in southern New South Wales. *Plant and Soil*, **143**: 115-125.
- Blair, G.J., Lefroy, R.D.B., and Lisle, L. (1995). Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. *Australian Journal of Agricultural Research*, **46**: 1459-1466.
- Bolland, M.D.A. (1992). Residual value of superphosphate for wheat and lupin grain production on a uniform yellow sandplain soil. *Fertilizer Research*, **31**: 331-340.
- Bolland, M.D.A. and Bowden, J.W. (1986). Summary of long-term rock phosphate experiments in south-western Australia. *The Journal of the Australian Institute of Agricultural Science*, **4**: 227-236.
- Bray, R.H. and Kurtz, L.T. (1945). Determination of total organic and available forms of phosphorus in Soil. *Soil Science* **59**: 39-45.

- Buschbacher, R., Uhl, C., and Serrao, E.A.S. (1988). Abandoned pastures in eastern Amazonia. II. Nutrient stocks in the soil and vegetation. *Journal of Ecology*, **76**: 682-699.
- Cellier, K.M., Boardman, R., Boomsma, D.B. and Zed, P.G. (1985). Response of *Pinus radiata* D. Don to various silvicultural treatments on adjacent first- and second-rotation sites near Tantanoola, South Australia. I Establishment and Growth up to Age 7 Years. *Australian Forest Research*, **15**: 431-437.
- Colwell, J.D. (1963). The estimation of the phosphorus fertilizer requirement of wheat in southern New South Wales by soil analysis. *Australian Journal of Experimental Agriculture and Animal Husbandry*, **3**: 190-8.
- Condon, L.M. and Newman, R.H. (1998). Chemical nature of soil organic matter under grassland and recently established forest. *European Journal of Soil Science*, **49**: 597-603.
- Conteh, A., and Blair, G.J (1998). The distribution and relative losses of soil organic carbon fractions in aggregate size fractions from cracking clay soils (Vertisols) under cotton production. *Australian Journal of Soil Research*, **36**: 257-271.
- Conteh, A., Blair, G.J., and Rochester, I.J. (1998). Soil organic carbon fractions in a vertisol under irrigated cotton production as affected by burning and incorporating cotton stubble. *Australian Journal of Soil Research*, **36**: 655-667.
- Cross, A.F. and Schlesinger, W.H. (1995). A literature review and evaluation of the Hedley fractionation: applications to biogeochemical cycle of soil phosphorus in natural ecosystems. *Geoderma*, **64**: 197-214.
- Dalal, R.C. and Hallsworth, E.G. (1976). Evaluation of the parameters of soil phosphorus availability factors in predicting yield response and phosphorus uptake. *Soil Science Society of America Journal*, **40**: 541-546.
- FAO-Unesco (1990). Soil map of the world. Revised legend. FAO, Rome
- Farrell, P.W., Flinn, D.W., Squire, K.O. and Craig, F.G. (1986). Maintenance of productivity of radiata pine monocultures on sandy soils in southeast Australia. In: Forest Site and Productivity. (Ed. S.P. Gessel). pp. 127-136, Martinus Nijhoff Publishers, Dordrecht, Netherlands.
- Fillery, I.R. and McInnes, K.J. (1992). Components of the fertiliser nitrogen balance for wheat production on duplex soils. *Australian Journal of Experimental Agriculture*, **32**, 887-899.
- Grove, T.S., Malajczuk, N, Burgess, T., Thomson, B.D., and Hardy, G. (1991). Growth responses of plantation eucalypts to inoculation with selected ectomycorrhizal fungi. In 'Proceedings IUFRO Symposium, Intensive Forestry: The Role of Eucalypts.' pp. 86-93. (South African Forest Research Institute: Pretoria.)
- Grove, T.S., O'Connell, A.M. and Dimmock, G.M. (1986). Nutrient changes in surface soils after an intense fire in jarrah (*Eucalyptus marginata* Donn ex Sm.) forest. *Australian Journal of Ecology* **11**: 303-317.
- Grove, T.S., Thomson, B.D. and Malajczuk, N. (1996). Nutritional physiology of the eucalypts: Uptake, distribution and utilization. In 'Nutrition of Eucalypts' (Eds. P.M. Attiwill and M.A. Adams). pp. 77-108. (CSIRO Publishing, Collingwood).
- Hedley, M.J., Stewart, J.W.B. and Chauhan, B.S. (1982). Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society of America Journal*, **46**: 970-976.
- Helyar, K.R. and Porter, W.M. (1989). Soil acidification, its measurement and the processes involved. In 'Soil Acidity and Plant Growth'. Ed. A.D. Robson. pp. 61-101. (Academic Press, Sydney).

- Hingston, F.J., Galbraith, J.H. and Dimmock, G.M. (1995). 'Evaluating the effect of soils and climate on productivity of *Eucalyptus globulus* plantations on contrasting sites in south west of Western Australia. Final Report to RIRDC on Project CSF-41A, 72 pp.
