FOREST HARVESTING, FOREST NUTRITION AND RESEARCH TRIALS TO ASSESS LONG-TERM FOREST PRODUCTIVITY

DR. ELAINE M. BIRK

1994 GOTTSTEIN FELLOWSHIP REPORT

JOSEPH WILLIAM GOTTSTEIN MEMORIAL TRUST FUND

The Joseph William Gottstein Memorial Trust Fund was established in 1971 as a national educational Trust for the benefit of Australia's forest products industries. The purpose of the fund is *"to create opportunities for selected persons to acquire knowledge which will promote the interests of Australian industries which use forest products for the production of sawn timber, plywood, composite wood, pulp and paper and similar derived products."*

Bill Gottstein was an outstanding forest products research scientist working with the Division of Forest Products of the Commonwealth Scientific Industrial Research Organization (CSIRO) when tragically he was killed in 1971 photographing a tree-felling operation in New Guinea. He was held in such high esteem by the industry that he had assisted for many years that substantial financial support to establish an Educational Trust Fund to perpetuate his name was promptly forthcoming.

The Trust's major forms of activity are,

1. Fellowships - each year applications are invited from eligible candidates to submit a study programme in an area considered to be of benefit to the Australian forestry and forest industries. Study tours undertaken by Fellows have usually been to overseas countries but several have been within Australia. Fellows are obliged to submit reports on completion of their programme. These are then distributed to industry if appropriate.

2. Seminars - the information gained by Fellows is often best disseminated by seminars as well as through the written reports.

3. Wood Science Courses - at approximately two yearly intervals the Trust organises a week-long intensive course in wood science for executives and consultants in the Australian forest industries.

4. Study Tours - industry group study tours are arranged periodically and have been well supported.

Further information may be obtained by writing to,

The Secretary,
J.W. Gottstein Memorial Trust Fund,
Private Bag 10,
Rosebank M.D.C.,
Clayton, Victoria, 3169 Australia

FOREST HARVESTING, FOREST NUTRITION AND RESEARCH TRIALS TO ASSESS LONG-TERM FOREST PRODUCTIVITY

A REPORT ON INTERNATIONAL WORKSHOPS ATTENDED IN NEW ZEALAND, IN MARCH 1994, AS A J.W. GOTTSTEIN FELLOW

ELAINE M. BIRK

Dr Elaine Birk is a Research Scientist with State Forests of New South Wales. One of her responsibilities is to design and carry out research into specific problems relating to the impacts of forest management and site characteristics on the growth, form, productivity, and nutrition of plantations and native forests. She has a PhD in Botany from the University of North Carolina, a Master's degree in Environmental Studies from Griffith University and a Bachelor's degree in Biological Science from Macquarie University. The emphasis of her current work programme is on the impacts of harvesting on soil quality and forest productivity. Her Gottstein Fellowship enabled her to accept invitations to participate in three interrelated international workshops in New Zealand and to inspect research trials in that country. Her study tour and future work will enable her to provide information to forest managers to ensure that long-term productivity is sustained in an environmentally acceptable manner. To date there has been very little research in Australia in this area.

ACKNOWLEDGEMENTS

International meetings and visits provide important avenues for information exchange and a forum in which to challenge accepted paradigms. I am most grateful to the Joseph William Gottstein Memorial Trust Fund for providing the financial support which enabled me to meet with colleagues from around the world to discuss issues related to forest management.

I would also like to thank my employer, State Forests of New South Wales, for supporting my participation in this study tour.

For their hospitality and efforts to help me gain as much as possible from this tour and for the visits to and discussions regarding experimental trials in the North and South Islands, I especially thank my hosts and colleagues at the New Zealand Forest Research Institute Ltd: Dr C.T. Smith, Dr P. Clinton and Dr W.J. Dyck (now of Carter Holt Harvey Forests Limited).

Table of Contents

SUMMARY

As a Gottstein Fellow, the author of this report participated in meetings and inspected forest harvesting trials in New Zealand. The aim of this tour was to gain knowledge in the area of harvesting impacts on forest site productivity. This report is a summary of major presentations and discussion in the workshops attended and a summary of research being carried out in NZ to understand the effects forest harvesting on second rotation productivity of radiata pine plantations. These activities were of interest because there is a similar need to understand harvesting impacts on forest productivity in Australia. The final section of this report presents a perspective on the need for experimental studiesof the effects of harvesting in Australian forests and provides some details of similar investigations being carried out elsewhere.

INTRODUCTION

There is increasing concern world wide regarding the long-term viability of managed forest ecosystems. Forests are the focus of broad-ranging environmental concerns including global change, alternative sources of fuel, biodiversity, water quality, soil degradation and sustainable productivity. Whilst forests are accepted as a source of wood-based products and fibre for fuels, harvesting operations are simultaneously viewed as undesirable, environmentally damaging and unsustainable. These conflicts are common in developed countries around the world; the environmental opposition to forest operations is strong and there are large gaps in our knowledge as to the long-term consequences of harvesting at local, regional and global levels.

Similar concerns have been addressed by previous Gottstein Fellows. Francis (1992), for example, highlighted current and potential forestry issues by drawing on North American experiences. Pressure to conserve forest lands for their intrinsic values is expected to result in more intensive forest operations in order to increase productivity from the smaller areas available for commercial operations. Our ability to meet these demands will in part depend on the suitability and sustainability of forest management practices. Forecasting the consequences of different harvesting and management practices is difficult, in part because of the long time scale (ranging from decades to hundreds of years) which may be required to detect significant change. The author of this report undertook a study tour to gain a greater appreciation of research being carried out to assess the impacts of forest operations on sustainable productivity and to consider options for related research in Australia.

International collaboration among forest scientists with these common management concerns is an important mechanism for developing suitable propocols to investigate the consequences of forest operations on long-term sustainability. No one country has well developed knowledge in this area, but several including Sweden, U.S.A., Canada, and New Zealand and Australia have been investigating the problem for a number of years. The requirement for sustainable forestry, including the maintenance of site productivity, is embodied in the Australian Forestry Policy Statement (NFPS, 1992) but there is limited information to draw upon to formulate standards against which to assess the significance of change in forest soil properties and growth. By working together and coordinating research efforts the maximum value can be obtained from efforts of individual countries and Australian agencies carrying out research in this area.

There is much to be gained from the experiences gained by other countries. The purpose of my study tour was two-fold. My primary objective was to attend international workshops where these issues and other related topics would be discussed. My second objective was to inspect long-term harvesting trials in New Zealand to consider their objectives and designs, the difficulties of installation, early results and lessons learned. This report summarises both the issues presented and discussed at the meetings, and features of the harvesting trials. The potential for similar trials in Australian forests is considered.

WORKSHOPS ATTENDED

Three workshops were attended in New Zealand in March 1994 (the travel and workshop itineraries are summarised in Appendix 1). The principal meeting attended was an International Energy Agency/Bioenergy Implementing Agreement Task IX/Activity 4 workshop on "Understanding Plant Nutrient Uptake and Supply - Opportunities for Managing Site Productivity". This was preceded by a mini-workshop on "Diagnosing Nutrient Deficiencies" and both were organised by the N.Z. Forest Research Institute. The third meeting was a "Trees and Soils" workshop at Lincoln University to consider issues in designing long-term field trials to assess the effects of exotic trees on soils.

Background information IEA/BE

The International Energy Agency (IEA) was founded in 1974 by member countries of the Organization for Economic Cooperation and Development (OECD) to examine ways in which member countries could cooperate to reduce their dependence on imported oil. In 1978 a number of countries signed an agreement for a progam of research, development and demonstration related to forest energy, the Forest Energy Agreement, which was subsequently replaced (May 1986) by the Bioenergy Implementing Agreement (BE).

Task IX of IEA concerns "Harvesting and Supply of Woody Biomass for Energy" and Activity 4 within this Task addresses "Environmental Consequences of Intensive Harvesting". This Activity follows on from previous Activites on "Nutritional Consequences of Intensive Forest Harvesting" and "Environmental Impacts of Harvesting". The 1994 workshop was the 10th since the Task's inception in 1983 and the final meeting for this Activity. The member countries participating in the Activity are New Zealand (Leader), Canada, Sweden, U.K. and U.S.A.. Australia is not a member country but scientists from several organisations participate in the scientific meetings.

The aim of the Bioenergy Agreement Activities is to "communicate and where possible, coordinate national programmes of work in the area of forest energy. This is to be achieved through information exchange on national research, development activites, and planning of national programmes as well as through the development and carrying out of cooperative projects". The objective of the current activity - "to determine the environmental impacts of intensive management and harvesting of biomass crops" - was "to develop a better understanding of, and the ability to forecast, the consequences of different harvesting operations and associated practices on the environment". The 1994 workshop on Understanding Plant Nutrient Uptake and Supply was the third and final meeting for the current Activity. As my association with IEA only commenced when I attended the 1993 workshop in Canada, I have limited first hand experience with this Activity and the Task generally. However, a strength of this Activity is the dissemination of information through publications. This material has increased my awareness of the critical issues important in developing appropriate management and harvesting strategies for Australian forests. At the 1994 workshop, which I attended as a Gottstein Fellow, I presented one of the Keynote papers on forest nutrient management.

1994 IEA/BE WORKSHOP ON "UNDERSTANDING PLANT NUTRIENT UPTAKE AND SUPPLY - OPPORTUNITIES FOR MANAGING SITE PRODUCTIVITY"

Faced with the challenge of conducting long-term research and improving decision support tools for predicting the consequences of increased biomass removal on long-term productivity, collaborators in the IEA Bioenergy Activity "Environmental Impacts of Harvesting" agreed that understanding the factors controlling plant nutrient uptake and supply would improve our chance of reaching this goal.

The workshop objectives were to improve our ability to manage site productivity by:

1. Reviewing knowledge of plant nutrient uptake, species demands, nutrient allocation and nutrient use efficiency.

2. Reviewing knowledge of nutrient supply mechanisms theorised to be affecting nutrient uptake.

3. Examining the application of theory in models and management strategies for controlling site productivity.

The workshop commenced with a field tour of research projects and forestry operations in the North Island of New Zealand, followed by technical sessions involving oral presentations, posters and discussions. The proceedings will be published as a special issue of the New Zealand Journal of Forestry Science. A summary of the main contributions is provided here.

Session 1: Plant Nutrient Uptake and Use

Various aspects of the dynamics of nutrient uptake and use by forest species were addressed in presentations by Dr Tom Ericsson (Swedish University Agricultural Sciences), Dr Tom Gower (University of Wisconsin), Dr Mike Proe (Macauley Land Researh Institute, Scotland) and Dr Neil Foster (Natural Resources Canada, Sault Ste Marie, Canada). Dr Ericsson drew attention to processes which occur within plant tissues once nutrients have been absorbed to establish a basis for explaining relationships between nutrient status and growth. By comparing the nutrition of numerous contrasting tree species grown in solutions under controlled conditions, Dr Ericsson and his colleagues have shown that there is a consistent trend in element ratios. They have also found similar relationships between growth rates and internal nutrient concentrations. Species therefor appear to differ more in the efficiency with which they acquire nutrients, that is, the efficiency of uptake under fied conditions, than in their internal physiological requirements. Understanding controls over these processes may help understand what happens in the field situations.

Plant growth responses to nutrient stresses vary according to the element(s) concerned due to interactions between nutrient supply and carbon allocation (the distribution of carbohydrates assimilated during photosynthesis). Dr Ericsson showed that under controlled conditions, plants preferentially allocate assimilates to roots when nitrogen, phosphorus and sulphur are limiting, and this reduces the rates of above-ground growth. But the reverse occurs when potassium, magnesium and manganese are limiting. In this case, carbohydrates accumulate in above ground tissues at the expense of root growth, and the capacity for nutrient uptake is reduced further, perhaps eventually resulting in mortality.

For individual species, interactions between nutrients and carbon under field conditions change during stand development. Net primary productivity (NPP) peaks then declines (as the energetic cost of accumulating structural materials increases), and internal redistribution of nutrients reduces the demand placed on soil supplies to meet nutrient requirements for growth.

Comparing species under field conditions is more difficult than laboratory conditions because species differ in the rate at which these processes are changing, which is related to species longevity, and because environmental factors, particularly light, have a major effects on growth rates throughout stand development. When carbon and nutrients accumulation are examined together, the available data show that the efficiency of nutrient use for biomass production increases as stands age because carbon continues to accumulate, largely in stems, while nutrients are being recycled from senescing tissues (foliage, heartwood) to new tissues. Under limiting nutrient supplies, nutrient use efficiency also increases; more biomass is produced per unit of nutrient taken up from the soil, but growth rates are reduced.

Dr Ericsson's review suggested broad differences in the efficiency of nutrient use between the major groups of trees - conifers, deciduous broadleaved and evergreen broadleaved trees. Deciduous species are highly productive but more nutrient demanding than the other groups of trees. However, broadleaved evergreen trees, particularly the eucalypts appear to be more more nutrient efficient at comparable growth rates and an be very productive under the right conditions.

Dr Gower focused his presentation on field experiments rather than laboratory studies in considering the effect of nutrient availability and leaf longevity on nutrient uptake and use by temperate conifers (red pine, ponderosa pine and Douglas-fir). His studies involved nitrogen fertilisation to modify nitrogen availability. He found that more N was retranslocated from senescing foliage of fetilised trees compared with controls but there was only a weak relationship between retranslocation and above-ground NPP. Redistribution of N at the stand level (kg N/ha/y) was also higher in fertilised trees. Nitrogen use efficiency (NUE = above ground NPP/N uptake) declined within increasing N supply and with increasing litterfall N.

Under controlled, experimental conditions, Dr Gower found higher N uptake and higher instantaneous NUE in new foliage (= P_S/leaf N) of deciduous species compared with the evergreens. The results suggested that under controlled, that is comparable nutient conditions, deciduous species were more efficient than evergreen species at using nitrogen although this goes against conventional wisdom regarding the growth of evergreen and deciduous species. Dr Gower pointed out, however, that in nature, deciduous species typically occur in more fertile soils than evergreen species, and under such conditions all species are less efficient. The effetc of fertilisation on leaf longevity was consistent with this in that N fertilisation decreased leaf longevity, thereby shifting evergreen species toward a more 'deciduous' nature.

Dr Foster compared patterns of nutrient uptake, retranslocation and nutrient use efficiency as a function of stand age in Jack pine forests of differeing site quality. His examination of changes in leaf nutrient concentrations, rates of nutrient accumulation in the above-ground biomass, and nutrient use efficiency showed that internal processes change markedly during stand development and stressed the importance of comparing stands of similar age when examining these processes. It seemed relavant (to me) to consider both the age and stage of development.

A peak in nitrogen use efficiency at around 35 years for the stands investigated suggested that nitrogen supplements would have enhanced growth rates at this time.

The importance of nitrogen derived from retranslocation increased substantially with increasing age meeting 35 % of annual requirements in younger stands and more than 65 % in older stands. Retranlsocation (as a percentage of canopy N and P) did not vary across sites of different quality, but the absolute amounts retranslocated were higher in the highest quality site, as were uptake and annual nutrient requirements.

Dr Proe investigated links between nitrogen and carbon uptake and accumulation. He used controlled glasshouse studies and labelled nitrogen to trace the movement of N within sitka spruce plants. He found that uptake and growth were 'uncoupled' during spring growth, when most of the N required was supplied by N remobilised from elsewhere in the plant, whereas N uptake from the soil became more important later in growing season. The amount of N remobilised in the current growth period depended on the the amount of N stored from the previous growing season and not on the current levels of N supply. Tree size affected the capacity to store nitrogen as larger trees had more sinks for storage. In a operational (fertilisation) context, the results suggested that N absorbed will be stored in available tissues - wood, then foliage - and both the amount of N stored and the timing at which it becomes available will affect growth in subsequent seasons.

It was difficult to transfer the information presented in this session to field management situations, though there was a view that tracking internal nutrient movements may be useful for assessing if nutrients were in adequate supply. The data on nutrient retranslocation, however, suggested (to me) that the capacity of woody plants, to remobilise large amounts of their accumulated nutrients and to store large amounts after fertilisation, provides substantial flexibility for plantation managers with regard to nutritional management, providing they understand the processes involved.

Session 2: Nutrient Supply and Uptake

Dr Nick Comerford (University of Florida) reviewed nutrient uptake from the perspective of factors involved in getting nutrients into the roots. The main factors involved in uptake are the availability of and characteristics of the absorbing surfaces (roots, mycorrhizae) and energy demanding processes of transport across the root membranes. The effectiveness of roots/mycorrhizae depends on the surface area available, particularly the root zones with the highest absorption capacities. The rate limiting process for ion uptake, however, is frequently the availability of ions supplied through mineralisation or inorganic equilibria although contact between roots and soil, strength of the uptake 'sink' relative to the supply and the spatial distribution of roots are also important. Roots can also affect uptake processes, for example, through the production of phosphatases.

In natural conditions it is common to find nutrient depletion zones around roots, particularly for ions with low diffusion rates such as phosphorus and ammonium. Dr Comerford stressed the importance of competition between roots due to clumping which effectively reduces uptake. However, a point not made by Dr Comerford is that roots continually grow to nutrient sources (providing that carbon is available from above-ground). Hence, the new surfaces are key sites for uptake. If root growth is not impeded by compacted, or water logged soil, then uptake is unlikely to be impeded unless roots cannot make contact with soil particles. Drought and nutrient availability will affect growth, the concentration of nutrients in the soil solution and the rate of nutrient uptake, however.

Changes in soil physical properties changes induced by harvesting, and which could affect nutrient uptake, where addressed by Dr David McNabb (Alberta Environment Centre, Canada). The important processes to considered were shear strength, gas diffusion, water flux (the potential and volume of water availability) and heat flux (important in cold regions). Dr McNabb focused on shear strength and diffusion, initially establishing the important role of soil moisture and mineralogy in determining responses to compression and shearing forces. Soil properties such as bulk density, macro pore size distribution, and penetration resistance are all affected by soil moisture, and the effects are related to clay content. Clay particles are covered in a layer of water which reduces the level of particle to particle contact compared with sandy soils. Hence, measures of soil compaction and changes due to harvesting should only be carried out under standardised moisture conditions.

Air filled porosity is an appropriate surrogate or index of gas diffusion, which is a critical property potentially affecting the supply of nutrients and water, particularly in soils which may become water logged. Dr McNabb stressed that we need to determine and assess the critical processes on a site-specific basis. While there was a general appreciation of the importance of soil physical properties among the workshop participants, it was quickly pointed out that we do not have threshold values that can be used to indicate when tree growth will be affected, and to what extent. Some experimental trials have been initiated in the USA with the objective of generating empirical relationships between growth and critical soil properties, but given the complexity of soil factors involved, considerably more work is required in this area. There is little data available to develop threshold values for Australian forest soils and species. Soil models are limited at this stage by the lack of an acceptable theory relating soil porosity, soil strength, moisture and mineralogy.

Session 3: Application of Theory in Management

Two papers addressing management were presented: an agricultural perspective in applying theory to management in New Zealand, by Dr Ian Cornforth (Lincoln University), and a review of nutritional management in Australian plantation forests, which I presented (see Appendix 2). In summarising the various fertiliser regimes which have been adopted across Australian plantations, I attempted to identify the main factors affecting fertiliser practices, particularly treatments applied at and following establishment (e.g. soil texture, climate, inherent fertility, nutrient retention capacity, nutrient deficiencies, silvicultural practices including weed control and cultivation). Fertiliser treatments in Australia are still largely empirically determined, but have evolved from an understanding of a soil nutrient supplying and nutrient retention characteristics and are targetted at periods of high nutrient demand during stand development. There has been little direct application of information on nutrient uptake rates in the development of fertiliser practices.

In addition to the natural cycles of elements via plant uptake and decomposition, grazing in pastures introduces another mechanism of nutrient cycling, uneven redistribution of nutrients in animal wastes, leaching, and loss in animal products. Dr Cornforth presented a nutrient response curve relating relative pasture yield to nutrient supply from soil and fertiliser inputs, which formed the basis of a simple model to predict long-term fertiliser requirements to maintain the system. Accurate short term predictions are not feasible, but soil testing provides short term corrections to the model. The model is based on the notion that the size of the cycling pool of nutrients should remain reasonably constant if production is to remain constant. Hence fertilisers should be applied to replace depletion from the cycling pool. It is assumed that nutrients derived from plants and dung have the same value as nutrient derived from fertiliser, that there is no nutrient loss if there is no production, and that total nutrient losses are related to pasture production on a diminishing returns curve. This model has been tested over a range of sites. For individual farms, fertiliser requirements are predicted using animal stocking rates and pasture production requirements with reasonable success.

The time frames of pasture systems and plantation systems differ substantially, both in terms of crop turnover and frequency of fertilisation, but the conceptual model presented by Dr Cornforth is generally applicable to both management systems and would be interesting to consider the model's value for predicting fertiliser requirements in plantations.

For radiata pine plantations growing on the sandy soil systems in southern Australia, Dr Clive Carlyle (CSIRO Forestry) presented results of an interesting trial examining the effects of residue retention after thinning and fertilisation on N uptake and growth. In sandy soils there is a high potential for N to be lost through leaching after harvesting, particularly clearfelling, because the process of nutrient uptake is interupted. After thinning, however, Dr Carlyle found that uptake by the standing trees was equivalent to uptake by an unthinned stand. When harvest residues were retained, uptake over several years following thinning was greater than in unthinned stands, and in stands with residues removed. This occured because some of the fertiliser N was initially immobilised in organic residues, subsequently released through decomposition and absorbed by the trees. Where thinning residues were removed, the pulse of higher uptake after fertilisation was relative short and not much different if 200 kg N or 400 kg N were applied. Much of the N was lost through leaching. Dr Carlyle suggested that these results indicate that in sites with low nutrient retention capacities, such as the sandy soils in southern Australia, there is scope for manipulating the N supply in thinned stands via residue management. Fertiliser could be applied at times when uptake will be high, perhaps even prior to thinning, and the slash retained from harvested trees would be a source of 'slow release fertiliser'.

General Comments

One aspect of nutrient aquisition and use which was not specifically addressed in the presentations, but which came up in discussions, was genetic variability. There is increasing evidence showing that there are family differences in tree nutrition. It is likely that the efficiency of nutrient uptake or nutrient use could be enhanced through genetic improvement. Family differences in nutrition are currently being assessed in trials being carried out by the Forest Research Institute in New Zealand. Plantations of mixed genetic material are managed according to the average growth response to silvicultural treatments such as fertilisation. It is conceivable, however, that in a clonal system all individuals would be capable of the better response. If there is significant genetic variation in tree nutrition and foliage nutrient status, it has implications for diagnosing nutrient deficiencies (averages are now used) and the value of critical concentrations determined from stands of mixed genotypes. It also provides greater scope for managing stand nutrition.

As in other IEA meetings the general workshop discussions addressed the broad question of harvesting impacts and environmental concerns in addition to questions about nutrient uptake. It has become increasingly evident from field trials that we cannot make broad generalisation about the consequences of harvesting. The effects of removing whole trees as opposed to removing stems only vary across sites and appropriate management decisions will also be site dependent. The important factors involved, which are thought to include for example, site fertility and the relative amounts of the nutrient pool tied up in organic matter, are currently being investigated in some long-term harvesting trials. However, trials are required over a broader range of sites to provide a basis for extrapolating findings. There is a need to quantify the effects of harvesting and to develop response surfaces, and models to improve our ability to predict those sites where organic matter removal and soil disturbace will be a problem.

The brief summary of papers presented here covers key points raised in major presentations and group discussion. The full workshop proceedings will be published as a special issue of the New Zeland Jounral of Forestry Science.

Future IEA Activities

There is sufficient demand for timber as energy within the IEA member countries that the future scope of this Activity group is being broadened to directly consider impacts of intensive harvesting systems, that is, whole tree harvesting. Its aim will be to "evaluate the environmental consequences of intensive harvest systems and to develop guidelines to ensure the environmental soundness of such systems". The specific objectives will be to:

"a) to investigate and characterise the environmental consequences of intensive biomass systems, including ecological balances, diversity, and conservation.

b) develop guidelines for the development of bioenergy technologies"

WORKSHOP ON DIAGNOSING NUTRIENT DEFICIENCIES IN PLANTATION FORESTS

Plant nutrient status is used to indicate whether nutrient supplies are adequate to maintain growth rates, particularly in managed, plantation forests. Acute deficiencies usually result in visual symptoms but sub-optimal supply rates can reduce productivity without any visible symptoms. This means that we have to be able to detect limitations before visual symptoms appear to avoid productivity decline.

This workshop provided a forum for assessing methods of diagnosing nutrient deficiencies in managed plantations forests. The objectives were to:

1. Present methods for diagnosing nutrient deficiencies in commercially important tree species.

2. Examine the status of information systems for predicting potential nutrient deficient sites.

3. Assess the possible implication of changing species/breeds on nutritional management strategies.

The technical sessions were complemented by a field tour of the Central North Island volcanic plateau radiata pine plantations around Rotorua. We were introduced to nutritional problems and forest management in this area of New Zealand.

The main emphasis of the technical sessions was on individual presentations related to techniques for diagnosing deficiencies in a variety of forest species including radiata pine, loblolly pine, eucalypts, sitka spruce, and norway spruce. There seemed to be an unstated assumption that current methods of diagnosis are not satisfactory, since all the presentations offered new alternatives. Some options were not widely tested and others were still in developmental stages.

Foliage analysis is the most commonly used method of diagnosing nutrient deficiencies prior to the onset of visual deficiency symptoms. Critical levels have been identified for common plantation species based on nutritional data bases of varying quality. For new species, including most of the plantation eucalypts currently being established in Australia, there is little if any data including foliar nutrient concentrations to draw on for the development of diagnostic criteria. However, even for those species for which we have substantial data, such as *Pinus radiata*, there are some doubts about the value of foliage analysis. For example, the nutrient status of plant tissues changes with age; the concentration of mobile elements eg. nitrogen is usually highest in the first couple of years after planting and declines thereafter. Our data on critical levels are not age-based; they have largely been developed for young stands prior to crown closure, as this is the period of maximum nutrient demand. Fertilisers obviously can change nutrient status markedly, but even with regular treatments, it has been found that foliage concentrations will decline to levels below the critical concentrations despite the fact that trees are growing vry rapidly. In some situations the standard criteria do not appear to be meaningful.

Climate, particularly rainfall, also has an marked effect on foliage concentrations, resulting in annual fluctuations. For several elements including phosphorus and boron it is necessary to take rainfall in the previous growing season into account when interpreting nutrient data.

Dr John Raison (CSIRO Forestry) suggested that information on plant water status could be used to infer plant N status. For *P. radiata*, a water stress integral (previously developed by B. Myers, CSIRO) based on temporal integration of pre-dawn leaf water potentials reflects both water and nitrogen status. When water is not limiting, the water stress integral is inversely related to mean annual litterfall nitrogen concentration, and litterfall N is closely related to N availability. Dr Raison also suggested that litterfall N could be used to indicate N uptake since there appear to be linear correlations between these parameters, but caution from others was suggested in this regard, since contradictory pattern have also been found for *P. radiata*.

Techniques based on litterfall N would integrate N supply information over a whole stand (spatially) and over time. It would it would be relatively time consuming and labour intensive though freshly fallen needles could be collected from the ground during the period of peak litter fall. The water potential technique could be used when trees are not water stressed, but it would be difficult to implement operationally.

Alan Thorn (NZ FRI) suggested using multi-spectral image processing techniques to detect nutrient deficiencies, and presented data showing a negative linear relationship between leaf reflectance and foliage nitrogen concentration. The work was based on glass house trials and still requires field testing, but like Raison's water potential approach, the techniques depends on plants not being water stressed, since the required signal can only be detected under non-water limiting conditions. If multi-spectral scanning proves to be satisfactory, the data could be captured remotely which would greatly increase the aerial coverage and potentially reduce the processing time required.

Dr Peter Beets (NZ FRI) discussed a problem of element interactions which appears to be confounding diagnosis of nutrient status in older stands of *P. radiata* suffering from "upper mid-crown yellowing". This problem is related to magnesium supply to the foliage, and the ratio of K to Mg appears to be a more suitable diagnostic tool than magnesium concentrations alone. High levels of K relative to Mg (rather than low Mg availability per se) appear to inhibit the transport of Mg from roots to foliage. Some sites affected were previous pasture which received potassium fertiliser supplements but second rotation stands are also affected on sites where the first rotation was not affected.

The problem presented by Dr Beets raises a question about what a nutrient 'deficiency' actually means and highlights the problem of using concentrations of individual elements for diagnosis. This work is still in the research phase and has a strong focus is on visual symptoms, which require aerial reconissance to be detected. Of major interest in this work is the heritability of "apparent magnesium deficiency".

Another proposed alternative method for diagnosing nutrient deficiencies involves using labelled elements and bioassay procedures. Dr John Dighton (Merlewood Research Station, U.K.) suggested using a root bioassay to integrate plant demand and soil nutrient supply, usingthe rate of uptake of ^{32}P by exercised roots. Once trees get large foliage sampling can be difficult and in fast growing eucalypt plantations for example, this can be a problem even in young stands. In the field it would be necessary to fertilise small plots of trees in areas where diagnosis is required and after a week or two the root bioassay would be conducted. The magnitude of the difference in activity between fertilised and unfertilised roots would be the main criteria assessed rather than the absolute values obtained.

Other contributors also discussed the use of ^{32}P (Janet Dutch, The Forestry Authority, U.K., and Marianne Clarholm, Swedish University Agricultural Sciences). Dr Dutch showed results of a trial to assess the potential of foliage analysis and root bioassay methods to predict growth responses of sitka spruce to P, N and K fertilisers. The conventional foliar analysis method indicated that P was deficient and N levels were marginal, while he root bioassays suggested that P and K were limiting. The fertiliser trial only showed a growth response to P. Clearly the root bioassay was not an improvement on foliage analysis in this case.

Only one contributor (Dr Steven Colbert, North Carolina State University) addressed the difficulty of predicting the *magnitude* of a growth response to fertiliser addition. He reported work concerned with improving the efficiency of mid-rotation fertilisation in loblolly pine plantations after thinning. While we can predict with reasonable confidence from foliage analysis data that there will be a growth response to fertiliser after thinning, the magnitude of the response varies with specific site and stand conditions. Dr Colbert and his colleagues have developed a model based on stand leaf area index (LAI) as a surrogate for productivity, as LAI is closely related to volume growth. Foliage N is less clearly related to volume production than LAI, even when N is the primary limiting element. Low LAI therefore can indicate a likely response to fertilisation The fundamental relationships in the model are developed from standard fertiliser trials. There does appear to be considerable potential for this conceptual model to be used more widely.

Dr Don Mead (Lincoln University) presented an expert system for estimating deficiencies in *P. radiata* using the conventional approach. It uses a "Windows" environment and is linked to data bases and spread sheets. This system uses foliage analysis information, soil data and visual symptoms to predict the probability of particular element deficiencies. The system is also programed to provide background information to the problems identified. It is limited by the currently available knowledge for *P. radiata* but this type of system would enable plantation managers to interpret the analytical results obtained from commercial laboratories with reasonable confidence. In the final analysis there was no clear alternative to foliage analysis as a diagnostic tool for plant nutrient status and several limitations of approaches being suggested as alternatives were identified. Much more basic research is still required, including thorough evaluation of the utility of foliar analysis.

TREES AND SOIL WORKSHOP - DESIGNING LONG-TERM TRIALS

A common question asked about plantation forests is whether or not they are sustainable. Plantations usually contain exotic species and there is much speculation about the effects of exotic trees on soils and about the implications of any changes in soil properties associated with different species. Because there are limited instances in which the arguments can be quantified, it is essential that field trails be designed which can address the question of long-term sustainability.

The objectives of this workshop were to:

1. Review experiences with trials designed to examine tree species effects on soils

2. Produce a protocol or guidelines for designing experiments to compare effects of trees on soils.

In establishing the focus and need for this workshop, Dr Don Mead (Lincoln University) identified the kinds of limitations which have influenced much of the work on effects of exotic species on soils. Of some concern are the conclusions drawn from studies carried out on sites where historical information has been lacking, as often happens in chronosequence studies. In many cases the question of species effects has been addressed retrospectively; controls were often inadequate and variations in underlying geology have confounded results.

These problems were developed further in an excellent review by Dr D. Binkley (Colorado State University) of the current knowledge regarding tree species effects on soils. An important point raised here was that previous investigators' initial preconceptions of species effects have influenced the questions addressed and both strongly influence the outcomes. "Understanding of the effects of species on soils has been heavily clouded by premature inferences based on limited information, and the unwarranted extrapolation of the inferences". Furthermore, there seem to be many instances in which soil changes eg. a decrease in pH have been considered in isolation and, assumed to indicate "degradation"; the implications of complete suites of effects in general have not be considered objectively. "No studies have shown that any species uniformly pushes all soil variables in unfavourable directions". To overcome these problems, questions about species effects need to be tied to specific soil properties or processes, and in terms of the workshop objectives, to the question of whether changes in these factors affect the sustainability of tree growth.

Binkley's review of species effects was developed around a conceptual model which is depicted in Figure 1. Trees "filter" inputs to the system such as dry and wet deposition and alter the rate at which these materials reach the soil. Trees and soils are interactive; trees provide organic matter both above and below ground while absorbing water and nutrients for plant uptake. Organic matter provides the food for soil organisms which eventually provide the essential nutrient resources for plant uptake. The role of trees in determining the nature and activity of the soil community is not altogether clear, but there is some indication that decomposer organisms may be adapted to specific litter types. Trees may also affect soil physical properties by altering soil temperature, moisture and aeration which in turn can affect organic matter turnover. There are many studies which provide examples of differences in soil properties under different species. There are fewer examples demonstrating changes in soil properties due to the planting of exotic species. Furthermore, 'management' effects may exceed those due to the trees per se. Long-term consequences have not been addressed to any great extent, particularly in terms of sustaining the growth of the species of interest through successive rotations under specific management regimes.

This theoretical foundation was supported by other presentations, several of which provided good examples of the limitations identified by Mead and Binkley. During the remainder of the workshop, the participants discussed the key factors to be considered in developing a suitable experimental design.

Dr. Mead had both a specific and general objective in mind in organising this workshop. He wanted to draw on the collective expertise of many scientists to consider the fundamental issues, and to do so with a trial(s) in New Zealand, particularly in the Canterbury Plains, in mind. This influenced some of the detailed design considerations.

We discussed several topics: trial objectives, site selection, tree species selection, experimental design, measurements, cost control and timelessness, and stand management. The major points raised and some important issues which arose in these discussions are summarised below. The group decided that in order to focus on the science, it was necessary to overlook practical and financial considerations in the first instance, while recognizing that they would ultimately limit what could be achieved.

Research Objectives:

During the discussions it became more and more apparent that there could be a variety of specific objectives in this type of investigation, and that one's bias in this regard had an overwhelming influence on all other considerations. Two different views positions emerged, separated according to ones perceptions of the importance of forest management in the fundamental question of species effects on soils. The group which felt that management practices were important argued that the objective would be to assess the effects of species and associated (alternative) management impacts on soils and long-term productivity. The non-management group, had a more ecological perspective, and argued that the objective would be to find out if plantations of exotic species *per se*, including a broad range of plant characteristics, could be sustained, independent of management practices.

Two other issues also divided the group: firstly, the impacts of understorey species, and whether or not they should be explicitly included in the design; and secondly, the definition of an experimental 'baseline' situation, which is tied to the understorey issue because some sites selected for a trial could have existing understorey species.

Moreover, keeping track of changes in the 'original' site could mean that the original land use and management regimes would have to be maintained. In the Canterbury regions of N.Z. this would mean maintaining pasture as the baseline site condition, perhaps to the extent of continuing sheep grazing. However, the majority of N.Z.'s pine plantations have not been established on pasture country. This problem was not resolved, in part because there was no consensus on the basic objectives. but it was clear that measuring temporal was important in both the original and experimental sites.

Site Selection:

Given the potential for site factors to influence species-soil interactions, it was agreed that a "species effects" trial should be installed over a diverse range of sites, and that site factors needed to be analysed in some detail before the final selection. A response surface could be developed from a matrix of key soil and site factors which affect productivity. Important factors include landscape position, mineralogy, soil texture, precipitation and temperature regimes, soil moisture characteristics, initial vegetation, including species composition, above- and below-ground biomass. A GIS would be an essential tool for selecting appropriate sites.

Tree species selection:

There are numerous plant characteristics which could have differential effects on soil properties: leaf litter 'quality' and carbon chemistry, deciduous/evergreen habit, leaf area index, moisture use patterns, root distribution, nutrient use efficiency, nutrient accumulation characteristics, N-fixation capacity, leaf longevity, and foliage effects on rain interception and stem flow.

Some species may be 'politically' interesting. Potential species need to be considered with an open mind and futuristic approach, particularly given the rapidly changing environmental and political scene against which production forestry is examined by the public. This issue highlighted several preconceptions about the future directions of plantation forestry. The two extreme positions were a) that monocultures of commercial species would continue to be the cornerstone of plantation forestry in much the way they are at present in NZ and Australia and b) that public concerns about biodiversity will see mixed species operations, possibly including understorey species replace monocultures in managed forests including plantations. An increase in the demand for timber as a source of energy could also affect species selection. Trial designs which are flexible enough to consider future issues are more likely to remain relevant over the long term.

Genetic material affects species performance and hence would probably affect species effects on soils. But the effect of plantation management on soil properties could be larger than subtle effects anticipated with genotypic variation, except where there is a substantial growth effect among genotypes.

A core group of species could be established at all sites with a sub-set of additional species on a broader range of sites. Some of the species suggested for a trial in New Zealand were:

Radiata pine - evergreen, important commercially into the foreseeable future,

Poplar - deciduous, "high" quality leaf litter

Eucalyptus (nitens?) - evergreen

Douglas-fir - high leaf area index

Acacia (melanoxylon?, mearnsii?) - N-fixation, potential for species mixtures

Larch - deciduous, high N turnover

Cupressus

Rimu - N.Z. native, grows on wide range of sites

How the stands are to be 'managed', if at all, also needs consideration before a trial is established. A species effects trial is not the same as a management trial yet the stands have to be managed with the best available knowledge while minimising the intensity of management impacts such as heavy equipment loads on soil.

Other questions were raised but not resolved: Should the trees be grown under realistic management regimes with the objective of producing the optimum wood product for each individual species concerned ? eg sawlogs for *P. radiata*; how important is the extent to which we can define the 'best management practice' for each species ? We can do this with confidence for *P. radiata* but not for most other species; should the design include the option to test species x management interactions?; what stocking regime(s) is optimal to test species effects ? should it be constant across all species ?. One option is to aim for full site occupancy in 5 years to push the site x species interaction, and thin to achieve final stocking levels at 10 years. How will different species rotation lengths and longevity be managed in the long term design? How would nutritional requirements be managed ? If pasture is used as a control it would need to be fertilised to be sustained as pasture which implies that the trees should also be fertilised, yet their nutrient requirements would differ from the pasture if 'best management practices' were adopted.

Experimental Design:

Factors to be considered include:

(i) number of sites

(ii) number of species

(iii) experimental controls

(iv) size of plots

(v) treatments

(vi) controlling costs

(vii) planning for timelessness of the design

(i) *Sites and species.* If the species effect is expected to be significant and consistent across sites, it would be better to maximise species selection and minimise the number of sites. However a consistent response is unlikely due to differences in each soil's capacity to buffer against change. Nevertheless, work load will probably be a significant constraint on the number of sites selected. It may be possible to install the trial at two or possibly three sites considering the practical work load involved in establishment and subsequent measurement. Replication within sites is important to detect significant changes in soil properties and sufficient attention should be given to measuring initial condition to enable covariance analyses to be carried out. This approach seem preferable to 'blocking'. Some participants considered that one would need a minimum of four species to test a species effect on soil properties.

(ii) *Controls.* If pasture is the baseline condition, there may be a need for a grazed control and an ungrazed control. Pasture control should be on northern side of the trial.

Much of NZ forestry is not based on pasture as the previous land use. If pasture is used as the control, then one must ask about the broader relevance of the trial. How important is the initial condition in the long term if species effects are significant ? (We don't know enough to answer this)

(iii) *Plot size.* Minimum of 0.25 ha if future split-plot treatments are desirable. Large buffers are essential, more so in sites where lateral roots development may be considerable; 20 m buffer in sandy soils, 10 m buffer in clay soils.

(iv) *Other treatments besides controls.* Species could be mixed in mosaic designs rather than in alternating patterns. Species mixes could be chosen specifically on the basis of their potential to be successful (some would not be sustained due to competitive effects), or their potential usefulness eg acacia with eucalyptus. One could consider harvesting the acacia as a short term crop and using this as part of the thinning regime although in this case the mixed species option would not be long-term.

Buffers could be useful to testing mixed species effects if it is not possible to test these explicitly due to practical limitations on the experimental design.

(v) *Cost control*

Considerations of costs should not compromise the experimental design. The primary requirement is to make sure the conceptual model is rigorous, then identify the potential main effects to prioritise resource allocation. Use the model to identify the main processes that are likely to be affected but as mechanistic studies are expensive, wait until significant changes in major soil properties are detected before process studies are initiated.

(vi) *Timelessness*

Include extreme treatments.

Make sure the trial has low maintenance requirements.

Allow for new hypotheses to be tested by making plots as large as possible.

Set up a trust to ensure that the trial is ongoing and independent of the comings and goings of individual researchers and political influence.

Measurements:

Measurements are required before the trial is established (some of them would be covered in site selection) and after trial establishment. A protocol would be developed for periodic measurements and sampling/analysis of microclimate, stand and soil attributes. Samples would need to be archived to provide the option for additional analyses.

Repeated site measurements may be required (for how long?) to provide an estimate of background variation, but in part this is addressed by having appropriate controls. Appropriate spatial and temporal scales for sampling and ***in situ*** measurements need to be determined before the trial is established and reassessed afterwards in case they need to be changed once plantations have been established.

A number of factors were suggested for measurement but the options are considerable and no consensus was reached. The relative importance of some factors could vary according to site and species and would need to be considered in this context. It would be easy to get carried away with measuring, which is a very costly exercise. Climate data need to be measured continuously, whereas state variables need periodic measurement - the time frame (annual? 5 years?, 10 years?) will depend on the time frame over which directional changes are likely to be detected. We need to be somewhat circumspect about measuring processes and work within the context of the trial objectives. If the basic design is sound, other scientists and students would most likely become involved in measuring some of the more detailed processes and participate in ongoing studies.

Some measurement options include :

aerial climate factors (rainfall, throughfall, temperature, light penetration).

water chemistry (rainfall, throughfall, soil leachate)

forest floor mass and composition, nutrient content , carbon chemistry, N mineralisation characteristics

standard soil fertility parameters (pH, organic matter, base saturation, nitrogen, phosphorus etc)

soil physical properties (strength, texture, moisture availability characteristics, soil displacement), focus on attributes which may be affected by species

biological attributes (earthworm activity, soil enzyme activity)

vegetation attributes (height and diameter, leaf area index, biomass and chemistry, species abundance (in mixes), understorey biomass and composition, litterfall mass and chemistry

Conclusion:

In the final analysis, it was clear that most if not all participants arrived with preconceived notions about important design features and were exposed to a diversity of alternative views. It was clear that all dimensions of this type of trial are critically tied to the objectives, which need to be very clearly identified as the first step. Long-term funding and management is critical to success; a trust with significant financial resources, such as at Rothamstead in the UK where experiments have run for 150 years, is required for continuity. To remain relevant, there is a need for forward thinking and a consideration of issues which could be important to future generations will help to ensure that a "species effect" trial can be maintained long enough to determine long-term impacts. It is to be hoped that some "species" trials could make a valuable contribution to the assessment of plantation forests as sustainable operations and to examine the current dogma that exotic species degrade soils.

REPORT ON INTENSIVE HARVESTING TRIALS IN NEW ZEALAND RADIATA PINE PLANTATIONS

Since the mid-1980's, several intensive harvesting trials have been installed in Radiata pine plantations in various regions of the North and South Islands of New Zealand by the Forest Research Institute. Their objective is to investigate the effects of harvesting intensity and site preparation intensity on second rotation productivity. The basic hypothesis being tested is that harvesting and site preparation operations which remove substantial amounts of organic matter have the potential to lower soil productivity. (Soil productivity means the potential to produce plant biomass, and is therefore indicative of forest productivity)

During the course of this study tour I visited each of the six trials in N.Z., which increased my appreciation of the importance of various treatments being evaluated and helped me to appreciate some of the difficulties involved in establishing this type of trial. I have summarised key features of each trial below.

The six trials have similar objectives but they are not identical as local practices and concerns vary across the range of site types being managed. Local timber companies were involved in the design of trials within their plantations and made a substantial contribution to the research by carrying out the harvesting operations and preparing the sites for planting.

The trials fall into two groups: one group includes two trials in the South Island under the management of Dr Peter Clinton; Group 2 includes three trials in the North Island and one in the South Island, managed by Dr C.T. Smith. They have been established across a variety of soil parent materials at different locations because soil physical and chemical properties were expected to influence the growth responses to harvesting and site treatments.

Group 1 Harvesting Trials:

These trials were established in 1989 (planted in 1990) and have the same design. One is located in Berwick Forest near Dunedin and the other in Bernham Forest near Christchurch. The main treatments test the impact of harvesting intensity and organic matter removal. The plots are clearfelled with a) stems only removed, b) whole trees removed (stems plus crown), and c) whole trees plus the forest floor removed. Since the objective is to evaluate the impact of removing organic matter and nutrients therein, harvesting was carried out with minimal physical soil disturbance. The trees were hand felled and mechanically lifted off the plots to prevent compaction from harvesting machinery and skidding. This is the major part of the installation process; it is expensive, labour intensive and needs to be well supervised.

The site preparation treatments included a) continuous, and total weed control, b) fertiliser and c) weed control plus fertiliser . Cultural treatments were applied to randomly selected plots in the harvesting treatments. There were no mechanical site preparation treatments in the main trial design. Broadcast weed control is a standard operation procedure in these areas. The soils at Berwick Forest are not routinely cultivated whereas windrowing is standard practice in Bernham Forest. The Bernham trial therefore has an extra, unreplicated treatment to assess the impact of windrowing.

After five years some trends are apparent and some lessons have been learned. Firstly, there has been no reduction in productivity due to organic matter removal and secondly, there are different responses to weed control in the two sites. At Berwick Forest there has been no effect of weed control on growth, which is unusual since weed competition is usually sufficiently intensive to reduce the resources available to young pines. However, rainfall around Dunedin is relatively high so moisture may not have been limiting. In contrast, weed control had a significant effect on early growth in the Bernham trial, located on the Canterbury Plain where annual rainfall is about 600 mm per year. In both trials, the young pines in plots with weed control and particularly in plots with both weed control and fertilisation were very bushy with some multiple leaders. This type of growth form reflects a shift in the distribution of organic matter to branches and foliage at the expense of stemwood production. It occurs on particularly fertile, N-rich soils, and can indicate that there is excess nitrogen in the soil relative to that required by the trees. In Australia, similar growth habits are observed in ex-pasture plantations and other sites where fertilisers have been combined with total weed control.