- Hutchinson, M.F. (1990). Climatic analyses in data sparse regions. In 'Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics'. Ed. R.C. Muchow and J.A. Bellamy. pp. 55-71. (CAB International 1991 Wallingford Oxon UK).
- 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.
- Keeves, A. (1966). Some evidence of loss of productivity with successive rotations of *Pinus radiata* in the south-east of South Australia. *Australian Forest*, **30**: 51-63.
- Lambert, M.J. (1981). Inorganic Constituents in Wood and Bark of New South Wales Forest Tree Species. Forest Commission of New South Wales Research Note No.45. 42 pp.
- Landcare Review Committee (1995). A Review of Landcare in Western Australia. Report 96 pp.
- Loginow, W., Wisniewski, W., Gonet, S.S., and Ciescinska, B. (1987). Fractionation of organic carbon based on susceptibility to oxidation. *Polish Journal of Soil Science*, **20**: 47-52.
- Mason, M.G. and Rowland, I.C. (1992). Effect of amount and quality of previous crop residues on the nitrogen fertiliser response of a wheat crop. *Australian Journal of Experimental Agriculture*, **32**: 363-370.
- McArthur, W.M. (1991). Reference soils of south-western Australia. 265 pp. (Department of Agriculture, Western Australia).
- McArthur, W.M. (1991). Reference soils of south-western Australia. 265pp.
- Mulcahy, M.J. (1973). Landforms and soils of south-western Australia. *Journal of the Royal Society of Western Australia*, **56**: 16-22.
- Murphy, J. and Riley, J.P. (1962). A modified single solution method for the determination of phosphate in natural water. *Analytica Chimica Acta* **27**: 31-6.
- Noble, A.D. and Randall, P.J. (1998). How soils affect trees. RIRDC Publication No. 98/16. 129 pp.
- Northcote, K.H. (1979). A factual key for the recognition of Australian soils. 124 pp. (Rellim Technical Publications, Adelaide, S.A).
- Northcote, K.H., Hubble, G.D., Isbell, R.F., Thompson, C.H. and Bettenay, E. (1975). A description of Australian soils. 170 pp. (CSIRO, Melbourne).
- O'Connell, A.M. and Grove, T.S. (1999). Eucalypt plantations in south-western Australia. In: Site Management and Productivity in Tropical Plantation Forests. (eds E.K.S. Nambiar, C. Cossalter and A. Tiarks). pp53-59. CIFOR, Bogor, Indonesia.
- O'Connell, A.M., Grove, T.S., Mendham, D. and Rance, S.J. (2000). Eucalypt plantations in south-western Australia. In: Site Management and Productivity in Tropical Plantation Forests, Third Workshop in Kerala, India, December 1999. (in press) CIFOR, Bogor, Indonesia.
- O'Connell, A.M. (1985). Nutrient accessions to the forest floor in karri (*Eucalyptus diversicolor* F. Muell.) forests of varying age. *Forest Ecology and Management* **10**: 283-296.
- O'Connell, A.M. and Grove, T.S. (1996). Biomass production, nutrient uptake and nutrient cycling in the jarrah (*Eucalyptus marginata*) and karri (*Eucalyptus diversicolor*) forests of south-western Australia. In 'Nutrition of Eucalypts'. (Eds. P.M. Attiwill and M.A. Adams) pp. 155-189. (CSIRO Publishing, Collingwood).

- Olsen, S.R., Cole, C.V., Watanabe, F.S. and Dean, L.A. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. U.S. Department of Agriculture, Circular No. 939.
- Ozanne, P. G. and Shaw, T. C. (1968). Advantages of the recently developed phosphate sorption test over the older extractant methods for soil phosphate. In 'Transactions of the 9th International Congress of Soil Science, Adelaide, Australia'. Vol. 2, pp 273-80.
- Raison, R.J., Connell, M.J. and Khanna, P.K. (1987). Methodology for studying fluxes of soil mineral nitrogen *in situ*. *Soil Biology and Biochemistry* **19**: 521-530.
- Raison, R.J., O'Connell, A.M., Khanna, P.K. and Keith, H. (1993). Effect of repeated fires on nitrogen and phosphorus budgets and cycling processes in forest ecosystems. In: 'Fire in Mediterranean Ecosystems' (Eds L. Trabaud and R. Prodon). pp. 347-63. (CEC, Brussels-Luxembourg).
- Rayment, G.E. (1993). Soil analysis: a review. *Australian Journal of Experimental Agriculture*, **33**: 1015-1028.
- Rayment, G.E. and Higginson, F.R. (1992). Australian laboratory handbook of soil and water chemical methods. 330 pp. (Inkata Press, Melbourne).