The other main effect at Burnham is reduced growth in the windrowed plots. Trees in this treatment also have lower foliar nutrient levels compared with non-windrowed plots suggesting that nutrients are limiting compared with the other site treatments. A number of studies in the literature studies report that growth is depressed in the areas between windrows. This effect is attributed to the removal of nutrients in the top soil during root raking and stacking.

Some additional procedural insights have been gained from these trials.

1. The trial at Berwick Forest was not adequately supervised by research personnel experienced in trial installation. This resulted in harvested trees being skidded across one section of the experimental plots. The disturbed area is quite visible 5 years later, and has reduced growth.

2. Routine plot maintenance is handled by the local foresters, but appear not to be of high priority. Hence, weed control treatments are not always carried out on time so there can be irregular cycles of weed growth and decomposition after spraying, which contributes additional variability to the treatments and growth responses.

3. Treatment plots in these trials were 30 x 60 m with a 5 m (1 tree) buffer, which was considered adequate at the time. However, Don Mead at Lincoln University has shown that edge effects can be substantial, particularly in coarse textured soils, and larger plots with wider buffers are now recommended.

4. The trial was planted at the normal plantation spacing of 2 m x 4 m, which is standard practice in most nutrition trials in N.Z.. However, spacing has been

decreased in more recent trails designed to test treatment effects on nutrient supply. At higher stocking levels, site occupancy can be achieved earlier, thereby stressing the nutrient supply more rapidly.

5. All treatments need to be adequately replicated, including the additional "management" treatments. The importance of this is clear in the Burnham trial; here, the one treatment which shows reduced growth rates was not replicated as it was considered an 'add on' treatment for that particular site. It will not be possible to adequately quantify the growth reduction due to windrowing, which is unfortunate since it is the managers' preferred form of weed control/site preparation in this area. Weeds are a serious problem in many New Zealand plantations; gorse and broom in particular vigorously compete with pines, achieving heights of at least 1.5 m.

Group 2 Harvesting Trials:

Like the Group 1 trials, the main treatment in these trials tests the impact of harvest intensity and organic matter removal on second rotation productivity: a) stem only, b) whole tree, and c) whole tree plus forest floor. There are three replicates of each treatment in all trials. The effect of fertilisation (an amelioration treatment) is assessed in a split-plot design in each of the harvesting treatments. Each of the main plots is split into two sub-plots, one of which is fertilised, while the other is left unfertilised. In contrast with the Group 1 trials, where total weed control is one of the treatments, weed control is standard across all treatments since it is has been widely recognised that weed control is required to achieve good early growth rates in most plantations.

The four Group 2 trials have been established on different soil types and different nutritional problems are anticipated in the second rotation stands, exacerbated perhaps by the intensive removal of nutrients in organic residues. The oldest trial was planted in 1986 at Woodhill Forest on the west coast north of Auckland. This is a coastal dune site where successful establishment of the first rotation required dune stabilisation with marram grass and N fixation by lupins (Appendix 3 contains a summary of research being carried out to improve nitrogen management in NZ sand dune forests). The sands have negligible organic matter and nitrogen, although considerable reserves accumulated in forest floor materials (27% total N to 90 cm depth) during the first rotation. The hypothesis in this trial is that second rotation growth will be correlated with harvest intensity. I t was anticipated that productivity would be lower in intensively harvested plots, due to a reduction in N availability following organic matter removal. Nitrogen was applied to the fertilised sub-plots at a rate of 50 kg N/ha (as urea) every 3 months, equal to 200 kg N/ha per year.

Growth results after 5 and 7 years showed that productivity was decreased by removing the forest floor but not by the removal of harvest slash. Forest floor materials contain nitrogen and other elements taken up by the trees and lost in litterfall as part of the natural recycling process. Nitrogen fertiliser increased early growth rates in all harvesting treatments, more than compensating for the loss of N in organic residues. The carbon-rich slash, largely branchwood, was beneficial in the short term because it provided a substrate for microbial immobilisation of fertiliser nitrogen which is readily leached from sandy soils. Only 11% of the fertiliser N was retained following whole tree harvesting (no slash retained) compared with 48% in the double slash treatment. Given that 200kg N /ha were applied each year, this represent a considerable loss of fertiliser and a substantial management cost. It is anticipated that N immobilised in the slash will become available over the longer term through decomposition. Incorporation of organic matter into these sandy soils could also be important for moisture retention. Economic trade-offs between slash retention and fertilisation need to be considered in the longer-term analysis.

The second trial was planted at Tarawera Forest, near Rotorua, in 1989. The soils at this site were derived from coarse scoria pumice gravel associated with the Mt Tarawera eruption about 100 years ago (circa 1886). As with other volcanic soils, these soils are prone to boron deficiency and problems with N and Mg are also anticipated. In addition to the standard treatments, this trial includes a treatment in which the top 10 cm of soil was removed to simulate the effects of windrowing. After 5 years there is no apparent effect of organic matter removal on growth, but fertiliser has increased productivity. The stands will continue to be monitored.

The third trial was planted in 1992 at Kinleith Forest, also near Rotorua. This is on relatively fertile, yellow-brown pumice soils although the problem of upper mid-crown yellowing, which occurs in other *P. radiata* plantations on this soil type, (see Appendix 4) is anticipated. The fertiliser treatment in this trial is a complete fertiliser including urea, superphosphate, ulexite (B) and calcium magnacite. Related studies on the upper mid crown yellowing disorder suggest that there may be an imbalance in the amount of magnesium relative to potassium being transported from roots to the foliage, though the actual mechanism is not entirely clear. Furthermore, susceptibility to upper mid-crown yellowing appear to vary among clones of *P. radiata.* The harvesting trial at Kinleith has been designed to test the growth and nutritional responses of 50 different families to the harvesting and remedial fertiliser treatments. If it can be demonstrated that some of the variation in plant nutrient status is controlled by genetics, it may be possible to develop genetic solutions to nutritional problems on specific sites instead of, or in addition to using fertilisers.

The fourth trial is currently being installed in Golden Downes Forest, near Nelson in the South Island. This site is on glacial outwash gravels, and unlike the other trials is located on steep slopes typical of forest operations in the region. In contrast with the other relatively flat sites, felled trees in this trial are removed from the plots by cable logging to avoid physical damage to the soils. The question of genetic control over nutritional disorders will also be tested in this trial.

As with the Group 1, these harvesting trials have been designed and installed by the Forest Research Institute in cooperation with the respective timber companies. There is a considerable cost to each company in the harvesting operation (which must be carried out without soil disturbance) and plot establishment, which is estimated to cost around $20-$25,000. Several hectares of plantation are taken out of routine operations for the long term, probably several decades. The managers therefore have a vested interest in making sure the design meets their management requirements but it also has to address specific scientific objectives. Improvements identified from the Group 1 and earlier Group 2 trials have been incorporated in more recent trials. In particular, the Group 2 trials are planted at 2 x 2 m spacing rather than a the standard 2 x 4 m spacing to enhance the rate of site occupancy and stress the nutrient supply more rapidly. To keep the stands growing in an open condition, which maintains a demand for nutrients to be supplied from soil reserves, the stocking will be reduced by 50% when the fastest growing treatment reaches crown closure, after about 5-6 years. A second thinning, again by 50%, is planned when the stands are about 10 years old. This will reduce the stocking to 625 stems per ha, which is consistent with the stocking rates in routine forest operations.

Future Harvesting Trials

In addition to soil organic matter content, soil physical properties, particularly the loss of soil porosity are affected by harvesting and may reduce future productivity. Further trials are envisaged to investigate interactions between soil nutrition as a function of organic matter removal and soil physical properties.

A PERSPECTIVE ON HARVESTING IMPACTS ON FOREST SOILS AND PRODUCTIVITY IN AUSTRALIA: THE INFORMATION BASE AND RESEARCH REQUIREMENTS

The alarm was raised over the sustainability of plantation productivity in Australia in the 1960's with the drop off in productivity of second rotation radiata pine plantations on deep sand dune soils in south east South Australia (Keeves 1966). A decade or so later, second rotation plantations in the same region were beginning to outperfom the previous first rotation plantations due in large part to silvicultural improvements which conserved and improved the supply of essential resources. The major changes eventually introduced included effective weed control to eliminate competition for water and nutrients, particularly nitrogen, improved cultivation techniques, and the conservation of forest floor litter and retention of harvest residues previously burned prior to site preparation (South Australian Woods and Forests 1987).

Residual organic matter proved to be an effective mulch which improved moisture retention in a region on the edge of the climatic limits for radiata pine in Australia (Boardman 1988), and provided a source of mineral nitrogen for the young stand. Once incorporated into the soil, organic matter also helped maintain soil structure which has a key role in the maintenance of overall soil function (Sands 1983). Soil physical properties, particularly density, and related properties such as soil porosity, were also found to have deteriorated over time in the S.A. sites. Repeated passes of heavy machinery compacted the sandy soils thereby increasing soil density and strength, and decreasing the size of soil pores which are important for aeration, moisture infiltration and root penetration. Forest productivity reflects the integrated plant response to changes in a soil's physical and chemical environment.

Figure 2 presents a conceptual model of the role of soil porosity and soil organic matter in regulating the processes of site productivity (Powers et al. 990). This model provides the theoretical basis explaining the observed productivity decline in South Australian pine plantations and for speculating that productivity declines may be occurring in response to harvesting over a long time frame in other forest systems. The difficulty is that there is little *direct* evidence of productivity declines which can be clearly linked to changes in *specific* soil properties. But there is considerable indirect evidence supporting the hypothesis that growth declines are likely in response to operations which lead to soil loss, remove organic matter, particularly the forest floor, and result in substantial compaction (Powers et al. 1990). Soil variables which could be used as surrogates for productivity have rarely been calibrated against forest productivity or a site's productive potential in Australia or elsewhere.

Except for the case in South Australia noted above, the evidence that removal of organic matter or impacts from heavy equipment have caused productivity declines are scant in Australia but so too are the number of valid studies on this topic. There are indications that the productivity of second rotation plantations in southern NSW is lower than expected compared with first rotation production, and lower in sites where slash was burned than where slash has been retained and chopper rolled prior to planting. Explaining the trends remains a matter of conjecture because there are inadequate soil data to quantify the *changes* in soil properties in affected sites.

Similar situations may exist or come to attention in other pine regions as the area under second rotation plantings increases. However, most forest agencies managing pine plantations have now adopted the approach of retaining harvest residues, but only where this is practical. It is not feasible to retain slash on sloping sites without gravity rolling systems which permit heavy chopper rolling equipment to negotiate steep grades. Except on steep sites, the practices of broadcast burning and windrow stacking, which have been linked to reduced productivity in other countries, have largely ceased in Australia. Harvest machines have also been modified to reduce physical impacts on soils but may still reduce subsequent growth. Furthermore, there is now a much greater emphasis on ameliorating soil conditions likely to limit growth in plantations; deep ripping, bedding or mounding, fertilising, controlling weeds and using improved planting stock will enhance productivity over and above levels that were possible with the technology available when the previous rotations were established. These improvements could either obscure soil deterioration perhaps even contribute to longer-term improvement in a soil's productive capacity.

The situation in native eucalypt forests is less clear even than in plantations, though there is some cause for concern. To my knowledge there are no records of changes in forest productivity due to harvesting and no studies of harvesting impacts. The level of soil disturbance in managed eucalypt forests is, however, sufficient to reduce growth rates (Williamson 1990, Lacey 1993, Lacey et al. 1993). Unlike plantations, the pattern of disturbance due to harvesting in native forests is more spatially variable ranging from highly disturbed and compacted snig tracks and log dumps to largely undisturbed sites. Harvest residues are usually routinely burned at moderate to high intensities to prepare the soil for the subsequent regeneration of seedlings, and fuel accumulations are routinely burned with low intensity fires to reduce the risk of subsequent wildfires. There is a risk that nutrient loss through burning is exceeding nutrient input in some eucalypt forests, particularly in the less fertile sites. In the most productive of our eucalypt forests (Mountain Ash in Victoria), however, the productivity of logged and unlogged stands was similar after the Ash Wednesday wildfire. Even though all organic matter was consumed at an intensity far exceeding any management burn, fertilisers did not increase the post-burn productivity.

Information pertaining to the potential impacts of forest management on soil disturbance and fertility in managed eucalypt forests was recently summarised in a report of the Technical Working Group on Forest Use and Management for JANIS by R.J. Raison (CSIRO Forestry) and P. Hopmans (Vic. Dept of NR) (Raison and Hopmans 1994). They too noted the paucity of data when it comes to making predictions about potential impacts of harvesting in eucalypt forests. It is interesting that comparable soil quality standards have not been requested for plantation forests in Australia, even though forest operations are more intensive than in most native forests, and generally affect the entire management area. The need will probably arise when EIS's are required for plantation forest operations.

In considering Codes of logging practices, Raison and Hopmans (1994) concluded that they are "largely qualitative descriptions of preferred practices based on general principles of environmental care". The Codes do not contain standards which indicate tolerable levels of change in soil properties or a procedure for monitoring change. One reason for this is that the information is not currently available. Raison and Hopmans stress the need to learn more about what to measure and how to conduct monitoring, while proposing a series of initial standards based on the best available knowledge, professional judgement and standards proposed in response to similar requirements in the United States.

The proposed standards address (i) the allowable area of major soil disturbance, (ii) the allowable change in soil porosity, and (iii) the allowable level of disturbance to forest floor litter and top soil organic matter and (iv) soil erosion mitigation. It is proposed that forestry organisations initially monitor specified soil variables within major forest types and areas selected for monitoring should vary according to the anticipated risks of harvesting impacts. The initial approach suggested follows the "case study" approach suggested by Turner (1993) for research concerning ecologically sustainable management in NSW.

By monitoring changes in soil properties in various disturbance classes, and the area of each disturbance class within routine operations in the case study forest types, forest organisations will develop a quantified 'picture' of harvesting which can be examined in terms of the proposed soil quality standards. Monitoring growth of the regenerating forest in plots located across a range of site types and disturbance areas, will provide a measure of post-harvest forest productivity in response to a range of soil conditions. It may provide information to help develop relationships between soil properties and productivity but this will be difficult because several soil properties will be affected simultaneously within each monitoring unit. Some experimental manipulation of soil conditions is also likley to be required to assist the process.

While it is essential for this type of comprehensive monitoring programme to be initiated across all States to quantify the level of disturbance currently occurring due to harvesting, there is also a need for a program specifically geared to developing relationships between soil properties listed in the standards and productivity. The tolerable level of change in a specific soil property is only meaningful in terms of its impact on forest growth. The standards need to be verified and calibrated according to forest and soil type and harvesting intensity.

An unstated assumption in the proposed standards is that the tolerable levels of change in soil porosity and organic matter translate into an tolerable change (decrease) in productivity. The US Forest Service considers that a 15% change in forest productivity over a planning horizon is the minimum that could be detected with current monitoring methods (USDA Forest Service 1987). The same limitations will apply in Australia. It does not imply that a 15% decrease in productivity is an acceptable practice; it is the minimum change likely to be detectable.

Experimental Assessments of Harvesting Impacts in USA and New Zealand: Research Trial Objectives and Designs

Monitoring soil quality is required by law in the USA and soil standards were developed based largely on professional judgement. To validate these standards, long-term experimental harvesting trials are being installed to test the hypothesis that proposed standards of change in soil porosity, and organic matter are realistic in terms of measurable changes in productivity (Powers 1990). They aim to understand how soil porosity and site organic matter interact to regulate long-term site productivity. A similar requirement for soil monitoring has arisen is Canada and harvesting trials are being installed in Ontario and British Columbia based on the US trial design.

The US trials, known as Long-term Site Productivity trials (LTSP) have been installed by the Forest Service and National Forest System. There are currently about two dozen trials with several replicates in each major forest type. More are planned including several cooperative trials with forest industry representatives. The core design involves 9 combinations of organic matter removal and soil compaction imposed during and post-harvest in a factorial design, to examine interactive effects of these treatments on productivity.

Ideally, each trial is established in previously uncut forest, and the trees are harvested without disturbing the soil. That is, the trees are lifted off each plot, preventing mechanical impacts. The three organic matter removal treatments are: a) bole only harvest, b) bole plus crown removal (whole trees), and c) whole tree plus forest floor removal. The three compaction treatments are a) no compaction other than through human impact, b) mechanical compaction to 85% of the growth limiting soil bulk density at 10 cm depth, and c) mechanical compaction to an intermediate level (between a and b). Each treatment plot (0.4 ha) is split; one half receives total weed control, the other has no weed control. The objective here is to assess effects of inherent soil fertility as well as weed competition on stand productivity. Supplementary treatments, particularly sub-soiling (ripping), and fertilisation are included to examine impacts of ameliorative treatments on productivity and soil properties.

There have been mixed reactions to the trial design, especially by industry. It is not difficult to see that the more extreme treatment combinations are likely to show that site disturbance lowers productivity. This could be misused by some to imply that forest management practices degrade site productivity despite management efforts not only to maintain, but to increase site productivity. The inclusion of mitigative treatments is essential, not only to bridge this gap, but so that their impacts on soil quality are also clearly understood.

A related problem is that some of the trial results seem to be intuitively obvious. We could expect productivity to decline over the long-term with increasing organic matter removal and with greater compaction, based on the conceptual model depicted in Figure 2. However, we don't intuitively know the response to various combinations of these factors, nor their relative importance overall in different soil types in contrasting environments. It is also important to appreciate that the key to this trial design is in the fact that the treatments imposed are the means by which the critical soil properties are manipulated and provide the basis for quantifying relationships between soil properties like porosity, and productivity. Some people have argued that nine treatments will not provide sufficient data points to develop such relationships, but no improvements other than increasing the number of treatments have been suggested. By including several replicates of each trial within each forest type, there is scope for developing relationships based on a large sample size.

Details of the harvesting trials in New Zealand were described earlier in this report. It is important to note here that the initial focus in New Zealand has been on the removal of organic residues as a potential drain of organic matter and nutrients from harvested sites. This addresses the primary concern of the IEA with regard to whole tree harvesting versus stem only harvesting, although as elsewhere, changes in soil physical properties through use of heavy machinery are also of concern. The next phase of the research in NZ is to design trials which examine the interaction between compaction and nutrition/organic matter. At this stage, there does not appear to be a requirement in NZ to develop soil quality standards or to monitor changes caused by forest operations, as there is in USA, Canada and Australia.

The NZ trials also differ from the US trials in that (i) they are limited to second rotation radiata pine plantations; hence, any damage incurred during the first rotation is built in to the base-line soil condition,

(ii) impacts of weed competition on pine growth are well documented and weed control is a necessity to achieve good growth rates; hence weed control is applied to all plots,

(iii) fertilisation is included as an amelioration treatment within the main trial design (split plot treatment), and

(iv) routine management practices are included as supplementary treatments, as appropriate.

While trials differ between countries according to differences in forest harvesting practices, there are common themes. Most importantly, an experimental approach has been adopted in which key soil properties have been manipulated while other have been held constant. This level of control is not possible within routine harvesting operations, although site stratification can be used to relate soil conditions to subsequent growth. Previous IEA activities (Task VI Activity 6) focused specifically on coordinating international effort in research design of field trials and associated soil process studies (Dyck and Mees 1991). Scientists involved in designing the US, Canadian and NZ harvesting trials have all been associated with IEA activities.

Suggested Harvesting Trials for Australian Forests

The National Forest Policy Statement in Australia sets out an agreed upon environmental baseline for forest industries which includes baseline standards for soil quality. The policy recognises that wood products will be derived from "a mix of sustainably managed softwood and hardwood plantations and native forests" (Drielsma 1994), but to date the requirement for soil standards and monitoring is limited to native forests (Raison and Hopmans (1994) report to JANIS). This suggests that initial harvesting trials should be established in native forests, though there is a clear need for need similar information for second rotation pine plantations, and eucalypt plantations.

A substantial difficulty with harvesting trials of the type described in previous sections is the initial cost; in NZ, the cost of harvesting carried out to avoid mechanical damage is around \$20 - \$25,000, and that cost was met by the participating timber company. In the US, the cost of installing a trial involving harvesting and compaction treatments is estimated to be $65,000US, and maintenance costs are about $4500 annually. With this limitation in mind, there probably will be few such trials in Australia. Another problem in eucalypt forests is that there could be a perception that the objective is to study the effects of clearcutting impacts if all trees in each plot are removed, even though clearcutting is no longer practiced in many hardwood forests. The design could, however, be modified to accomodate variations in the degree of cutting.

Candidate forest types should be selected based on their potential risk of harvest impacts; those in which organic matter removal could have a major effect on soil physical properties and nutrient supplying capacity and those where mechanical impacts could be significant. Some forest types may occur on a range of soil types/parent rock types which have different risks of damage - the most important site type relative to the overall forest type would be selected. Forest types which could be considered include the moist hardwood forests (for example, Brown Barrel) in NSW, Blue Gum in Tasmania , Mountain Ash in Victoria and Karri in Western Australia), the sub-tropical eucalypts (for example Flooded Gum), and drier, open forests (for example the coastal mixed species in southern NSW and Jarrah in WA) . Trials in Flooded gum, Blue Gum and Jarrah forests would cover a considerable moisture, forest type, soil type and soil fertility gradients.

One option for harvesting research in Australian forests is to adopt the US LTPS design (interactive model) testing both organic matter removal and compaction treatments. The basic design could be modified to include ameliorative treatments such as fertilisers and the intensity of harvesting could be adjusted. Alternatively, the NZ intensive harvesting trial design (which involves manipulation of only one site component) could be considered. However the need to validate, and where necessary modify, soil quality standards should be central to the design objectives.

Pine plantations have been established on a different range of sites/soils than the major hardwood forests noted above. They are generally drier and less fertile, except perhaps for some improved ex-agricultural country. Thus it cannot be assumed that results obtained for native forests would be transferrable to plantations, and vice versa. The only information currently available for pine is for coarse, infertile sands, which are particularly vulnerable to both compaction and nutrient loss. Sites in moister regions and on finer textured soils should be considered for harvesting trials.

There is so little data on harvesting impacts in pine plantations that a similar approach seems warranted there also. However, forest managers have increased organic matter conservation in pine plantations in anticipation of potentially harmful soil effects due to organic matter loss. So, even though we do not fully undestand the effects of organic matter removal in most pine systems, mitigative measures are in place already. Thus, initial studies in pine plantations could be focused on mechanical impacts on soil properties, across a range of soil types. Forest managers accept that soil compaction is a problem, and mitigative practices such as ripping and bedding are part of routine site preparation. But the longer--term effects on soil properties of these actions are largely unknown, and in many plantations, ripping is carried out as a matter of course, with no understanding of the actual needs on a site by site basis.

Whole tree harvesting for energy is rather a remote possibility in Australian plantations or native forests in the foreseeable future; in native forests, residues including bark are routinely left on harvested coupes and often burned. Forest floor organic matter and top soil organic matter are disturbed and we should probably focus on these components of the system. Three organic matter removal treatments could be a) the intact forest floor and soil, b) FF removed, and c) FF and some top soil removed, with fertilisation as an ameliorative treatment in each case. Top soil removal can be used to simulate the effects of soil redistribution/mixing during logging and the effects of erosion. Harvest residues and slash burning need to be accounted for in the design. One option could be to include bark and slash in each treatment, and burn according to routine practice. This would keep the number of treatments to a minimum but interpretation of the results would be more difficult. It would be preferable to determine effects of slash burning and organic matter removal independently. Several combinations of the slash/bark retention treatments can be envisaged but more detailed consideration is necessary.

If a factorial design is accepted, then compaction treatments should be combined with each of the organic matter removal treatments. The level(s) of compaction imposed need to be determined in relation to the levels of disturbance that are occurring routinely. Note that trees harvested from the research plots would needs to be removed without mechanical damage to the soil. In the US trials it has not been physically possible to achieve the desired levels of compaction. Input from specialists in this area is necessary to design appropriate treatments.

In developing this aspect of harvesting research it is important to recognise that there are already some harvesting practices, for example debarking on site, which aim to reduce harvesting impacts, and where possible these practices should be incorporated in trial designs. Routine management practices could be included as a pecific treatment. Experimental trials such as those described are required to quantify some fundamental soil and plant growth relationships especially over the long-term. Appropriate features of the trial designs generated in the Workshop on Designing Long-Term Trials should be considered in develoing the detailed working plans.

The Standing Commitee on Forestry (of the MCFFA; Ministerial Council on Forestry, Fisheries and Agriculture) Research Working Group on Soils and Nutrition (RWG 3) had input in developing the proposed standards for soil quality , through John Raison, as a member of the JANIS Technical Working Group on Forest Use and Management. It seems appropriate for members of RWG 3, in consultation with their management agencies, to develop and implement appropriate designs for long-term harvesting trials in Australian forests to validate the soil quality standards and further our understanding of harvesting impacts on soil properties and plant growth. A nationally coordinated approach is necessary because there may only be sufficient resources for a few trials. A series of joint trials could become key sites for collaborative forest research in

Australia among several agencies, with additional research carried out by students and other scientists covering a broad range of forest research disciplines.

References

Boardman, R. 1988. Living on the edge - the development of silviculture in South Australian pine plantations Australian Forestry 51: 135-56.

Drielsma, J.H. 1994. The National Forest Policy Statement: A State Perspective. Newsletter of the Institute of Foresters of Australia Inc. 35: 5-10

Dyck, W.J. and Mees, C.A. (eds) 1991. Long-term field trials to assess environmental impacts of harvesting. Proceedings IEA/BE T6/A6 report No. 5. FRI Bulletin No. 161.

Keeves, A. 1966. Some evidence of loss of productivity with successive rotations of *Pinus radiata* in the south-east of South Australia. Australian Forestry 30: 51-63.

Lacey, S.T. 1993. Soil development and erosion in forestry. Forestry Commission of NSW Technical Report, Sydney. 62p.

Lacey, S.T., Ryan, P.J. and Huang, J. 1993. Soil physical property change from forest harvesting in New South Wales. Report to LWRRDC and RIRD (in press).

Powers, R.F. 1990. Are we maintaining the productivity of forest lands? Establishing guidelines through a cooperative national program. p 98-112. *In* D.L. Schweitzer and M.J. MacNaughton. Proceedings: National Workshop on Monitoring Forest Land Implementation, May 14-17, 1990. Minneapolis, MN.

Powers, R.F., Alban, D. and Miller, R.E. Sustained site productivity in North American Forests: Problems and Prospects. p 49-79 *In* Gessel, S.P., Lacate, D.S., Weetman, G.F. and Powers, R.F. (eds) Sustained productivity of Forest soils: Proceedings of the 7th North American Forest Soils Conference, 1988. Vancouver, BC.

Raison, J.R. and Hopmans, P. 1994. Chapter 3. Soils. pp 27-42. *In* Draft Report on the Development of Consistent Nationwide Baseline Environmental Standards for Native Forests. Technical Working Group on Forest Use and Management, Joint ANZECC-MCFFA National Forest Policy Statement, Implementation Sub-Committee.

Sands, R. 1983. Physical changes in sandy soils planted to radiata pine. p 146-52 *In* R. Ballard and S.P. Gessel (eds) USDA Forest Service General Technical Report PNW-163.

South Australian Woods and Forests Department. 1987. Forestry Manual Volume 2. Adelaide.

Turner, J. 1993. Research and ecologically sustainable management - a discussion paper. Technical Paper No. 61. State Forests of NSW 26p.

USDA Forest Service. 1987. Soil management Handbook pp 2.04-2.21. Forest Service Handbook 2509.19, 10/87. Washington DC.

Williamson, J.R. 1990. The effects of mechanised forest harvesting operations on soil properties and site productivity. Tasmanian Forest Research Council Report no. 5, 193p.

APPENDIX 1 Study Tour Itinerary (27 February to 20 March 1994)

27 February :	Flew from Sydney to Christchurch
28 February to 2 March:	Trees and Soils Workshop, Lincoln University
3 - 4 February:	Diagnosing Nutrient Deficiencies Workshop, Forest Research Institute, Rotorua
5 February:	Free day hiking around Rotorua
6 February:	Travel to Auckland; IEA Workshop Registration
7 - 9 February:	Field tour of the IEA meeting in the Northland
10-12 February	Technical sessions of IEA workshop; Return to Rotorua
13 February:	Free day hiking around Rotorua
14 February:	Inspection of Intensive harvesting trials in Tarawera and Kinleith Forests with Dr. C.T. Smith (FRI)
15 February:	Travel to Picton, South Island to meet Dr. P. Clinton, my host for the South Island visit.
16 February:	Inspection of harvesting being carried out at the Golden Downes harvesting trial near Nelson.
17 February:	Visit to plantations managed by Timberlands West Coast, near Greymouth
18 February:	Inspection of harvesting trials at Berwick, near Dunedin managed by Wenita Forestry. Inspection of Bernham Trial near Christchurch, managed by Selwyn Plantation Board.
19 February;	Free day in Christchurch
20 February:	Returned to Sydney

APPENDIX 2 Paper presented in Session 3 of the IEA Workshop

FERTILISER USE AND NUTRITIONAL MANAGEMENT OF PINE AND EUCALYPT PLANTATIONS IN AUSTRALIA: A REVIEW OF PAST AND CURRENT PRACTICES

ELAINE M. BIRK

RESEARCH DIVISION
STATE FORESTS OF NEW SOUTH WALES

(This review is the draft manuscript presented at the 1994 IEA/BE Workshop on "Understanding Plant Nutrient Supply and Uptake: Opportunities for Managing Site Productivity" held in New Zealand in March 1994. It is currently in review for publication in the New Zealand Journal of Forestry Science)

FERTILISER USE AND NUTRITIONAL MANAGEMENT OF PINE AND EUCALYPT PLANTATIONS IN AUSTRALIA: A REVIEW OF PAST AND CURRENT PRACTICES

ELAINE M. BIRK

State Forests of New South Wales, P.O. Box 100, Beecroft NSW Australia 2119

ABSTRACT

Fertiliser use in Australian plantations, primarily exotic pines, is reviewed in the context of soils and climate and historical factors affecting plantation distribution and attitudes toward nutritional management. The diverse nature of nutritional problems encountered in pine plantations across Australia, and the separate management Agencies involved, resulted in a strong divergence of policies and practices regarding the use of fertilisers among the different States until the 1980's. At this time various common pressures including increasing land costs prompted reconsideration of productivity gains and returns on investments. As a result there was increased interest in the potential use of integrated silvicultural practices to increase productivity. Several important changes have occurred in nutritional management; nutrition is regarded as one component of total crop management; plantations are managed on a site-specific basis; management tends to be more intensive with increased productivity per hectare; soil moisture and nutrients are managed more efficiently; and genetic improvements in nutrition and other parameters are being sought to increase performance, health and form. Nevertheless, actual fertiliser practices vary

considerably due to vast differences in soil and climatic conditions. Fertiliser practices in eucalypt plantations are still being developed although there is considerable information transfer from experience gained with exotic pines.

Keywords: nutrition, nitrogen, phosphorus, trace elements, site-specific management, later-age fertilisation, weed control, slash retention, fertiliser prescriptions

INTRODUCTION

Timber production from approximately 12.5 million ha of native eucalypt forest and 900,000 ha of plantation forest currently supports 50 % of Australia's wood requirements (Squire *et al.* 1991). While research suggests that fertilisers could be used to increase the productivity of some regrowth eucalypt forests (O' Connell and Grove 1991), this practice has not yet been adopted on an operational scale. Exotic pine plantations, however, are intensively managed, and fertilisers are a major factor contributing to increased growth rates. The aim of this paper is to review the status of nutritional management of plantation forests in Australia, principally the exotic pine forests, to identify factors contributing to the development of current practices and where possible indicate how they relate to nutrient supply and demand.

PLANTATION FORESTS: SPECIES, LOCATIONS AND CLIMATE

The major plantation species in Australia are exotic pines, principally radiata pine (*Pinus radiata* D. Don), which represented approximately 66 % of the total plantation estate in 1990 (Table 1). Maritime pine (*P. pinaster*) has been planted on poorer sandy soils in Western Australia (W.A.), Victoria (Vic) and South Australia (S.A.) and tropical pines are the major exotic conifers in Queensland (Qld) and northern New South Wales (NSW). Loblolly pine (*P. taeda*) and Slash pine (*P. elliottii*) were planted initially, but in Qld these have been replaced by Honduras Caribbean pine (*P. caribaea* Mor var. *hondurensis* Barr. and Golf.) and more recently by the F1 hybrids of Honduras Caribbean pine and slash pine (Simpson and Grant 1991). Hybrids between Honduras Caribbean pine and Tecun Uman (*P. tecunumanii* P. Eguiluz and J.P. Perry) are currently being assessed. Native conifers (*Araucaria* spp.) are planted in Queensland and northern New South Wales (NSW). Eucalypts form the dominant broadleaved plantations across temperate and sub-tropical regions; *E. nitens* and *E. regnans* are suited to high elevations and relatively high rainfall areas, *E. globulus*, tolerates drier conditions at low elevations while *E. pilularis* and *E. grandis* are the dominant sub-tropical species. A range of species including *E. astringens* are planted in W.A., particularly on soils degraded by salinisation.

Plantations in Australia have been established around the eastern and southern coasts and along the tablelands of the Great Dividing Range, the Darling Scarp in W.A. and in Tasmania. Almost half the radiata pine plantations receive less than 900 mm year^{-1} of rainfall and 90% receive less than 1200 mm year^{-1}, with summer, winter and uniform patterns of distribution (Boomsma and Hunter 1990). The lower limit is around 600 mm per year. Moisture availability can severely limit growth at this extreme due to the large moisture deficient which develops during the growing season. Volume growth can be directly related to rainfall (Whitehead 1985 in Boomsma and Hunter 1990) which has been shown to be the primary factor causing growth differences between radiata pine forests in Australia and New Zealand (Turner and Lambert 1986a). The regions with a silvicultural emphasis on water use efficiency are southern eastern and central S.A. and western Victoria, and W.A..

The lower rainfall limit for commercially viable eucalypt plantations appears to be about 800 mm /yr (Orme *et al.* 1991, Weston 1991, Stanton 1991) although they are extended beyond these limits in drier areas where plantations are established for the purpose of effluent treatment (Boardman 1991, Boomsma and Hunter 1990).

SOIL FERTILITY AND NUTRITION

In the absence of extensive coverings of volcanic ash or loess, parent materials have had a major role in determining the types of soils developed in Australia, by setting limits to clay and nutrient content, particularly phosphorus and trace elements. According to Waring (1981) there is greater similarity between Australian soils and those of the upper coastal plain of the south eastern USA than with soils in New Zealand due to the reserves of unweathered minerals in New Zealand sands. In south eastern Australia (including Tasmania) many soils form in situ on exposed sediments and metamorphic rocks of the Ordovician, Silurian and Devonian Periods (Waring 1981). Soil parent materials in this region range from highly siliceous sandstones to basic rocks rich in ferro-magnesium minerals. Deeply weathered laterites occur in W.A. and central S.A. although deep transported coastal sands are more widespread and similar to the siliceous sands in south eastern S.A. and south western W.A.. Exotic pine plantations in Qld are generally confined to infertile sandy soils of the coastal lowlands in the south east and to granitic outwash soils north of the Tropic of Capricorn.

Plantations in south eastern Australia have been established over a very diverse geological base which has been a major factor explaining variations in plant nutrient status and plantation productivity (Turvey *et al.* 1986, Turner and Holmes 1985, Knott and Ryan 1990, Turvey *et al.* 1990). Figure 1 from Knott and Ryan (1990) shows variations in basal area of inventory plots from unfertilised plantation on a range of rock types in NSW. The highest basal area increments were found on granodiorite and basalt and the lowest were on quartzose sandstone and rhyolite.

Many reviews over the past few decades have documented aspects of pine plantation nutrition and growth responses to fertilisation in Australia generally (Waring 1971, 1981, Woollens and Snowdon 1981, Neilsen 1982, Turner and Lambert 1986a, Boomsma and Hunter 1990) or in particular States (including Kessel and Stoate 1938, Stoate 1950, Rapauch *et al.* 1969, Boardman 1974, Knott and Turner 1990, Simpson and Grant 1991). Nutritional problems in *P. radiata* and other exotic pines can be predicted if parent material is known due to the strong influence of soil parent materials over nutrient supply (Turner and Lambert 1986a). Phosphorus is the major growth limiting element and substantial growth responses can be achieved with fertiliser treatments. Phosphorus deficiency occurs on a wide range of soils including those derived from deposited sands, sandstones, sedimentary rocks, acid volcanics, granites, metamorphics, and weathered laterites. Critical foliage concentrations are used to identify phosphorus deficiencies in established stands but they vary as a function of soil/rock type, stand age and rainfall (Figure 2) (Turner and Lambert 1986a, Lambert and Turner 1988).

Calcium deficiencies in *P. radiata* are relatively localised, occurring on acid volcanics and sandstones in association with phosphorus deficiency, while potassium deficiency occurs on deep aeolian sands in W.A. and on podsols in south east Qld. Magnesium deficiencies have not been common although low foliar magnesium levels are occurring in young stands on improved pasture sites where soils have been stripped of exchangeable base cations though acidification reactions (Birk 1992).

Micro nutrient deficiencies are common on specific soil types and failure to address these problems has frequently resulted in failed plantations. Hill and Lambert (1981) have reviewed trace element deficiencies in Australian plantations. Zinc deficiency is a problem for *P. radiata* on siliceous sands and it can be associated with copper and molybdenum deficiencies (Boardman and McGuire 1990). Copper deficiency also occurs on deep humus podsols or poorly drained podsolised sands. Boron deficiency can occur on soils derived from igneous rocks and is exacerbated by water stress and by weed competition in pasture sites. Like boron, sulphur deficiency has been found on soils derived from igneous rocks (Lambert and Turner 1977) although it can be induced by application of nitrogen fertilisers or leguminous nitrogen fixers on former pasture sites (Turner and Lambert 1986).

Nitrogen is rarely a primary growth limiting element in young stands but it often becomes limiting once phosphorus deficiencies are corrected, particularly on ex-native forest sites (Turner and Lambert 1986a) and in later-aged stands (Turner and Knott 1991) and second rotation sites. Foliage nitrogen, phosphorus, aluminium and manganese are higher in pine plantations on improved pastures compared with plantations on cleared native hardwood forest soils and problems associated with high nitrogen have been observed in recent years (Carlyle *et al.* 1989, Birk 1990). High levels of nitrogen can induce deficiencies of several elements; phosphorus and sulphur in *P. radiata* (Lambert 1986), boron, copper and zinc in radiata and tropical pines (Hill and Lambert 1981) and copper in *Eucalyptus nitens* (Turnbull[1] pers. comm.).

HISTORICAL PATTERN OF PLANTATION ESTABLISHMENT

Of the wide range of exotic pines tested for afforestation purposes in southern Australia around the turn of the century, *P. radiata* and *P. pinaster* were those which showed the most promise across a range of sites. There was a mistaken idea that the demands of Monterey Pine could be readily satisfied by the poorest of soils, and given the priority allocation of good lands to agriculture, pine plantations were restricted to infertile regions, particularly along the coastal plains (Kessel and Stoate 1938). Selection of planting sites had little to do with soil qualities (Turner[2] pers. comm.). In South Australia, uneconomic agricultural land was released for reforestation whereas in NSW, plantation establishment on timbered sites of low commercial value continued for some time to concentrate plantings in large blocks to attract industry. In Tasmania, cheap land was cleared to plant trees to overcome unemployment during the depression.

The demand for timber increased in the later 1960's and 1970's following the first Softwood Forestry Agreement with the Commonwealth Government (1966 to 1971) resulting in an upsurge in plantation establishment. This forced expansion onto a wider range of site types including higher quality eucalypt forests in south eastern States. Conversion of native forest to pine continued for a number of years although it attracted considerable public attention. By the late 1970's and through the 1980's the

[1] C. Turnbull, Cooperative Research Centre for Temperate Hardwood Forestry, Hobart, Tasmania
[2] J. Turner, Director, Research Division, State Forests of New South Wales, Beecroft

clearing of native forest (S.A.) or of publicly-owned forest (Victoria) for conifers was banned and other State agencies changed their policies accordingly (Fergurson 1991).

Prior to 1970 the largest planting areas were in S.A. and Victoria, predominantly on deep, unconsolidated sandy soils. Since 1970, the highest rate of new plantings has been in NSW, largely on fine textured soils. Turner and Lambert (1991) summarised the area of pine plantations according to soil parent material and recent changes in the distribution of plantations (Table 2). The major parent rock types represented across all plantations include shale, siltstone and mudstone soils (Argillaceous rocks). Characteristics of soils associated with each parent rock classes are summarised in Table 3. Since the late 1970's, large areas of plantations in south eastern Australia have been established on agricultural land "improved" with fertilisers (P, N) and introduced legumes, and degraded through erosion, compaction, acidification and salinisation.

The area of second rotation plantings has increased substantially over the last decade but in several areas there is little or no expansion of the plantation estate; all plantings in S.A. are now second or subsequent rotations. Second rotation plantings exceed first rotation establishment in NSW, Victoria and Tasmania (Table 4) and were expected to by 1993 in Qld.

INITAL APPROACHES TO THE NUTRITIONAL MANAGEMENT OF EXOTIC PINE PLANTATIONS

The widespread development of pine plantations on poor soils pre-empted the need for fertilisers but pines were introduced with a philosophy that climate set the limits to growth. Based on Northern Hemisphere experiences, considerable effort was expended on matching species to specific site types. Vigorous debate continued through several decades about the importance of soil factors. Most foresters supported the view that water limitations were controlling growth, and stressed the importance of moisture holding capacity, soil depth and root penetration into sub-soil. In South and Western Australia, *P. pinaster* was planted on soils where *P. radiata* was unsatisfactory or failed. There was little support for the idea that nutrients limited growth until a few innovative foresters found that fertilisers corrected growth disorders thought to be pathological problems. Notably, superphosphate overcame needle fusion on several soils (Ludbrook 1937, Young 1940, Kessel and Stoate 1938) and zinc sulphate sprays overcame rosetting and tip dieback on aeolian sands (Kessel and Stoate 1938). These developments generated an alternative school of thought contending that there may be insufficient quantities of essential elements in some soils for good growth (Kessel and Stoate 1938). By about 1950 remedial fertilisation and establishment fertilisation were routine for *P. pinaster* and *P. elliottii*, and to some extent for *P. radiata* because in the poorest of soils they would not grow at all without superphosphate.

General attitudes toward fertiliser use have changed from the days when they were considered a 'luxury' to their present day use as a basic management tool. The areas treated increased substantially through the 1970's and particularly in the 1980's (Boomsma and Hunter 1990, Knott and Turner 1990). Fertiliser treatments are integrated with other silvicultural practices to increase utilisation of native soil supplies and recycle nutrients in harvest residues (Squire *et al.* 1991, Hopmans *et al.* 1993) in order to sustain or increase productivity and to maintain stand health. Attention has also been given to improving pine growth and form by selection and breeding, particulartly in S.A. (Boardman 1988) and Qld (Simpson and Grant 1991, Simpson and Osborne 1993).

Minimal attention was given to site preparation beyond hand diggging prior to planting pines, and burning the logging debris left after eucalypts were cleared. Improved growth in cultivated fire breaks had been observed in W.A. in the 1930's and survival and growth after the first summer was increased after ploughing (Kessel and Stoate 1938). Ploughing with disc ploughs to eradicate scrub, and other practices such as bedding and mounding were widespread by the 1950's. The winged ripper, developed in New Zealand, is now more commonly used for cultivation (Johnston 1982). Chemical sprays including atrazine were subsequently developed for weed control and introduced relatively early in S.A. and Qld, but residual herbicides were not a practical option until the late 1970's (Flinn et al. 1979, Boomsma 1982).

STATE TRENDS IN FERTILISER USE UP TO THE 1980'S

Being independent management agencies each State evolved different management policies and practices to deal with the regional problems. They are evident from a comparison of developments in several regions. I have summarised past practices in south eastern S.A., NSW and south eastern Queensland based on information from publications on fertiliser use (Boardman 1988, Simpson and Grant 1991, Simpson 1991, Knott and Turner 1990), forest management manuals (S.A. Woods and Forests 1987) and unpublished materials (R. Boardman[3], pers. comm, J. Turner pers. comm.) to show the divergent attitudes, policies and practices during the first few decades of

[3] R. Boardman, Department of Primary Industries, Adelaide, South Australia

plantation management. Of necessity these are brief summaries and leave much unsaid about the overall development of silvicultural practices in these regions.

Exotic Pines in South Eastern South Australia

Routine fertilisers other than zinc sprays were not used in S.A. prior to the mid-1950's when superphosphate was applied to *P. radiata* and *P. pinaster* on sites of marginal fertility. Research trials indicated that large areas of deep infertile sands in south eastern S.A. were responsive to phosphorus fertilisation as a function of site quality (a function of native P supplies) and soil moisture. Dry sites did not respond to phosphorus due to moisture limitations while the response on wet sites was enhanced by cultivation due to its control of competing vegetation (Boardman 1974). With low organic matter content and low P fixation capacities, P retention was a problem and refertilising was required after 2 and 4 years growth (Boardman pers. comm.). Growth rates were related to foliage concentrations (Raupach *et al.* 1969) and foliar analysis became an important tool for predicting the need to fertilise in established stands. Parallel improvements occurred during this period in weed control technology resulting in a combination of manual and periodic chemical (residual) control measures.

Plantation establishment on marginal native forest sites ceased by the 1970's which brought an end to the planting of *P. pinaster*. All new plantations were established on ex-agricultural land and only *P. radiata* was planted. The diversity of soil types increased but the energy costs involved were reduced since establishment fertilisers other than trace elements were not required in previously fertilised country. Second rotation establishment increased during this period and after productivity declines were identified (Keeves 1966) there was an intensification of both research and management input into second rotation management. This culminated with Woods (1976) Maximum Growth Sequence (MGS) aimed at sustaining growth after clearfelling. The MGS involved repeated N, P and trace elements treatments in which nitrogen was the key element (300 kg/ha) applied with at leat six other nutrients in conjunction with chemical weed control treatments. Application rates increased progressively to match perceived increases in nutrient demand over the first four years of a new plantation. The MGS transformed plantations into stands of "outstnding uniformity, health and great vigour" (Boardman 1988) and became the routine practice for a period of about 3 years (1976 - 1979) while additional research was carried out to identify stand requirements on a site specific basis (Boardman pers. comm.). The program was justified economically at that time in that Site Quality IV (minimum acceptable growth) could be achieved and maintained (Woods 1980) but fertiliser costs were scrutinised and alternative strategies involving intensive silviculture, particuarly, weed control were investigated (Cellier et al. 1985).