- Reiners, W.A., Bouwman, A.F., Parsons, W.F.J., and Keller, M. (1994). Tropical rain forest conversion to pasture: Changes in vegetation and soil properties. *Ecological Applications*, **4**: 363-377.
- Robson, A.D. and Gilkes, R.J. (1980). Fertiliser responses (N,P,K,S, micronutrients) on lateritic soils in south Western Australia - A review. In 'Lateritisation Processes'. pp. 381-390. International Geological Correlation Programme Project No. 129. (Oxford and IBH Publishing Company: New Delhi).
- Rovira, A.D. (1992). Dryland mediterranean farming systems in Australia. *Australian Journal of Experimental Agriculture*, **32**: 801-809.
- Rowland, I.C., Halse, N.J. and Fitzpatrick, E.N. (1984). The role of legumes in Australian dryland agriculture. In: 'Proceedings of the International Congress on Dryland Farming, Adelaide'. pp. 676-698. (South Australian Department of Agriculture: Adelaide).
- Rowland, I.C., Mason, M.G. and Hamblin, J. (1988). Effect of lupins and wheat on the yield of subsequent wheat crops grown at several rates of applied nitrogen. *Australian Journal of Experimental Agriculture*, **28**: 91-97.
- Smethurst, P.J., and Nambiar, E.K.S. (1990). Effects of slash and litter management on fluxes of nitrogen and tree growth in a young *Pinus radiata* plantation. *Canadian Journal of Forest Research*, **20**: 1498-1507.
- Sparling, G. and Zhu, C. (1993). Evaluation and calibration of biochemical methods to measure microbial biomass C and N in soils from Western Australia. *Soil Biology and Biochemistry*, **25**: 1793-1801.
- Sparling, G.P. and West, A.W. (1988). A direct extraction method to estimate soil microbial C: calibration *in situ* using microbial respiration and ¹⁴C labelled cells. *Soil Biology and Biochemistry*, **20**: 337-343.
- Syers, J.K. and Craswell, E.T. (1995). Role of soil organic matter in sustainable agricultural systems. In: 'Soil Organic Matter Management for Sustainable Agriculture', ACIAR Proceedings No. 56. (Eds. R.D.B. Lefroy, G.J. Blair and E.T. Craswell). pp. 7-14.
- Tennant, D., Scholz, G., Dixon, J. and Purdie, B. (1992). Physical and chemical characteristics of duplex soils and their distribution in the south-west of Western Australia. *Australian Journal of Experimental Agriculture*, **32**: 827-843.

- Tuohey, C.L., and Robson, A. D. (1980). The effect of cropping after medic and non-medic pastures on total soil nitrogen, and on the grain yield and nitrogen content of wheat. *Australian Journal of Experimental Agriculture and Animal Husbandry*, **20**: 220-228.
- Turton, A.G., Marsh, N.L., McKenzie, R.M. and Mulcahy, M.J. (1962). The chemistry and mineralogy of lateritic soils in the south-west of Western Australia. CSIRO Australia. Soil Publication No. 20.
- Turton, A.G., Marsh, N.L., McKenzie, R.M. and Mulcahy, M.J. (1962). The chemistry and mineralogy of lateritic soils in the south-west of Western Australia. CSIRO Australia. Soil Publication No. 20.
- Veldkamp, E. (1994). Organic carbon turnover in three tropical soils under pasture after deforestation. *Soil Science Society of America Journal*, **58**: 175-180.
- Walkley, A. (1947). A critical examination of a rapid method for determining organic carbon in soils - effect of variations in digestion conditions and of inorganic soil constituents. *Soil Science*, **63**: 254-264.
- Wang, D., Bormann, F.H., Lugo, A.E. and Bowden, R.D. (1991). Comparison of nutrient use efficiency and biomass production in five tropical tree taxa. *Forest Ecology and Management*, **46**: 1-21.
- Whitebread, A.M., Lefroy, R.D.B. and Blair, G.J. (1998). A survey of the impact of cropping on soil physical and chemical properties in north-western New South Wales. *Australian Journal of Soil Research*, **36**: 669-681.
- Woods, R.V. (1976). Early silviculture for upgrading productivity on marginal *Pinus radiata* sites in the south-eastern region of South Australia. Woods and Forests Department South Australia Bulletin 24.
- Woods, R.V. (1981). Management of nitrogen in the *P. radiata* plantations of the south east of South Australia. In: 'Managing Nitrogen Economies of Natural and Man Made Forest Ecosystems'. (Eds R.A. Rummery and F.J. Hingston). pp. 354-367. CSIRO, Division of Land Resources Management, Perth.
- Zen, S. and do Couto, H.T.Z. (1991). Length of rotation and spacing for *Eucalyptus grandis* and *Eucalyptus saligna*. In: 'Intensive Forestry : The Role of Eucalypts'. (Ed. A.P.G. Shonau). pp. 952-963.