Several studies showed that it was critical to eliminate weed competition, particularly for soil moisture, and that role of nitrogen fertiliser was less significant during establishment that was previous thought (Squire 1977, Cellier and Stephens 1980a, b, Cellier et al. 1985, Sadanandan and Cellier 1985). Added nitrogen had a small direct effect on total production but without N, second rotation productivity was lower than in comparable first rotation stands due to differences in the mineralisation rates of soil organic matter (Theodouou and Bowen 1983). With suitable combinations of silvicultural inputs, the productivity of second and first rotations were found to be equal. Studies on similar soils in Victoria, which focused on slash retention and weed control, showed that undecomposed litter and harvest residues acted as a surface mulch maintaining more favourable soil conditions compared with slash burned soils (Squire et al. 1979). Strip weed control with slash was found to be as effective as total weed control in the absence of slash (Squire et al. 1991). Smethurst and Nambiar (1989, 1990a, b) examined interactions between weed control and slash retention and showed that more nitrogen than is required by the young pines is available for at least 3 years after planting, through the mineralisation of residual organic matter.

The MGS was subsequently revised to ensure the retention of harvest residues and places weed control at a higher priority than establishment fertilisers. Fertilisers are applied at establishment only if there is a demonstrated requirement based on growth rates achieved in the first rotation (less than the minimum acceptable level of SQ IV on the S.A. yield tables (Lewis *et al.* 1976)). Early growth rates are closely monitored and stands are fertilised or refertilised if early growth measurements (30 and 42 months post-planting) indicate that growth is below the minimum acceptable for S.A.. The same principles are followed in both the south east (mostly deep aeolian sands) and in the central region where the landscape is more complex and includes both high and low P-fixing soils. The rates of application, the fertilisers used (usually DAP or OSP with a trace element mix of Cu, Zn and Mo on some sites, or a complete fertiliser mix) and the frequency of treatment vary according to the soil P-fixing capacity and current growth rates (S.A. Woods and Forests 1987).

Exotic Pines in South Eastern Queensland

In Queensland, the early plantations of *P. taeda* and later *P. elliottii* were established on better drained sites on the coastal lowlands. Being coarse textured and of low nutrient status, phosphorus was essential for their growth and economic viability (Simpson and Grant 1991). In the 1940's, total soil phosphorus was used to determine the species to be planted and the need for phosphorus fertilisers, but the system developed limitations once the plantation expanded across a broader range of soil types. Applications of 50 kg/ha of phosphorus as Nauru rock phosphate applied prior to three years after planting became routine in the 1950's (Simpson and Grant 1991). There were unsuccessful attempts to relate site index to total soil phosphorus to determine site specific application rates (Pegg 1967). As site preparation/cultivation techniques improved, plantings of exotic pines, mainly slash pine, were extended in the 1970's to less fertile soils with poorer drainage. Rock phosphate was replaced with more soluble fertilisers. Initially (ordinary) super phosphate (OSP) was applied by air, but OSP was replaced by triple superphosphate (TSP) and later by mono-ammonium phosphate which is now preferred because N encourages early growth and can be applied at little extra cost. Manual application or tractor mounted equipment, which applies fertiliser to individual trees or as a band along the planting row were required. Honduras Caribbean pine (PCH) and more recently the hybrid between PCH and slash pine, replaced slash pine in the 1980's and plantings were extended onto more ex-agricultural land.

Research focused on identifying limiting elements and their interactions across the range of sites and for the range of species/taxa being planted (Simpson and Osborne 1993). Different phosphorus response curves were identified for wet and dry sites and for sedimentary and granitic soils with the result that standard fertiliser trials were introduced on a site-specific basis to identify nutrient requirements, and fertiliser requirements prescriptions (Simpson and Grant 1991).

Foliage nutrient concentrations were monitored in routine stands to to diagnose responsiveness to phosphorus fertilisation in established plantations and calibrate nutrient data from trials (Bevege and Richards 1972) as the initial dressings were not considered adequate for a full rotation. Standard refertilising trials were established on a soil basis and these resulted in routine treatments of 40 kg/ha of phosphorus as MAP in aerial applications to established slash pine plantations older than about 12 years of age. All of the slash pine plantation had been refertilised by the late 1991/2 (Simpson and Grant 1991).

Exotic Pines in New South Wales

Early plantings of *P. radiata* in NSW extended from the coast to the tablelands on rock types including sandstones, shales, acid volcanics, conglomerates, and granites, most of which are nutritionally poor. In keeping with approaches in other States, there were attempts to match species to sites, and failures were attributed to poor climate and "inappropriate country". After Ludbrook (1937) demonstrated that phosphorus alleviated 'needle fusion', limited areas with visual P deficiency symptoms received a single, low cost phosphate treatment. However, the view that climate rather than soil fertility set the limits on growth (Henry 1963 cited by Knott and Turner 1990) meant that phosphorus fertilisers were not widely used for several decades - longer than in other States - despite research trials demonstrating phosphorus limitations in climatically suitable regions. By the early 1970's, limited areas of 10 year old plantations were receiving broadcast applications of superphosphate at rates up to 100 kg P /ha.

Brockwell and Ludbrook (1962), Gentle *et al.* (1965) and later Turner (1982) carried out trials which demonstrated that there were sustained responses to the early broadcast applications of superphosphate. Gentle *et al.* (1986) reported that responses lasted through two rotations on the P-fixing sanstone soils south of Sydney. Site quality increased due to higher organic matter levels, total nitrogen and calcium contents (Turner and Lambert 1986b). With high soil P-fixation capacities, soils research focused on the chemistry of soil reactions (Gentle and Humphreys 1968) in relation to different rock types and on quantifying growth responses to alternate forms of phosphate fertiliser (G. Windsor Forestry Commission unpub. reports 1972-1977, Humphreys 1964).

Establishment fertilisation commenced in a limited way in plantations on sandstone south of Sydney in the early 1960's using a "spot" or "band" of lime-super at 240 P kg/ha. In the 1970's ordinary superphosphate (OSP) replaced lime-super due to changes in fertiliser availability. Application rates varied from 500 to 1000 kg OSP /ha, applied broadcast at planting (Gentle *et al.* 1965). Subsequent studies by Waring (1973) confirmed the importance of fertilising at establishment; he found that the merchantable volume of stands fertilized with phosphate at planting was 235% greater than unfertilised stands after 8 years; the volume of stands fertilized at 4 years was only 118% greater than the unfertilised stands. However, the total weed control measures required to achieve these growth rates were not routinely practiced at this time.

Foliage analysis confirmed that additional phosphorus applications would be required within a few years after planting. Establishment fertilisation and refertilisation with superphosphate after 5 years at 75 kg P/ha (Lambert and Turner 1986) became the standard practice.

Despite the 'softening' of policy against fertilisation during the 1970's, the cumulative area being treated was relatively small and limited to areas south and west of Sydney. It was not until the 1980's that broad scale fertilisation of NSW plantations was extended to include *P. radiata* plantations in the southern and northern Tablelands (Figure 3). The surge in fertiliser use at this time coincided with the development of high analysis fertilisers. "Starter 12" (22.8 %P, 11% N) replaced superphosphate being applied at establishment and the method of application reverted to an individual tree basis at rates of 90 to 150 g/tree. Second rotation plantings had the highest priority for treatment and ex-pasture first rotation (1R) sites the lowest priority.

Routine foliage analysis (crop logging) across the State's plantations formed a basis for developing relationships between geology and nutrition (Gentle *et al.* 1968, Lambert and Turner 1988). Lambert and Turner (1977) identified relationships between geology and boron and sulphur deficiency, and the potential for nitrogen to induce sulphur deficiency (Kelly and Lambert 1972, Lambert 1986). Operational treatment of boron deficiencies commenced in the late 1980's with attention concentrated on large areas of ex-pasture plantations on low boron parent materials. low solubility products were used according to their availability in preference to borax which is readily leached; the main boron fertilisers changes from colemanite (calcium borate) to chilexite (calcium-sodium borate) and more recently to ulexite (sodium borate.

USE OF NITROGEN FERTILISERS AT ESTABLISHMENT

Nitrogen is rarely the primary growth limiting element at establishment in Australian plantations and its use in routine operations was limited prior to the 1970's.

Nitrogen fertilisers were applied at planting to first rotation stands (and second rotation in S.A.) in S.A., W.A. and Tasmania (mostly on an experimental basis) but not in NSW (Humphreys 1977) or Victoria (Flinn *et al.* 1979, 1982). N treatments later ceased in S.A. until the benefits could be demonstrated (Woods 1981). The results were often conflicting and there were inconsistent responses in trials (Nambiar and Cellier 1985) and operations (including growth depressions). Nitrogen caused root damage and in some sites nitrogen induced trace element deficiencies (Woods 1976).

There was nevertheless an accumulating body of research data showing that once phosphorus deficiency was alleviated, *P radiata* stands responded to additions of nitrogen (Waring 1971, 1981) - providing weeds were controlled. Most sites examined (all ex-native forest) showed strong N by P interactions, but the ratio of N to P was critical because soil type affected P fixation capacity and hence the actual availability of N relative to P. Optimum N to P ratios varied from 11:2 on sands to between 1 and 2:1 on moderately fertile soils in NSW, Victoria and Tasmania (Crane 1981). Legumes were introduced to supply N for *P. radiata* on deep weathered laterites in W.A., and have been tried on infertile sands in S.A. but competition for water use is a problem with perennial lupins (Nambiar and Nethercott 1987). Annual lupins appear to be a more suitable alternative, but should be early maturing varieties.

A variety of factors govern the nitrogen response in pine plantations:

1. Weed competition confounded many fertiliser trials and higher levels of nitrogen fertiliser are required for pine when weeds were not controlled (Crane 1981).

2. There is no additional growth response to N over that due to P alone when sulphur levels are inadequate (Turner 1981).

3. Growth rates are depressed when too much nitrogen is applied relative to phosphorus at all stages of a rotation (Crane 1981).

4. Nitrogen induces copper deficiency (S.A., W.A., Victoria, Queensland; Turvey 1984), zinc deficiency (McGrath and Robson 1984), boron deficiency (NSW and Victoria; Lambert and Turner 1977) and sulphur deficiency (Lambert 1986).

5. Nitrogen responses are ephemeral, particularly in comparison with phosphorus.

The complex and largely unpredictable nitrogen response limited its routine use in establishmnet fertiliser programs in most regions prior to the 1980's. It was introduced with the advent of high analysis fertilisers, which reduced fertiliser application costs, and with increased understanding of factors affecting growth response. Mono-ammonium phosphate (MAP, "Starter 12), di-ammonium phosphate (DAP), ammonium nitrate ("Starter 15") and double and triple superphosphate were the principal fertilisers which replaced superphosphate. Specific fertiliser mixes including trace elements were also developed in some regions and are still important in W.A. (Agras) and S.A. (Forest Mix 4, Forest Special Mix). As broadcast methods were not suitable for applying N fertilisers to young stands, there was a general shift to spot, banded or slit treatments, which required mechanisation to reduce labour costs. Improvements are still being sought in this area.

Nitrogen in Ex-Agricultural Sites

Problems associated with excess nitrogen in young stands were initially relatively localised; they occurred where excess N fertiliser was applied or where plantations were located on high quality soils derived from basalt (Lambert and Turner 1977).

Excess nitrogen causes severe tree form problems in plantations on fertile, ex-agricultural land, particularly in NSW and north eastern Victoria (Carlyle *et al.* 1989, Birk 1990). Ex-pastures were initially treated with high analysis NP fertilisers at planting but this practice has largely ceased; in Victoria, *P radiata* on ex-agricultural sites are treated with superphosphate at 20g/tree (Hopmans[4] pers. comm.) and in Queensland superphosphate is applied according to the intensity and duration of previous pasture fertilisation (Simpson and Grant 1991); no NP fertilisers are used on improved/fertile ex-pasture sites W.A. (McGrath[5] pers. comm.) or on 2R plantings on ex-pasture sites in south east S.A. unless previous growth rates were inadequate (S.A. Woods and Forests 1987); in NSW, most new plantings in 1993 were not fertilized with N or P and increased attention was given to weed control (Pettit[6] , pers. comm). Recent trials indicate either no response or a negative response to N on improved pastures (McGrath pers. comm., Hopmans, pers. comm., Ryan[7] , pers. comm.) but on unimproved pastures, significant growth responses responses have been obtained with P (Cellier et al. 1985) and N plus P Ryan (pers. comm.) on some soil types.

NUTRITIONAL MANAGEMENT AND FERTILISER USE IN THE 1990'S

We entered the 1990's with a more diverse plantation resource, identified markets for plantation products, increased demands for high quality logs and wood products, increasing land costs (the shift to ex-agricultural land brought an end to 'free land') and the need to sustain long-term productivity. The various pressures prompted

---

[4] P. Hopmans, Centre for Foret Tree Technology, Department of Conservation and Natural Resources, Kew, Victoria
[5] J. McGrath, Department of Conservation and Lands, Busselton, W.A.
[6] M. Petitt, State Forests of NSW, Tumut, NSW
[7] P. Ryan, CSIRO Division of Forestry, Canberra, formerly of State Forests of NSW, West Pennant Hills, NSW

reconsideration of productivity gains and returns on investments (Turner and Lambert 1991).

In contrast with the development of seemingly divergent policies and practices of previous decades, these issues focused attention on the role of silvicultural practices in increasing productivity and resulted in a general convergence of practices and policies across all plantation regions. Four common themes emerged in relation nutritional management and fertiliser use:

1. Site-specific management throughout a rotation with supporting data bases and GIS systems to facilitate information transfer and decision making.

2. More intensive management to increase production per hectare

3. More efficient use and conservation of resources including water, organic matter, and fertilisers

4. Genetic improvement for nutritional characteristics to increase plantation performance.

The concept of site-or soil-specific management has been adopted throughout the country for pine plantations and more recently for eucalypt plantations. As each site presents specific resource limitations, the management aim is to select the appropriate species, provenance or family for a site, and to ameliorate site factors which restrict growth, with the aim of achieving levels of productivity per hectare which are closer to the site's biotic potential (Boardman and Simpson 1988). The emphasis in breeding programs is on volume growth, tree form, wood quality and resistance to disease and pests (Nambiar and Booth 1991) but there may be some opportunity for improving nutritional characteristics through breeding (Nambiar 1984) or for selecting gentic material which can perform well on sites with specific nutrient problems (Simpson and Osborne 1993). The strong genetic control over stem deformation in *P. radiata* on ex-pasture sites (Bail and Pederick 1989) indicates that some families can tolerate the unusually high levels of mineral N in these soils. Cuttings of resistant families also handle ex-pasture sites better than seedlings. Hybridisation programs in Queensland have greately increased the range of genetic material available for plantations on the coastal lowlands in south east Queensland and the superiority of the F1 hybrid between slash pine and Honduras Caribbean pine (PCH) has been demonstrated across a wide range of sites and in response to fertilisation (Simpson and Osborne 1993). Foliar nutrient concentations varied among the taxa on the same sites and suggested that the both hybrid and PCH may be suited to high nitrogen/copper sites, and PCH may better tolerate low phosphorus/potassium sites (Simpson and Osborne 1993).

The development of a Pine Soil Technical Classification (TSC) specifically for *P. radiata* plantations (Turvey 1987) has increased the opportunity for selecting appropriate silviculture and suitable fertiliser regimes in operational forestry. The classification enables management areas to be stratified into uniform units and provides a basis for extrapolating research results within and between forests and agencies (Turner *et al.* 1990). The TSC classifies parent rocks by soil forming properties which are related to *P. radiata* productivity through their relationships with nutrient supply, moisture supply, the development or restriction of roots, and resilience to mechanical load or pressure. The properties used are all observable in the field and include parent rock, texture profile, depth to and nature of the impeding layer, texture and condition of the uppermost 10 cm, character of the surficial horizons as determined from the occurrence of a paler sub-surface zone or exposed subsoil and condition and colour of the subsoil (Turner *et al.* 1990). Turvey *et al.* (1990) showed that parent rock alone explained 31% of the variance in merchantable volume of 11-year old unfertilised *P. radiata* from sites in NSW, Victoria and S.A. and most properties were individually related to wood production. The classes of parent rock identified (Table 2) are organised such that they set upper limits on the total amount of clay, primary quartz and many plant nutrient that can be released through mineral weathering (Turner *et al.* 1990). It is not surprising therefore that the parent rock classes are strongly discriminated on the basis of soil chemistry, especially total P and exchangeable bases (Ryan and Knott 1991) which also explains foliar nutrient status across different rock types (Knott and Ryan 1990). Plantations can be grouped according to properties in the classification which are related, for example, to potential deficiencies in macro and micro nutrients, disease and tree deformation, and soil physical problems including erosion or trafficability problems. Appropriate fertiliser regimes can be allocated to specific management units from the results of field trials on comparable sites.

Plantations in all regions of Australia are now stratified on a soils basis (nutrient and moisture considerations) and land is classified prior to purchase to determine suitability and appropriate management regimes. All NSW pine plantations have been classified by parent rock type (and previous land use) and information on parent rock type, nutrition and growth is incorporated into a relational data base (Knott and Ryan 1989) for access by forest managers. In Tasmania, soils mapping is being carried out to prepare a data base and will include other soil factors (organic matter and nutrient contents) in addition to growth data (Neilsen[8] pers. comm.). Fertiliser trials were

[8] W. Neilsen, Tasmanian Forestry Commission, Hobart, Tasmania

initiated in NSW and Queensland during the 1980's using standard fertiliser designs across a broad range of site types more typical of those being planted at the time to refine fertiliser prescriptions aimed at optimising production.

Site based management has greatly increased the opportunity to make operations more cost effective, but improvements are also occurring through more intensive site preparation and weed control in conjunction with fertilisation (and residue conservation measures in 2R sites). Substantial gains in productivity can be achieved by reducing the level of environmental resistance (Boardman and Simpson 1981). Some management agencies have reduced, delayed or eliminated fertilisers (especially N) at planting, while reducing weed competition and cultivating to enhance root penetration (Hopmans, pers. comm., McGrath, pers. comm., S.A. Woods and Forests 1987). Turner (1984) suggested that on better quality sites, the main effect of intensive, interactive treatments is a reduction in competitive effects rather than the alleviation of nutrient deficiency. On poor quality, nutrient deficient sites, intensive treatments may be necessary to supply sufficient resources to achieve significant productivity gains. The net result is that fertilisers are now being used more conservatively and applied where they are expected to be most effective. The basic objective is to time fertiliser application to match periods of high demand and to direct limited fertiliser resources to sites when their use will be optimal.

Knott and Turner (1990) stated that the major reasons for fertiliser treatments in Australian plantations in the current decade are:

1. To assist in successful plantation establishment.

2. To correct recognised deficiencies which result in economically significant mortality, disease or losses in growth potential.

3 (a). To increase the rate of wood production in young, actively growing stands where no deficiency symptoms are obvious but where nutrient levels are potentially limiting.

(b). To maximize the economic benefit of increased wood production following stand release after thinning by increasing nutrient availability.

Treatments are targeted for different stages of a rotation with an emphasis on the period prior to canopy closure when nutrient requirements are primarily met from soil reserves. Establishment fertilisation, trace element supplements and "booster"/ refertilisation treatments generally receive the highest priority for fertiliser monies. Deficiency treatments in older stands have been required in many areas to compensate for the lack of fertilisation in the 1970's. The relative importance of post-thinning fertilisation varies among the States; for example, in W.A. it is at least as important as establishment fertilisation whereas in S.A. and NSW, fertiliser monies become available for post-thinning treatments provided other priorities have been met. However, the areas being treated appear set to increase as the economic benefits are more clearly demonstrated.

Current Strategies for Fertilisation

Several strategies for applying fertiliser during a rotation have evolved in response to; (i) the capacity of a site to supply and retain the nutrients required for the species concerned, (ii) the potential of a soil to sustain productivity, and (iii) the management objectives for the plantation, that is, the growth rates required to meet wood production requirements. The importance of these factors varies among the management agencies. In W.A., for example, the aim is to achieve the maximum wood production possible across the whole plantation under the site limitations (W.A. Dept. C.A.L.M. undated report, McGrath pers. comm.) whereas pine sites in S.A. are upgraded with silvicultural inputs to reach minimum acceptable levels of productivity to meet the expected wood production requirements (S.A. Woods and Forests 1987). The approach being developed in Tasmania is to monitor soil factors and to manage nutrition accordingly (Neilsen pers. comm.)

A soil's water and nutrient supplying capacity and its nutrient retention characteristics appear to be the main site factors affecting the frequency of fertilisation (within economic constraints). The main strategies are summarised below:

1. *Establishment fertilisation (within 2 months of planting) followed by repeated "booster" treatments pre- (and possibly post-) crown closure*. There may be subsequent refertilisation after thinning. This practice is carried out on infertile soils (generally sands) with low nutrient retention capacities (S.A., W.A.) and on soils with high P-fixing capacities in S.A.. Note that establishment fertilisers are not applied in S.A. if weed control is not adequate (S.A. Woods and Forests 1987); a second attempt to establish the plantation is mandatory. Growth rates are monitored, and if minmum acceptable levels have not been achieved at 30 months post-planting, the stands are refertilised at 38 months and possibly at 50 months (S.A. Woods and Forests 1987). This is equivalent to the MGS fertiliser regime.

2. *Establishment fertilisation (within 2 months of planting) followed by a single "booster" treatment within a few (3 to 5) years (usually prior to crown closure).*

Subsequent refertilisation would be delayed until after thinning. This regime is generally carried out in first rotation *P. radiata* on moderately fertile but phosphorus limited soils in NSW, Tasmania, and Victoria. It is the most common regime followed in S.A. although the "booster" fertiliser is only applied if growth rates fail to reach prescribed minima for height and basal area. Growth rates are monitored to ensure that minimum acceptable levels are achieved in the middle of the third and fourth years post-planting. Fertilisation occurs eight months after measurement if growth is below acceptable levels (S.A. Woods and Forests 1987). Plantations on drought-prone sites in W.A. are fertilised at planting but may not receive any "booster" fertiliser. Established stands of Honduras Caribbean pine plantations on podsols on Queensland require supplements of potassium within a few years after establishment (Simpson and Grant 1991).

3. *No establishment fertilisation: initial treatment is delayed for several (3+) years and subsequent refertilisation is delayed until after thinning.* This regime has been adopted for some of the more fertile soils and will apply to radiata pine and tropical pines on many ex-pasture sites. In NSW residual pasture fertilisers are adequate to achieve the required early growth rates (Ryan pers. comm.) and simliar trends are reported for slash pine in Qld (Simpson and Grant 1991). The practice of delayed fertilisation currently applies to moderately fertile second rotation (2R) sites in S.A. where productivity in the first rotation (1R) reached the minimum acceptable level (SQ III or better). 2R growth rates are monitored to ensure that minimum acceptable levels are achieved in the middle of the third and fourth years post-planting. Fertilisation occurs eight months after measurement if growth is below acceptable levels (S.A. Woods and Forests 1987).

4. No fertilisation prior to thinning. This approach is planned for *P. radiata* in W.A. on fertile ex-pasture sites (W.A. Dept. of C.A.L.M. undated report) and it applies to some stands on better quality site in S.A. providing minimum acceptable growth rates are maintained (S.A. Woods and Forests 1987).

Establishment and "Booster" Fertilisers

Phosphorus, nitrogen and occasionally potassium are the principal macro elements applied at establishment and in "booster" treatments. The main trace elements applied are zinc, copper, molybdenum and boron. Table 5 lists the rates and types of fertilisers currently being used for radiata pine, maritime pine (W.A.), Honduras Caribbean pine and the F_1 hybrid (Qld). On 1R sites, N is applied at about half the rate of P applied (except in Tasmania). Treatments are usually carried out in spring within a few weeks or months after planting to take advantage of good growing conditions and to avoid loss through leaching. It has to be completed within a few weeks in summer drought prone areas or the benefits will be lost in dry soil.

Decisions to refertilise are based foliar analysis and/or growth measurements. Single "booster" treatments are generally carried out about 3 to 5 years after planting (Table 6). Phosphorus and trace elements are applied on finer textured soils whereas P, N and trace elements are applied on sandy soils. Plantations in S.A. may be treated with a Forest Starter Mix which is a complete fertiliser, to alleviate the risk of inadequate supplies of cations and sulphur (Boardman 1984, S.A. Woods and Forests 1987). There is no consistent pattern in the timing of "booster" fertiliser treatments for sites which were not fertilised at planting. The duration of benefits derived from fertilisers applied to former pastures depends on the number of years since fertilisers were last applied, the rate of application, and the soil type. Data for slash pine stands in Qld indicate that supplementary treatments may not be required for at least 14 years (Simpson and Grant 1991). Ex-pasture sites in Victoria and NSW will be fertilised after 5 years if foliar analysis indicates that treatment is required.

The timing of repeated "booster" treatments is rather complex; plantations on coastal sands in W.A. are refertilised approximately every two years for 6 years and on the poorer sites treatments may continue for up to 25 years (Table 6). Second rotation sites in S.A., refertilisation occurs annually for the first 4 years if required, as noted in the previous section.

Trace Element Treatments

Zinc, copper and molybendum are included in routine fertiliser mixes used as establishment and "booster" treatments in S.A. and W.A.. In some sites additional trace element treatments are required; zinc is applied as a spray because zinc movement through the soil is restricted (Brennan and McGrath 1988).

Boron deficiency is either treated at planting with 30g ulexite/tree (4.2 g P/tree) in Victoria or applied broadcast after about 2-3 years at 5 kg B/ka (NSW) to 8 kg B/ha (Victoria) if foliage analysis indicates marginal or deficient concentrations. Stands with marginal B levels in NSW may be resampled the following year to confirm that treatment is required due to the periodic nature of this deficiency and its links with moisture stress (Lambert and Ryan 1990). Plantations in Victoria are resampled after 4 to 5 years in anticipation of the need for retreatment.

Later Age and Post-Thinning Fertilisation

After crown closure there is a decrease in the demand from soil reserves and an increase in internal nutrient redistribution. Substantial growth responses can be achieved in unthinned pine plantations on a reasonably wide range of soils including infertile aeolian sands and lateritic podsols in W.A. (McGrath, pers. comm.) aeolian sands in S.A. (Fife *et al.* 1993), podsols in Queensland (Simpson and Grant 1991), granites and siltstone derived soils in NSW (Turner *et al.* 1992) and metamorphosed sediments in Tasmania (Neilsen 1982, Neilsen *et al.* 1992). Some remedial fertiliser treatments are carried out after crown closure in plantations which did not receive the normal "booster" treatments and where growth responses to later age treatments had been demonstrated eg. *P. elliottii* in Queensland. But it is not a widespread practice now that establishment and early refertilisation has become routine.

In contrast, post-thinning fertilisation is of considerable interest in Australia. It provides managers with an option for carrying out heavier than normal thinning to meet immediate demands for additional timber given that the additional volume can be recovered by a growth response after fertilisation (Turner and Knott 1991). Managers can also use this strategy to prepare for anticipated future shortfalls in log availability. There is an additional economic benefit from the production of larger, high quality logs (Crane 1982, Turner and Lambert 1987, Turner *et al.* 1992). Research trials in several States have demonstrated the potential gains but the high cost of fertilisers in some cases combined with an uncertainty of the growth response on an operation basis is limiting the rate at which post-thinning fertilisation is becoming a routine treatment in some States. If fertiliser funds in S.A. and NSW are available after other higher priority treatments have been carried out then the managers have the option the carry out post-thinning fertilisation. Post-thinning fetilisation is recognised as a necessity for plantations on less fertile sands, especially in W.A.. Table 7 includes post-thinning treatments considered optimal for a range of *P. radiata* plantations. Nitrogen is consistently required at higher rates than phosphorus at this stage of the rotation but the rates of N and P applied vary considerably. N:P ratios vary between 1:1 and 6:1 and depend in part on the amount on P inherently available and the amounts provided in previous fertiliser treatments. Turner and Knott (1991) report optimum rates of nitrogen after first thinning on a range of soil types in NSW ranging from 200 and 400 kg/ha (Table 7).

Post-thinning responses to N and P are site-specific, as demonstrated by trials in NSW on ex-native forest sites on different parent materials (Turner *et al.* 1992, Turner and Knott. 1991). The absolute biological responses, and thus the potential economic responses observed in these trials varied among sites, as did the optimum rates of N and P applied. Growth responses increased and were sustained for four to five years after treatment but were not different from the control after seven years had elapsed. This period represents the usual interval between thinnings (Turner *et al.* 1992). The decline in responsiveness appeared due to a decrease in nitrogen availability rather than a loss of phosphorus.

An economic evaluation of these trials (Turner and Knott 1991) showed that the spatially complex regions such as the central tablelands in NSW needs to be stratified according to site and stand factors critical to the biological response (parent rock type, age, and thinning history) to select the most appropriate NP treatment on a compartment basis. Broad scale application of a standard NP fertiliser after may not be appropriate; if some sites have low or negative growth responses financial losses could be incurred.

The timing of fertiliser application after thinning is being delayed on infertile sites in W.A. and S.A. until at least one full growing season has elapsed. This delay minimises the development of a) a wide ring of low density (early) wood and b) a heavy crown which could cause damage from bending and windthrow, as well as larger branches (S.A. Woods and Forests 1987, W.A., Dept. of CALM undated report). Recent studies in S.A. suggest that it may be beneficial to apply nitrogen a year before thinning on sandy soils since N is absorbed by the unthinned stands and can be recycled in organic forms in thinning residues (Carlyle[9] pers. comm.). This strategy is likely to be adopted for second and later thinnings in S.A., and on high quality sites at first thinning if they are thinned on time or have had a pre-commercial thin (Boardman pers. comm.)

MANAGEMENT OF SECOND ROTATION SITES

There is considerable variation among States with regard to operational practices carried out between clearfall and stand establishment on second rotation sites. This reflects differences in the intensity of clearfall operations, technologies available, soil types and concerns regarding moisture stress, and nutrient and soil loss. Except in S.A., large scale replanting operations have only commenced over the last decade and suitable practices are still being developed.

Smaller-sized harvest residues are retained following harvest where mulching is a practical option, primarily in response to evidence that buring slash contributed to

---

[9] C. Carlyle, CSIRO Division of Forestry, Mt Gambier, S.A.

productivity declines in S.A. (Keeves 1966). However, slash retention also reduces soil erosion and in Tasmania it is retained to reduce the regeneration of radiata pine from seed. Slope angle and intensity of wood utilisation affect the decision to retain and mulch harvest residues; chopper rolling is not suitable on steep slopes and gravity rolling systems are not generally available at this time. Chopper rolling is also more practical if wood utilisation is high as large slash loads inhibit the efficient operation of cultivation equipment. Low residue logging at clearfall is now routine practice in S.A..

The main developments in second rotation management in Australia were discussed in the section on management practices in S.A. prior to the 1980's. Later studies in S.A. showed that N mineralisation associated with the decomposition of harvest residues retained on sandy soils exceeds the N requirement of young pine stands for up to three years after planting (Smethurst and Nambiar 1990a, b). In these soils, harvest residues contain a substantial proportion of the site nutrient reserves (Flinn et al. 1979). The mulching effect of logging residues improves early growth of radiata pine compared with burned sites (Squire *et al.* 1979, 1985, Farrell 1984), largely due to the conservaton of soil moisture and increased availability of nitrogen. Hopmans et al. (1993) found that higher growth rates were sustained for at least 15 years where logging residues were retained rather than cleared or burned.

On finer textured soils the proportional loss of nutrients through log removal and burning is relatively low (< 5%) compared with coarse textured sands (Hall 1984, Birk 1993). Nevertheless, in a trial on sedimentary soils in NSW, Hall (1985) found taller trees and higher foliar N and P concentations in plots with slash retention compared with the raked and burned plots. Ryan (pers. comm.) found significant early growth responses to NP fertilisers supplied at planting on slash burned sites in NSW and inventory data from second rotation plantations indicate that the productivity of chopper rolled sites in southern NSW is higher than on burned sites (R. Orman[10] pers. comm.). Foliage concentrations (P, N, B) on burned sites are lower in 2R plantations compared with first rotation sites (Knott and Ryan 1990). These trends suggest that nutrient availability and/or nutrient uptake is reduced through slash burning and further investigations of the effect of slash retention on nutrient availability in fine textured soils are warranted.

Fertilisers are used at planting in 2R sites in NSW, Tasmania, S.A. and Queensland although prescriptions are the same as for first rotation plantings on the respective soil types. Standard establishment fertilisers trials established in NSW in the 1980's included second rotation sites which had been windrowed and burned prior to cultivation. Windrowing is no longer the desired practice, but Ryan (pers. comm.) found significant growth responses to combinations of N and P and the optimum rates varied according toparent rock type. On granodiorite, the optimum combination was 50g N+ 70 g P/ tree; on trachyte, 25 g N + 70 g P on trachyte produced the best response. The point to note is that these rates are considerably higher than the rates currently being applied (34g P and 16.5 g N in 150 g "Starter 12") based on 1R prescriptions for NSW.

With an increasing poportion of the plantation estates in most States approaching maturity, there will be an increase in the proportion of second rotation sites which have had a history of fertilising. Some areas will benefit from first rotation superphosphate fertilisers and residual effects on growth have been detected more than 30 years after superphospate application on sandstone soils with high P fixation capactiy in NSW

[10] R. Orman, State Forests of NSW, Albury, NSW

(Gentle et al. 1986) and Qld (Simpson and Grant 1991). In addition to areas treated at or within a few years after establishment, there will be increasing areas fertilised after thinning, possibly only a few years before the final harvest. It may be economically desirable to delay fertilising the second in these situations, at least on some soil types. There is considerable scope for research to refine fertiliser practices in second rotation plantations in most regions.

NUTRITIONAL MANAGEMENT OF EUCALYPT PLANTATIONS

Given abundant natural forests, which are managed on a sustained growth basis, there has been little incentive for the timber industry to make the large investments required to establish, manage and protect eucalypt plantations. However, eucalypt plantations are attracting considerable public support on the belief that they are environmentally sound and can replace native eucalypt forests as our source of hardwood timber for sawlogs and pulpwood (Stanton 1992).

There are approximately 100,000 ha of eucalypt plantation in Australia in both public and private ownership (Figure 4) established over the past 30 years with substantial and increasing involvement of the private sector. The total area increased from 1.6 to 8.3% of the total plantation estate between 1970 and 1990 (Turner and Lambert 1991) and annual plantings (>10,000 ha) are now double the area of new exotic pine plantings (Table 4). The major planting activity is in Tasmania (>7000 ha in 1993) and W.A. (> 4000 ha in 1993).

New plantations are being established on cleared, sometimes steep eucalypt forest land (private) in Tasmania and on ex-agricultural land or otherwise degraded land elsewhere. Early plantations in W.A. were established to reduce problems of stream salinity (Ritson *et al.* 1992). Older plantations on the north coast of NSW were established after clearing and burning either to ensure successful regeneration ahead of the aggressive weed regrowth, or to increase productivity by changing species (Stanton 1992). These areas have been managed more like the surrounding regrowth forests.

The management of recent plantings has been intensive, capitalising on lessons learned from exotic pines. The emphasis on site-specific management extends to the selection of suitable land, appropriate species or provenances and silvicultural techniques to maximise early growth rates. A land capability system including climate and soils data has been developed for site selection in Tasmania (Lafan 1993) and land evaluation surveys are being carried out in W.A. (Harper[11] pers. comm.) and NSW (Stanton 1991). Walsh (1991) reported correlations between early growth rates and both soil and climatic indices in Tasmania. Moisture availability will probably limit growth on sites with less than 800 mm rainfall and fertiliser additions are not likely to be justified in these areas (Weston 1991), particularly if the soils are not at least moderately fertile (Orme *et al.* 1992).

Land converted to eucalypt plantations is intensively cultivated, ripped and often mounded to increase root penetration but the major concern is weed control as eucalypts are more susceptible to competition and to chemical treatments than exotic pines. There were early plantation failures and depressed growth rates following fertilisation in plantations established where weeds were not controlled. Fertiliser tablets (NP or NPK) have been widely used, generally to provide a nutrient source to enable trees to 'get away' quickly rather than to meet their nutrient requirements. It is

---

[11] R. Harper, Department of Conservation and Lands, Como, W.A.

unlikely that the rates applied are either biologically or economically optimal (Ritson *et al.* 1991, Weston[12] pers. comm.), given the dramatic increases in early growth rates demonstrated for both temperate (Cromer and Williams 1982,) and sub-tropical species (Birk and Turner 1992, Cromer *et al.* 1993a). Fertiliser rates applied in *E. grandis* super-culture trials (Birk and Turner 1992, Cromer *et al.* 1993a, b) demonstrate the limitations of the native soils nutrient supplies, even in moderately fertile sites, but exceeded optimum biological and economic rates.

Eucalypt plantations commonly respond to N and P but there are variations with soil fertility and species requirements. There appears to be a reduced response to N on more fertile soils in the Latrobe Valley of Victoria (Weston, pers. comm.) and this trend is expected on ex-pasture sites. On farmland sites in W.A., *E. globulus* and *E. sideroxylon* only responded to phosphorus while *E. microcarpa* did not respond to either N or P at planting (Ritson *et al.* 1991). However, the rates being applied in W.A.(McGrath pers. comm.) and in state-owned plantations in Tasmania (Neilsen 1990). are the same as for pine. One private company which has been establishing plantations for several years in Tasmania applies N and P (plus K) to *E. regnans*, *E. globulus* and *E. nitens* on ex-native forest sites at double the rate applied to *P. radiata* and the trees are refertilised after 12 months (Naughton[13] , pers. comm.). Many fertiliser trials have been established recently in new plantings of temperate and sub-tropical species to devevlop appropriate establishment fertiliser prescriptions for specific site types.

---

12 C. Weston, School of Forestry, University of Melborune, Creswick, Victoria

13 P. Naughton, Forest Resources, Tasmania

Fertiliser rates for eucalypt plantations are expected to be higher than the current prescriptions for pine because nutrient accumulation per tonne of dry weight (particularly P and Ca) by eucalypt plantations exceeds that of pine plantations and native eucalypt forests (Figure 5) (Birk and Turner 1992). The timing and quantity of fertiliser applied by Cromer *et al.* (1993b) was calculated to parallel the expected pattern of nutrient accumulation in *E. grandis* and the results showed a close relationship for the first 2 years; uptake subsequently declined despite continued applications (Figure 6). This decline is rapid compared with pine plantations and reflects the rapid rate of crown closure in eucalypt plantations. Our potential to use foliage analysis to monitor nutrition in routine eucalypt operations is currently limited by inadequate baseline data (Judd *et al.* 1991).

There is a concern that improving the nutrient status of eucalypt plantations with high rates of fertiliser will increase susceptibility to insect defoliation or disease (Adams and Atkinson 1991, Stone 1993). Some trials have been completely defoliated or lost through fungal attacks (Cromer *et al.* 1991). Provenance selection and tree breeding are being addressed to improve the productive potential of eucalypt plantations although initial emphasis is on characteristics of form and yield and insect and disease resistance (Nambiar and Booth 1991) rather than nutrient or water use .

THE POTENTIAL FOR IMPROVING FERTILISER PRACTICES

Empirical fertiliser trials have been and may continue to be the major research tool used to determine optimum fertiliser prescriptions in plantations. With more intensive management, however, there is a "need to develop a more comprehensive understanding of the timing of peak demands and changes in requirements, nutrient interactions, changes in nutrient availability and effects of climate" (Turner and Lambert 1986a). It is therefore important to complement empirical trials with process studies aimed at explaining the nature of responses observed. There have been notable examples where soil processes controlling nutrient supply have been examined including the work on phosphorus fixation (Gentle and Humphreys 1968, Truman *et al.* 1983, Truman and Humphreys 1985), boron retention (Ryan 1989, Lambert and Ryan 1990), zinc movement (Brennan and McGrath 1988), and nitrogen availability (Smethurst and Nambiar 1989, 1990a, b). For elements with strong reactions in soils with moderate to strong nutrient retention capacities (eg P in fine textured soils) there is a need to focus on interactions between fertilisers and geochemical properties of the soil whereas interactions between fertilisers and organic materials are of more concern in soils with low nutrient retention.

Current fertiliser regimes aim to recognise, and are geared to coincide with, major periods of nutrient demand. The efficacy of nutrient amendments is increased if supplied during periods when demand exceeds availability of native soil supplies, at rates which minimise the potential for loss of excess nutrients. Timing of fertiliser applications is critical in this regard, as is the type of fertiliser used, method of application, and the soil's capacity to retain nutrients. The timing of fertiliser treatment is more critical for elements with weak soil reactions (eg B, N) since they are more susceptible to loss from the system by leaching and ionic exchange processes.

It is also important to understand factors affecting changes in nutrient availability with and without fertilisers. Nitrogen appears to replace phosphorus as the primary growth-limiting element later in stand development and into the second rotation. Fertiliser prescriptions need to account for shifts in nutrient availability and changes in site nutrient capital. With the conservation and turnover of forest floor materials, and thinning and harvest residues, organic forms of N and P are likely to be more important that inorganic forms in older stands and later rotations. There is considerable scope for further research in this area and to understand the factors controlling changes in nutrient availability in plantation forests as they mature.

While these studies can be expected to improve the efficiency of nutrient and fertiliser use in plantations, other constraints will limit the operational use of fertilisers. Decisions to carry out treatments are based on economic considerations and trade-offs between various management objectives competing for limited dollars, including the environmental sustainability of forest soils,. There are additional pressures to reduce costs by carrying out uniform treatments to reduce labour costs associated with fertiliser application. Inevitably, nutritional management practices will continue to evolve in response to changes in management objectives, changes in fertiliser technology and increased understanding of nutritional requirements and soil processes.

ACKNOWLEDGMENTS

Much of the information regarding current practices in pine and eucalypt plantations was generously provided by forest managers and colleagues in each State. I wish to thank the following people for their contributions and suggestions: J. Turner, R. Orman, M. Pettit, M. Hall, C. Reinhart and C. Day from State Forests of New South Wales, R. Boardman and M. Bleby of the South Australian Department of Primary Industries, P. Hopmans of the Victorian Department of Conservation and Natural Resources, J. McGrath of the Western Australian Department of Conservation and Land Management, J. Simpson of the Queensland Forest Research Institute, B.

Neilsen of the Tasmanian Forestry Commission, R. Heathcote, formerly of Australian Paper Mills (Tas.), P. Naughton of Forest Resources (Tas.) and P. Ryan, P. Smethurst, C. Carlyle, R. Cromer and C. Turnbull of the CSIRO Division of Forestry. I also wish to thank R. Boardman, J. Simpson and J. McGrath for making helpful comments on the manuscript.

REFERENCES

ADAMS, M.A.; ATKINSON, P.I. 1991: Nitrogen supply and insect herbivory in eucalypts: the role of nitrogen assimilation and transport processes. *In* 'Third Australian Forest Soils and Nutrition Conference 'Productivity in Perspective' (P.J. Ryan, Ed). pp. 239-41. 7-11 October 1991. Melbourne. Forestry Commission of NSW: Sydney.

AUSTRALIAN BUREAU OF AGRICUTURAL RESOURCES AND ECONOMICS. 1992: Australian Forest Resources 1990 and 1991. Commonwealth of Australia.

BEVEGE, D.I.; RICHARDS, B.N. 1972: Principles and practices of foliar analysis as a basis for crop logging in pine plantations. II. Determinations of critical phosphorus levels. *Plant and Soil 37*: 159-70.

BIRK E.M. 1990: Poor tree form of *Pinus radiata* D.Don on former pasture sites in New South Wales. *Australian Forestry 53*: 104-12.

BIRK E.M. 1992: Nitrogen availability in radiata pine plantations on previously improved and unimproved pastures. *Plant and Soil 143*: 115-25.

BIRK, E.M. 1993: Biomass and nutrient distribution in radiata pine in relation to previous land use II Nutrient accumulation, distribution and removal. *Australian Forestry 56:* 148-56.

BIRK E.M.; TURNER J. 1992: Response of flooded gum (*E. grandis*) to intensive cultural treatments: biomass and nutrient content of eucalypt plantations and native forests. *Forest Ecology and Management 47:* 1-28.

BOARDMAN, R. 1974: Pine stand improvement in the south-eastern region of South Australia. Woods and Forest Department South Aust. Bulletin No 21

BOARDMAN, R. 1988: Living on the edge - the development of silviculture in South Australian plantations. *Australian Forestry 51*: 135-56.

BOARDMAN, R. 1991: Impacts on planted trees and soils of re-using effluents and waste waters in Australian environments - a review. *In* 'Third Australian Forest Soils and Nutrition Conference 'Productivity in Perspective' (P.J. Ryan, Ed). pp. 87-106. 7-11 October 1991. Melbourne. Forestry Commission of NSW: Sydney.

BOARDMAN, R.; MCGUIRE, D.O. 1990: The role of zinc in forestry II. Zinc deficiency and forest management: Effect on yield and silviculture of *Pinus radiata* plantations in South Australia. *Forest Ecology and Management 210*: 207-18.

BOOMSMA, D. B. 1982: Herbicide usage in the establishment of coniferous plantations in Australia and New Zealand. *In* 'Establishment of Coniferous Plantations'. pp. 59-72. 20-23th September 1982. Mount Gambier, S.A. Woods and Forests Department, S.A.:

BOOMSMA, D. B.; HUNTER, I.R. 1990: Effects of water, nutrients and their interactions on tree growth and plantation forest management practices in Australasia: a review. *Forest Ecology and Management 30*: 455-76.

BRENNAN, R.F.; MCGRATH, J.F. 1988: The vertical movement of zinc on sandy soils in southern Western Australia. *Australian Journal Soil Research 26:* 211-16.

BROCKWELL, J.; LUDBROOK, W.A. 1962: The response to phosphate of *Pinus* growth on infertile soils in New South Wales. CSIRO Division Plant Industry Division Report No. 22

CARLYLE, J.C.; TURVEY, N.D.; HOPMANS, P.; DOWNES, G.M. 1989: Stem deformation in *Pinus radiata* associated with previous land use. *Canadian Journal Forest Research 19*: 96-105.

CELLIER, K.M.; BOARDMAN, R.; BOOMSMA, D.B.; ZED, P.G.: Response of *Pinus radiata* D.Don to various silvicultural treatments on adjacent first and second roation sites near Tantanoola, South Australia. I. Establishment and growth up to age 7 years. *Australian Forest Research 15*: 431-47.

CELLIER, K.M.; STEPHENS, C.G. 1980a: Effect of fertiliser and weed control on the early growth of *Pinus radiata* D. Don in southern Australia. *Australian Forest Research 10:* 141-53.

CELLIER, K.M.; STEPHENS, C.G. 1980b: Effect of weed control and fertiliser placement on the establishment and early growth of *Pinus radiata* in southern Australia. *Australian Forest Research 10:* 361-9.

CRANE, W.J.B. 1981: Nitrogen fertilisation and *Pinus radiata*. *In* 'Managing Nitrogen Economies of Natural and Man Made Forest Ecosystems'. pp. 327-39. 5-9 October 1980. Mandurah, W.A. CSIRO Division Land Resources Management:

CRANE, W.J.B. 1982: Fertiliser treatment of *Pinus radiata* at establishment and at thinning - an evaluation of its potential in Australia. *New Zealand Journal Forestry Science 12:* 293-307.

CROMER, R.N.; CAMERON, D.M.; RANCE, S.J.; RYAN, P.A.; BROWN, M. 1993a: Response to nutrients in *Eucalyptus grandis*. 1. Biomass accumulation. *Forest Ecology and Management 62*: 211-30.

CROMER, R. N.; CAMERON, D.M.; RANCE, S.J.; RYAN, P.A.; BROWN, M. 1993b: Response to nutrients in *Eucalyptus grandis*. 2. Nutrient accumulation. *Forest Ecology and Management 62*: 231-43.

CROMER, R.N.; RYAN, P.A.; BOOTH, T.H.; CAMERON, D.M.; RANCE, S.J. 1991: Limitations to productivity of *Eucalyptus grandis* plantations in sub-tropical Australia. *In* 'Third Australian Forest Soils and Nutrition Conference 'Productivity in Perspective'. pp. 133-46. 7-11th October 1991. Melbourne. Forestry Commission of NSW: Sydney.

CROMER. R.N.; WILLIAMS, E.R. 1982: Biomass and nutrient accumulation in a planted *E. globulus* (Labill.) fertiliser trial. *Australian Journal of Botany 30*: 265-78.

FARRELL, P.W. 1984: Radiata pine residue management and its implications for site productivity on sandy soils. *Australian Forestry 47*: 95-102.

FERGURSON, I.S. 1991: Plantation development in Australia: past, present and perhaps. *In* 'Third Australian Forest Soils and Nutrition Conference 'Productivity in Perspective' (P.J. Ryan, Ed). pp. 7-14. 7-11 October 1991. Melbourne. Forestry Commission of NSW: Sydney.

FIFE, D.N.; NAMBIAR, E.K.S.; EVANS, R. 1993: Effects of nitrogen on growth and properties of stem wood of *Pinus radiata* families. CSIRO User Series No 8, 17p.

FLINN, D.W.; HOPMANS, P.; FARRELL, P.W.; JAMES, J.M. 1979: Nurient loss from the burning of *Pinus radiata* logging residue. *Australian Forest Research 9*: 17-23.

FLINN, D.W.; HOPMANS, P.; MOLLER, I.; TREGONNING, K. 1979: Response of radiata pine to fertilisers containing N and P applied at planting. *Australian Forestry 42*: 125-31.

FLINN, D.W.; JAMES, J.M.; HOPMANS, P. 1982:: Aspects of phosphorus cycling in radiata pine on a strongly phosphorus-adsorbing soil. *Australian Forest Research 12*: 19-35.

GENTLE, S.W.; HUMPHREYS, F.R. 1968: Experience with phosphatic fertilisers in man-made forests of *Pinus radiata* in New South Wales. *In* 'Ninth Commonwealth Forestry Conference, India'.pp. 37p. 1967. Forestry Commission NSW.

GENTLE, S.W.; HUMPHREYS, F.R.; LAMBERT, M.J. 1965: An examination of a *Pinus radiata* phosphate fertilizer trial fifteen years after treatment. *Forest Science 11*: 315-24.

GENTLE, S.W.; HUMPHREYS, F.R.; LAMBERT, M.J. 1986: Continuing response of *Pinus radiata* to phosphatic fertilisers over two rotations. *Forest Science 32:* 822-29.

HALL, M. 1984: Establishment of radiata pine on a high altitude second rotation site. I. Effect of site preparation on early survival and growthl. *Australian Forestry 48*: 79-83.

HALL, M. 1985: Establishment of radiata on a high altitude second rotation site. II. Effect of site preparation on nutrient capital. *Australian Forestry 47*: 194-98.

HILL, J.H.; LAMBERT, M.L. 1981: Physiology and management of micronutrients in forest trees in Australasia. *In* 'Proceedings Australian Forest Nutrition Workshop 'Productivity in Perpetuity'. pp. 93-103. 10 - 14th August, 1981. Canberra, Australia. CSIRO.

HOPMANS, P.; FLINN, D.W.; GEARY, P.W.; TOMKINS, I.B. 1993: Sustained growth response of *Pinus radiata* on podsolised sands to site management practices. *Australian Forestry 56*: 27-33.

HUMPHREYS, F.R. 1964: The nutrient status of pine plantations in central New South Wales. *Appita 18*; 111-21.

HUMPHREYS, F.R. 1977 Establishment fertiliser practice in NSW. *In* 'Use of fertilisers in New Zealand Forestry'. New Zealand Forest Service FRI Symposium No 19, pp. 123-4.

JOHNSTON, T. 1982: Cultivation. *In* 'Establishment of Coniferous Plantations'. pp. 25-9. 20-23th September 1982. Mount Gambier, S.A. Woods and Forests Department, S.A.:

JUDD, T.S.; ATTIWILL, P.M.; ADAMS, M.A. 1991: Foliar diagnosis of plantations of *Eucalyptus globulus* and E. *nitens* in southeastern Australia. *In* 'Third Australian Forest Soils and Nutition Conference 'Productivity in Perspective' (P.J. Ryan, Ed). pp. 162. 7-11th October 1991. Melbourne. Forestry Commission of NSW: Sydney.

KEEVES, A. 1966: Some evidence of loss of productivity with successive rotations of *Pinus radiata* in the south-east of South Australia. *Australian Forestry 30*; 51-63.

KESSELL. L.; STOATE, T.N. 1938: Pine nutrition. An account of investigations and experiments in connection with the growth of exotic conifers in Western Australian plantations. W.A. Forests Department Bulletin No. 50, 45p.

KELLY, J.; LAMBERT, M.L. 1972: The relationship between sulphur and nitrogen in the foliage of *Pinus radiata*. *Plant and Soil 37*: 395-407.

KESSEL,L, S.L.; STOATE, T.N. 1938: Pine nutrition. A account of investigations and experiments in connection with the growth of exotic conifers in Western Australian plantations. W.A. Forestry Department Bulletin No. 50. 45p.

KNOTT, J.; TURNER, J. 1990: Fertiliser usage in Forestry Commission of N.S.W. 1955-1989. Technical Paper No 51 Forestry Commission NSW 95p.

KNOTT, J.; RYAN, P. 1990: Development and practical application of a soils database for the *Pinus* plantations of the Bathurst Region. Research Paper No. 11, Forestry Commission of N.S.W. 85p.

LAFAN, M.D. 1993: Site productivity and land suitability for eucalypt and radiata pine plantations in Tasmanian State Forest: A framework for classification and assessment in land resources. Forestry Commission, Tasmania, Soils Technical Report No.3

LAMBERT, M.J. 1986: Sulphur and nitrogen nutrition of *Pinus radiata* at Nundle State Forest, New South Wales, Australia. *Canadian Journal Forest Research 16*: 1055-62

LAMBERT, M.J.; RYAN, P.J. 1990: Boron nutrition of *Pinus radiata* in relation to soil development and management. *Forest Ecology and Management 30*; 45-54.

LAMBERT, M.L.; TURNER, J. 1977: Dieback in high site quality *Pinus radiata* stands - the role of sulphur and boron deficiencies. *New Zealand Journal Forest Science 7*; 333-48.

LAMBERT, M.J.; TURNER, J. 1986: Post-establishment phosphatic fertiliser treatments in a New South Wales *Pinus radiata* plantation. *Fertilizer Research 10*: 263-68.

LAMBERT, M.J.; TURNER, J. 1988: Interpretation of nutrient concentrations in *Pinus radiata* at Belanglo state forest. *Plant and Soil 108*: 237-44.

LEWIS, N.B.; KEEVES, A.; LEECH, J.W. 1976: Yield regulation in South Australian *Pinus radiata* plantations. Woods and Forests Department South Australia Bulletin No 23

LUDBROOK, W.V. 1937: Needle fusion of species of *Pinus* in Southern New South Wales. Progress report, 1933-36. Coun. Science Industry Australia, Pamphlet No. 72.

NAMBIAR, E.K.S.; BOOTH, T.H. 1991: Environmental constraints on the productivity of eucalypts and pine: opportunities for site management and breeding. *In* 'Third Australian Forest Soils and Nutrition Conference 'Productivity in Perspective' (P.J. Ryan, Ed). pp. 215-31. 7-11th October 1991. Melbourne. Forestry Commission of NSW: Sydney.

NAMBIAR, E.K.S.; CELLIER, K.M. 1985: Nitrogen fertiliser in establishing *Pinus radiata* plantations on sandy soils: an evaluation of their use. *Australian Forestry 48*: 242-51.

NAMBIAR, E.K.S.; NETHERCOTT, K.H. 1987: Nutrient and water availability to and growth of young radiata pine plantations intercropped with lupins. *New Forests 1*: 117-34.

NEILSEN, W.A. 1982: Use of fertilisers in establishing and growing coniferous plantations in Australia. *In* 'Establishment of Coniferous Plantations'. pp. 79-92. 20-23 September 1982. Mount Gambier, S.A. Woods and Forests Department, S.A.

NEILSEN, W.A. 1990: 'Plantation Handbook' Tasmanian Forestry Commission, 270p:

NEILSEN, W.A.; PATCZEK, W.; LYNCH, T.; PYRKE, R. 1992: Growth responses of *Pinus radiata* to multiple applications of nitrogen fertiliser and evaluation of the quantity of added nitrogen remaining in the forest system. *Plant and Soil 144*: 207-17.

O'CONNELL, A.M.; GROVE, T.S. 1991: Factors contributing to the nutritional resiliance or vulnerability of jarrah and karri forests in Western Australia. *In* 'Third Forest Soils and Nutrition Conference "Productivity in Perspective" (P.J. Ryan, Ed). pp. 180-97. 7-11th October 1991. Melbourne. Forestry Commission NSW.

ORME, K.; ORR, S.; GERRAND, A.; TODD, G. 1992: Potential of low fertility sites for plantations in north-eastern Tasmania. *Tasforests July*: 69-75.

PEGG, R.E. 1967: Relation of slash pine site index to soil, vegetation and climate in south-east Queensland. Queensland Forest Department Research Note No. 19, 53p.

RAUPACH, M.; BOARDMAN, R.; CLARKE, A.R.P. 1969: Growth rates of *Pinus radiata* D.Don in relation to foliar levels of nitrogen and phosphorus in the south-east of South Australia. Soil Publication No 26 CSIRO, 28p.

RITSON, P.; PETTIT, N.E.; MCGRATH, J F. 1992: Fertilising eucalypt at plantation establishment on farmland in south-west Western Australia. *Australian Forestry 54*: 139-47.

RYAN, P.J. 1989: Boron retention within a catena of Rhyolitic soils and its effect on radiata pine growth and nutrition. *Australian Journal Soil Research 27*: 135-48.

RYAN, P J.; KNOTT, J.H. 1991: Use of the Technical Soil Classification in NSW Softwood Plantations. *In* 'Third Australian Forest Soils and Nutrition Conference 'Productivity in Perspective' (P.J. Ryan, Ed). pp. 39-51. 7-11th October 1991. Melbourne. Forestry Commission of NSW: Sydney.

SIMPSON, J.A. 1991: Changing land resource, taxa preference and fertiliser use in exotic pine plantations in south east Queensland. *In* 'Third Forest Soils and Nutrition Conference "Productivity in Perspective" (P.J. Ryan, Ed). pp. 31-32. 7-11th October 1991. Melbourne. Forestry Commission NSW.

SIMPSON, J.A.; GRANT, M.J. 1991: Exotic pine fertiliser practices and its development in Queensland. Queensland Forest Service Technical Paper No. 49, 17p.

SIMPSON, J.; OSBORNE, D.O. 1993: Relative fertiliser requirements and foliar nutrient levels of young slash pine, Honhuras Caribbean pine and the hybrid in Queensland. *Commonwealth Forestry Review 72*: 105-113.

SMETHURST, P.J.; NAMBIAR, E.K.S. 1989: Role of weeds in the management of nitrogen in a young *Pinus radiata* plantation. *New Forests 3*: 203-24.

SMETHURST, P.J.; NAMBIAR, E.K.S. 1990a: Distribution of carbon and nutrients and fluxes of mineral nitrogen after clearfelling a *Pinus radiata* plantation. *Canadian Journal of Forest Research 20*: 1490-97.

SMETHURST, P.J.; NAMBIAR, E.K.S. 1990b: 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*: 1498-507.

SQUIRE, R.O. 1977: Interactive effects of grass competition, fertilising and cultivation on the early growth of *Pinus radiata* D. Don. *Australian Forest Research 7*: 247-52.

SQUIRE, R.O. 1983: Review of second rotation silviculture of *Pinus radiata* plantations in southern Australia: establishment practice and expectations. *Australian Forestry 46*: 83-90.

SQUIRE, R.O.; FARRELL, P.W.; FLINN, D.W.; AEBERLI, B.C. 1985: Productivity of first and second rotation stands of pine on sandy soils II. Height and volume growth at five years. *Australian Forestry 48*: 127-37.

SQUIRE, R.O.; FLINN, D.W.; FARRELL, P.W. 1979: Productivity of first and second rotation stands of radiata pine on sandy soils. 1. Site factors affecting early growth. *Australian Forestry 42*: 236-42.

SQUIRE, R.O.; FLINN, D.W.; CAMPBELL, R.G. 1991: Silvicultural research for sustained wood production and biosphere conservation in the pine regions and native forests of south-eastern Australia. *Australian Forestry 54*: 120-33.

STANTON, R. 1991: Land evaluation for *Eucalyptus* plantation purposes in south-eastern New South Wales. *In* 'Third Australian Forest Soils and Nutrition Conference 'Productivity in Perspective' (P.J. Ryan, Ed). pp. 167. 7-11th October 1991. Melbourne. Forestry Commission of NSW: Sydney.

STANTON, R. 1992: *Eucalyptus* plantations in New South Wales. Forestry Commission of New South Wales Research Paper No. 15, 29 p.

STOATE, T. N. 1950: Nutrition of the pine. Forest and Timber Bureau Bulletin No. 30

STONE, C. 1993: Fertiliser and insecticide effects on tree growth and psyllid infestation of young *Eucalyptus grandis* and *E. dunnii* plantations in northern New South Wales. *Australian Forestry 56*: 257-63.

THEODOROU, C.; BOWEN, G.D. 1983: Nitrogen transformations in first- and second-rotation *Pinus radiata* forest soil. *Australian Forest Research 13*: 103-12.

TRUMAN, R.A.; HUMPHREYS, F.R. 1985: Prediction of phosphorus levels in the foliage of *Pinus radiata* in five forests in New South Wales by parameters derived from soil analysis. *Australian Forest Research 15*: 17-26.

TRUMAN, R.; HUMPHREYS, F.R.; LAMBERT, M.J. 1983: Prediction of site index for *Pinus radiata* at Mullions Range State Forest, New South Wales. *Australian Forestry 13*: 207-15.

TURNER, J. 1981: Interactions of nitrogen with other nutrients in coniferous stands. *In* 'Managing Nitrogen Economies of Natural and Man Made Forest Ecosystems'. pp. 311-26. 5-9th October, 1980. Mandurah, W.A. CSIRO

TURNER, J. 1982: Long-term super-phosphate trial in regeneration of *Pinus radiata* at Belanglo State Forest, N.S.W. *Australian Forest Research 12*: 1-9.

TURNER, J. 1984: Potential productivity gains in Australian east coast *Pinus radiata* plantations. *In* 'Proceedings IUFRO Symposium on Site and Productivity of Fast Growing Plantations'. pp. 947-56. Pretoria, South Africa.

TURNER, J.; HOLMES, G.I. 1985: Site classification of *Pinus radiata* plantations in the Lithgow District, New South Wales, Australia. *Forest Ecology and Management 12*: 53-63.

TURNER, J.; KNOTT, J. 1991: Prescribing fertilisers in New South Wales plantation forestry. *In* Forest Fertilisation: Nutrition and Growth of Western Forests. pp 265-71. College of Forest Resources, University of Washington, Seattle.

TURNER, J.; LAMBERT, M.J. 1986a: Nutrition and nutritional relationships of *Pinus radiata*. *Annual Reviews of Ecology and Systematics 17*: 325-50.

TURNER, J.; LAMBERT, M.J. 1986b: Fate of applied nutrients in a long-term superphosphate trial in *Pinus radiata*. *Plant and Soil 93*: 373-82.

TURNER, J.; LAMBERT, M.J. 1987: Nutritional management of *Pinus radiata* at Gurnang State Forest, New South Wales. *Fertilizer Research 13*: 127-37.

TURNER, J.; LAMBERT, M.J. 1991: Changed perspectives on soil processes associated with the changed land base of plantation forestry in Australia. *In* 'Third Australian Forest Soils and Nutrition Conference 'Productivity in Perspective' (P.J. Ryan, Ed). pp. 15-28. 7-11th October 1991. Melbourne. Forestry Commission of NSW: Sydney.

TURNER, J.; LAMBERT, M.J.; BOWMAN, V.; KNOTT, J. 1992: Two post thinning fertiliser trials in *Pinus radiata* in New South Wales, Australia. *Fertilizer Research 32*: 259-67.

TURNER, J.; THOMPSON, C.H.; TURVEY, N.D.; HOPMANS, P.; RYAN, P.J. 1990: A soil technical classification system for *Pinus radiata* (D.Don) plantations. I. Development. *Australian Journal of Soil Research 28*: 797-811.

TURVEY, N.D. 1984: Copper deficiency in *Pinus radiata* planted on a podsol in Victoria, Australia. *Plant and Soil 77*: 73-86.

TURVEY, N.D. (Ed.) 1987: 'A Technical Classification for Soils of *Pinus* plantations in Australia: Field Manual' Bulletin No.6. School of Forestry, the University of Melbourne.

TURVEY, N.D.; BOOTH, T.H.; RYAN, P.J. 1990: A soil technical classification system for *Pinus radiata* (D. Don) plantations. II. A basis for estimation of crop yield. *Australian Journal of Soil Research 28*: 813-24.

TURVEY, N.D.; RUDRA, A.B.; TURNER, J. 1986: Characteristics of soil and productivity of *Pinus radiata* (D.Don) in New South Wales. I. Relative importance of soil physical and chemical parameters. *Australian Journal Soil Research 24*, 95-102.

WALSH, J.P. 1991: Correlation of early growth rates of eucalypt plantations in Tasmania with environmental indices. *In* 'Third Australian Forest Soils and Nutrition Conference

'Productivity in Perspective' (P.J. Ryan, Ed). pp. 67. 7-11th October 1991. Melbourne. Forestry Commission of NSW: Sydney.

WARING, H. D. 1971: *Pinus radiata* and the nitrogen-phosphorus interaction. *In* 'Australian Forest-Tree Nutrition Conference'. pp. 144-60. 6-17th September 1971. Canberra. Forest and Timber Bureau: Canberra.

WARING, H. D. 1973: Early fertilisation for maximum production. *In* 'FAO-IUFRO International Symposium on Forest Fertilization'.pp. 215-42.

WARING, H. D. 1981: Forest fertilisation in Australia: early and late. In 'Australian Forest Nutrition Workshop Productivity in Perpetuity'. pp. 201-18. 10-14 August 1981. Canberra, Aust. CSIRO, Canberra

WESTON, C. J. 1991: Factors limiting the growth of eucalypts across a range of sites in Gippsland, Victoria. *In* 'Third Australian Forest Soils and Nutrition Conference 'Productivity in Perspective' (P.J. Ryan, Ed). pp. 158-159. 7-11th October 1991. Melbourne. Forestry Commission of NSW: Sydney.

WOODS, R.V. 1976: Early silviculture for upgrading productivity on marginal *Pinus radiata* sites in the south-eastern region of South Australia. Woods and Forest Department Bulletin No 24 90p.

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'. pp. 354-67. 5-9th Oct 1980. Mandurah, W.A. CSIRO

WOOLLONS, R.C.; SNOWDON, P. 1981: Theory and practice of forest fertilisation. *In* 'Australian Forest Nutrition Workshop Productivity in Perpetuity'. pp. 219-30. 10-14th August 1981. Canberra, Aust. CSIRO, Canberra

YOUNG, H.E. 1940: Fusion needle disease and its relation to the nutrition of *Pinus*. Queensland Forest Sevice Bulletin No. 13.

Figure Legends:

FIGURE 1- Relationships between stand basal area (m^2/ha)-and age for *P.radiata* grown (unfertilised) on different parent rock types in New South Wales (from Knott and Ryan 1990). For PRC codes see Table 3.

FIGURE 2- Foliage phosphorus concentrations and related Site Index (m) for *P. radiata* (from Turner and Lambert 1986a).

FIGURE 3- Areas of *Pinus* plantation in New South Wales treated with fertiliser between 1955-1989 (from Knottt and Turner 1990).

FIGURE 4- Areas of eucalypt plantation in Australia by ownership and State at 31st March 1991 (from Stanton 1992).

FIGURE 5- Nutrient accumulation (kg/ha) per unit of stand dry weight in *P. radiata* plantations, eucalypt plantations, and native eucalypt forests: a) phosphorus in eucalypt plantations and native forests, b) phosphorus in *P. radiata plantations*, c) calcium in eucalypt plantaitons and native forests, d) calcium in *P. radiata* plantations.(after Birk and Turner 1992).

FIGURE 6- a) Nitrogen applied to and accumulation in above-ground components of *E. grandis* F = fertilised; C = unfertilised control. b) Annual rate of nitrogen accumulation in above ground components (from Cromer *et al.* 1993b).

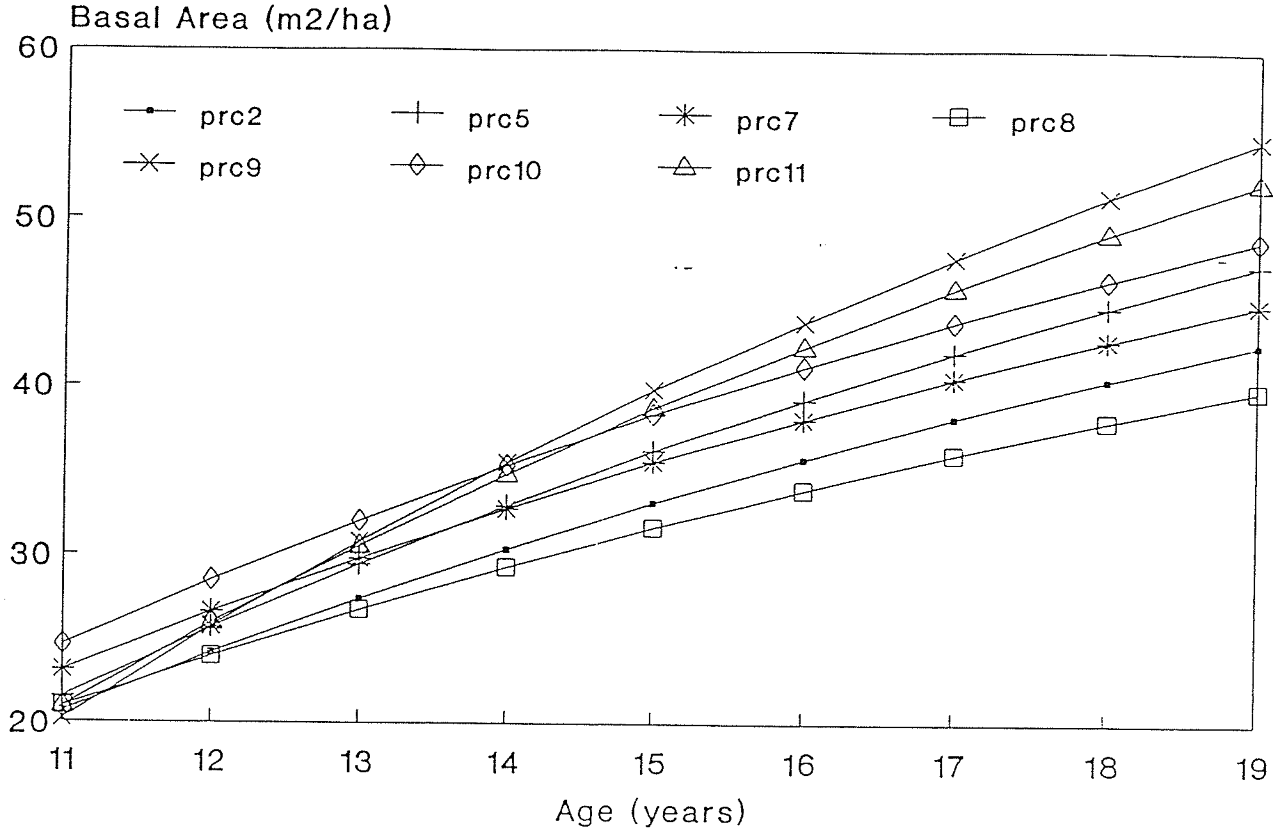


FIGURE 1- Relationships between stand basal area (m2/ha)-and age for *P.radiata* grown (unfertilised) on different Parent Rock Types in New South Wales (from Knott and Ryan 1989).

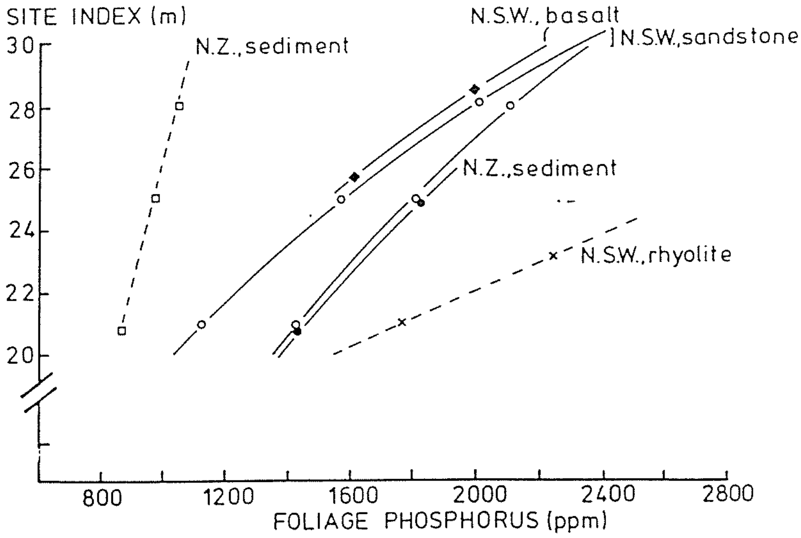


FIGURE 2- Foliage phosphorus concentrations and related Site Index (m) for *P. radiata* (from Turner and Lambert 1986a).

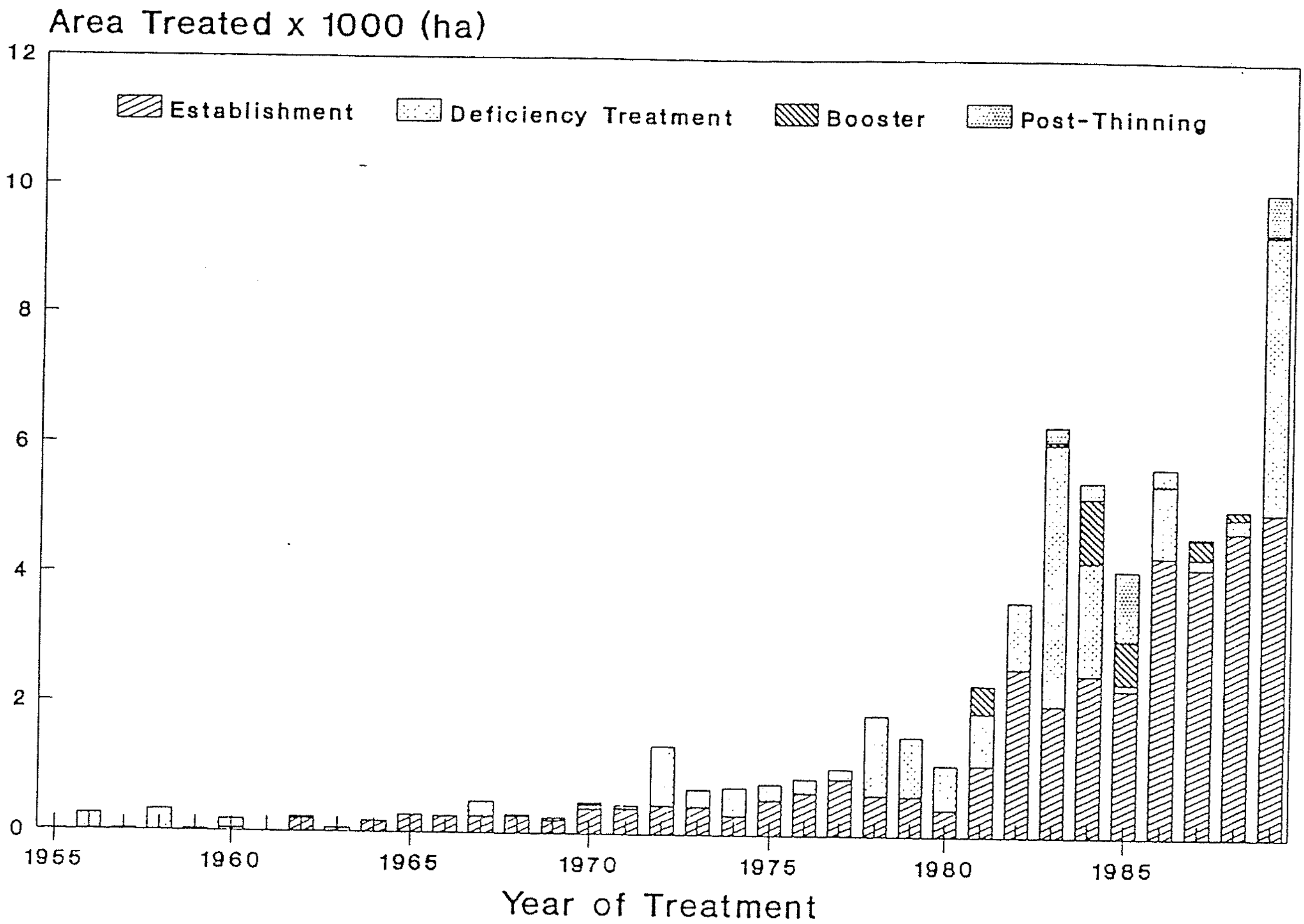


FIGURE 3- Areas of *Pinus* plantation in New South Wales treated with fertiliser between 1955-1989 (fróm Knottt and Turner 1990).

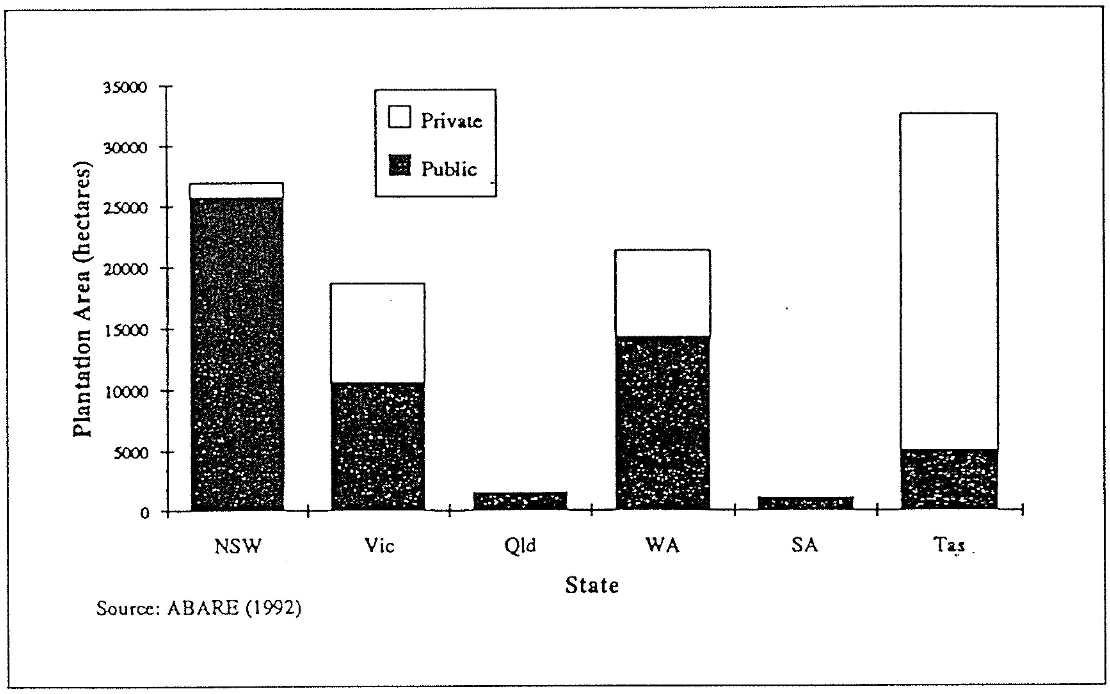


FIGURE 4- Areas of eucalypt plantation in Australia by ownership and State at 31st March 1991 (from Stanton 1992).

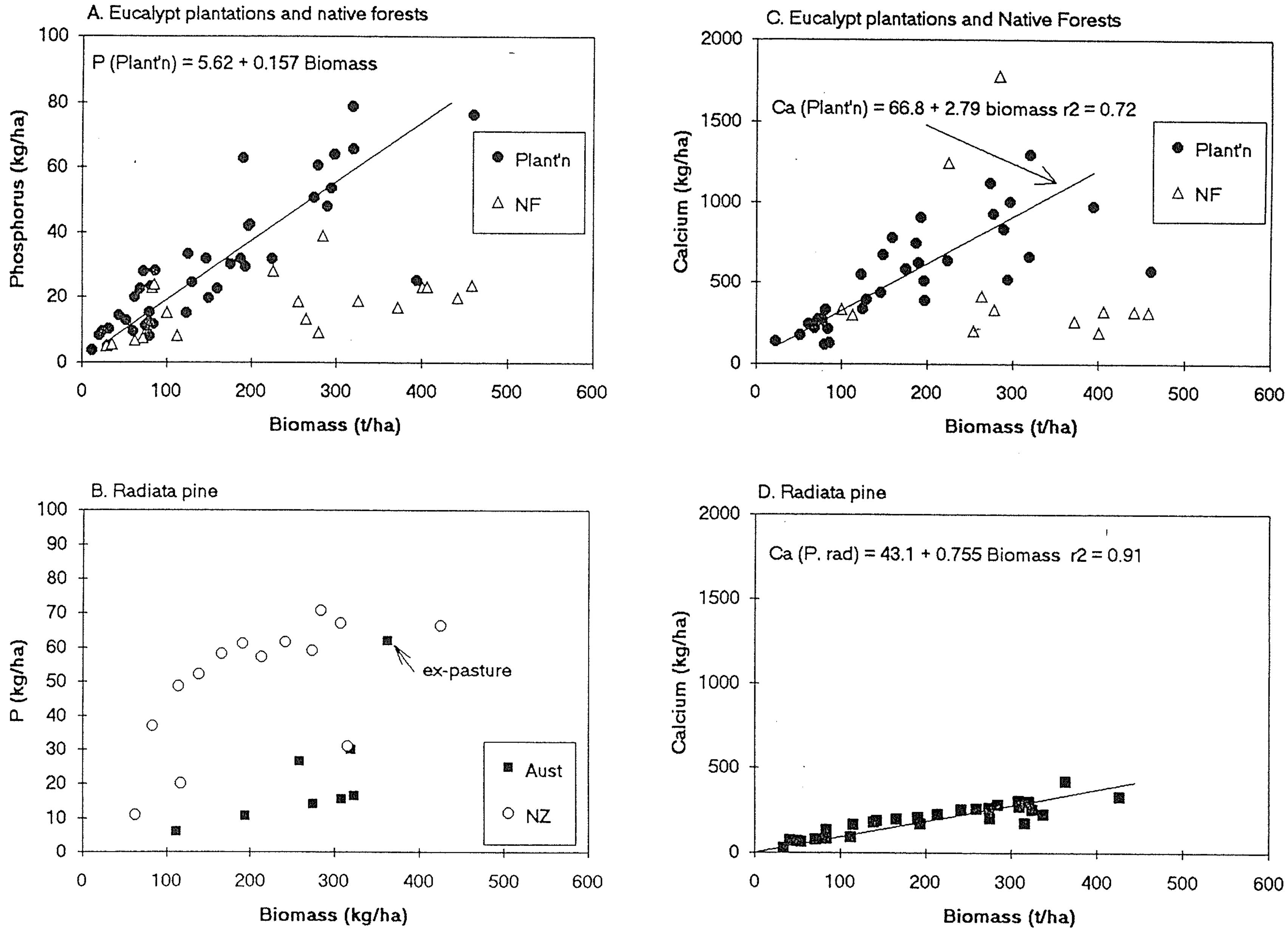


FIGURE 5- Nutrient accumulation (kg/ha) in *P. radiata* plantations, eucalypt plantations, and native eucalypt forests a) phosphorus in eucalypt plantations and native forests, b) phosphorus in *P. radiata plantations*, c) calcium in eucalypt plantaitons and native forests, d) calcium in *P. radiata* plantations.(after Birk and Turner 1992).

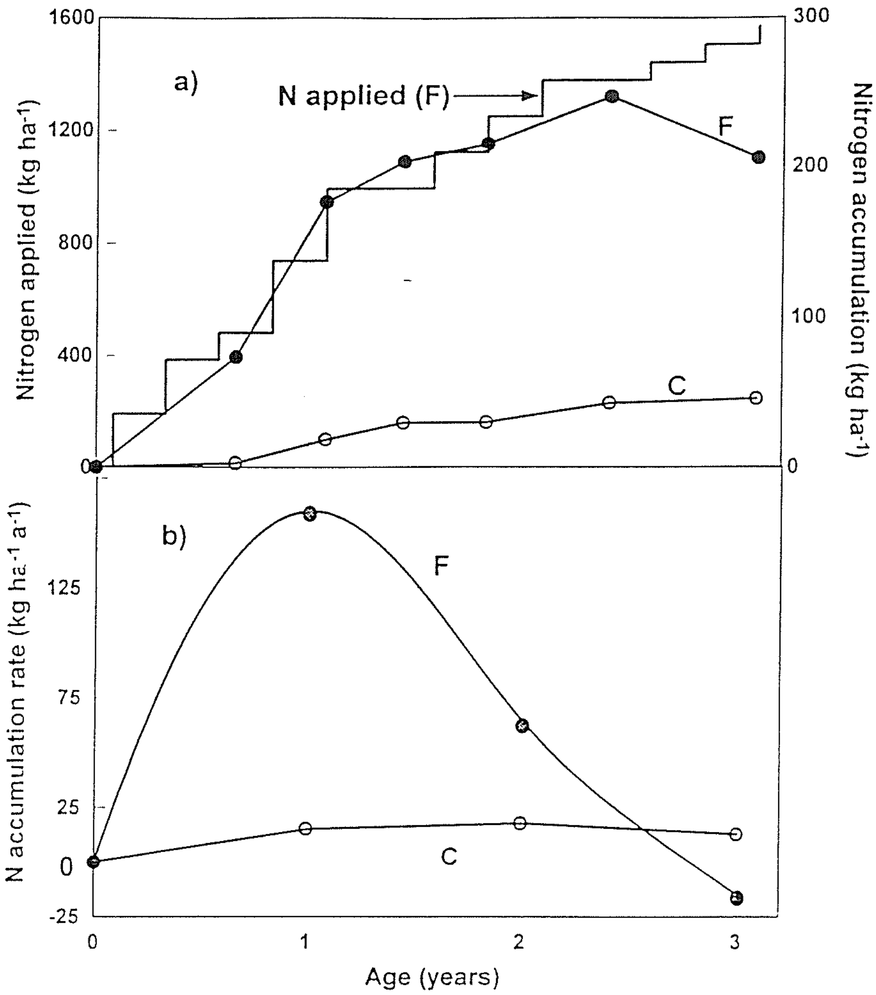


FIGURE 6- a) Nitrogen applied to and accumulation in above-ground components of *E. grandis* F = fertilised; C = unfertilised control. b) Annual rate of nitrogen accumulation in above ground components (from Cromer *et al.* 1993b).

TABLE 1-Plantation areas (ha) in 1991

	Public	Private	Total	% Total area	% Public ownership
P. radiata	443,850	236,795	680,645	66.5	65.2
Total conifers	664,472	261,934	926,406	90.6	71.7
Broadleaf	56,816	39,653	96,469	9.5	58.9
Total	721,288	301,587	1,022,875	100.0	70.5

Source: ABARE (1992)

TABLE 2-Estimate of soil parent materials according to Parent Rock Codes for Australian plantations (from Turner and Lambert 1991)

Parent Rock Code*		1970		1990	
		(ha)	(%)	(ha)	(%)
02		7,105	1.6	18,475	1.9
022	shallow	77,220	18.2	158,425	15.9
	deep	61,635	14.5	104,845	10.6
03		5,735	1.4	20,635	2.1
04					
05		147,920	34.9	352,565	35.5
06		940	0.2	1,800	0.2
07					
08		10,345	2.4	30,210	3.0
09		47,550	11.2	145,670	14.7
10					
11		65,485	15.5	161,355	16.2
12					
Total		423,935		993,965	

* see Table 3 for explanation of parent rock codes

TABLE 3-Classification of rock types according to dominant soil forming properties

Code	Parent Rock Class	Soil Forming Potential Dominated by:	Examples of rock type in each class	
			Consolidated	Unconsolidated
00	Unspecified	parent rock unknown		
01	Carbonaceous	carbon compounds	coal, carbonaceous shale	peat
02	Quartzose	quartz of secondary silica	quartzite, chert, jasper, silcrete, quartzose sandstone/conglomerate	quartz sand
03	Sesquioxide	iron and aluminium minerals or oxides	ferruginous sandstone/shale/sand, massive laterite/bauxite	
04	Calcareous	secondary calcium (and some magnesium) compounds, mainly carbonates	marble, limestone, dolomite, calcrete, highly calcareuos shale	marl, shelly sands
05	Argillaceous	clay and/or silt particles	slate, shale, siltstone, musdtone, peltic tuff, greywacke	clay mantles
06	Micaceous-chloritic	micas and/or chlorites	phyllites, schist	
07	Feldspathic-quartzose A	med. to coarse grained feldspar and quarta	granite, pegmatite, granitic gneiss, feldspathic sandstone	granitic saprolite
08	Feldspathic -quartzose B	fine to med. grained feldspar and quartz	rhyolite, ignimbrite, feldsite, rhyolitic tuff	tephra, pumice, rhyolitic ash
09	Feldspathic-micaceous	med. to coarse grained feldspar and mica	granodiorite, quartz diorite, monzonite, diorite	
10	Feldspathic	fine to med. grained alkali feldspar	trachyte, comendite, syenite	
11	Ferro-magnesium	dark silicate minerals, especially amphibole, pyroxine and olivene	spillite, basalt, dolerite, andersite, gabbro, greenstone	
12	Magnesium-silicate	ultra-basic magnesium silicates	serpentenite, periodite, talc	

Source: Turner et al. (1990), Ryan and Knott (1991)

TABLE 4-Area (ha) of plantations established in 1992

	Exotic conifers			
	2R	1R	Eucalypts	Total
NSW	1394	1348	101	2843
VIC	1114	743	325	2182
TAS	1548	464	7390	9402
WA	872	1942	4565	7379
S.A.	1723	0	24	1747
QLD	642	1808	0	2450

Source: 1991-92 or 1992-93 Annual reports from each State Agency

TABLE 5-Rates of phosphorus and nitrogen fertilizers applied at or following planting in exotic pine plantations. Alternative prescriptions in each State are selected according to site type and/or quality.

	P (g/tree)	N (g/tree)	K g/tree)	Preferred Fertilizer
P. radiata:				
NSW[a]	20-34	11-16	0	"Starter 12" (MAP Special)
	25-35	0	0	Single, or triple-superphosphate
Victoria[b]	20	0	0	Superphosphate + TE[$]
S.A. -southeast[c]	6	42	0	Forest Mix 4
S.A. - central[c]	4	0	0	Superphosphate + TE
W.A.[d]	13	16	0	Agras with TE
	11	0	0	Superphosphate + TE
TAS - public[e]	11	25	(30)[&]	EZ Lightening Pasture Fert. or EZ Orchard Mix (Ammnioum sulphate +superphosphate (+ KCl))[&]
TAS - private[f]	17	10	0	DAP/Sulfate of ammonia 10:17:0
P. pinaster:				
W.A.[d]	5.5	0	0	Superphosphate
P.caribaea x P. hondurensis				
QLD[g]	50-60*	30-35*	(50)*&	MAP* (+ potassium chloride)

[a] Knott and Turner (1990); [b] Hopmans pers. comm; [c] S.A. Woods and Forests Forestry Manual 1987; [d] W.A. Forestry Management Guide (unpub.); [e] Neilsen (1990), [f] Heathcote, (formerly Aust. Paper Mills) pers. comm.; [g] Simpson and Grant (1991).

$ TE = Trace elements

& KCl applied on on K deficient soils only

* Applied in a band along the planting row (1000 st/ha) at 50-60 kg P /ha, 30-35 kg N/ha; 50 kgK/ka and 5 kg Cu/ha area slo applied to podsols.

TABLE 6-"Booster" fertiliser treatments for *Pinus radiata* plantations

Region	Site Type	Treatment age (y)	P (kg/ha)	N (kg/ha)	K (kg/ha)	Fertilizer
NSW[a]	not specified[&]	3-6	68	0	0	Superphosphate[#]
		3-6	68	33	0	MAP Special
Victoria[b]	not specified[&]	5	64			Superphosphate[#]
TAS[c]	not specified	5	96	+	(48)[$]	50:50 Super- and rock-phosphate (+ KCl)
W.A.-central[d@]	lateritic podsols:	2, 4, 6	26	30	0	Agras + TE
	aeolian sands:	1	21	0	0	Superphosphate + TE
		2, 4, 6	26	30	0	Agras + TE
W.A. - south coast[d@]	bush & poor pasture:	2, 4, 6,	26	30	0	Agras + TE
		10, 18, 20	52	60	0	Agras + TE
	good pasture:	10, 19, 25	52	60	0	Agras + TE
S.A. - southeast[e]:	if CEG > III/IV	3, 4	0	0	0	
	if CEG < III/IV	3, 4	14*	26*	0	Forest Special Mix
S.A.- central[e]:	Prev. SQ ≤ VI on	1	26*	23*	0	DAP 18:20:0
	sands with high P-fixation ^	2	53*	48*	0	DAP 18:20:0
	CEG < SQ III/IV	3, 4	50*	45*	0	DAP 18:20:0

[a] Knott and Turner (1990); [b] Flinn et al. 1982; [c] Neilsen (pers. comm.); [d] W.A. Forest Management Guide (unpub.); [e] S.A. Woods and Forests Forestry Manual (1987) CEG= current equivalnt growth

[#]Superphosphate assumed to be 9.1% P; [$] applied on K deficient soils only

& decision to fertilise based on foliage analysis, fertiliser availability and costs

+ Responses to N have been demonstrated but the economics of routine treatments have not yet been assessed

* g per tree @ Examples of prescriptions being used in these regions; ^ Example for one site type in this region

TABLE 7-Rates of nitrogen and phosphorus fertiliser applied post-thinning.

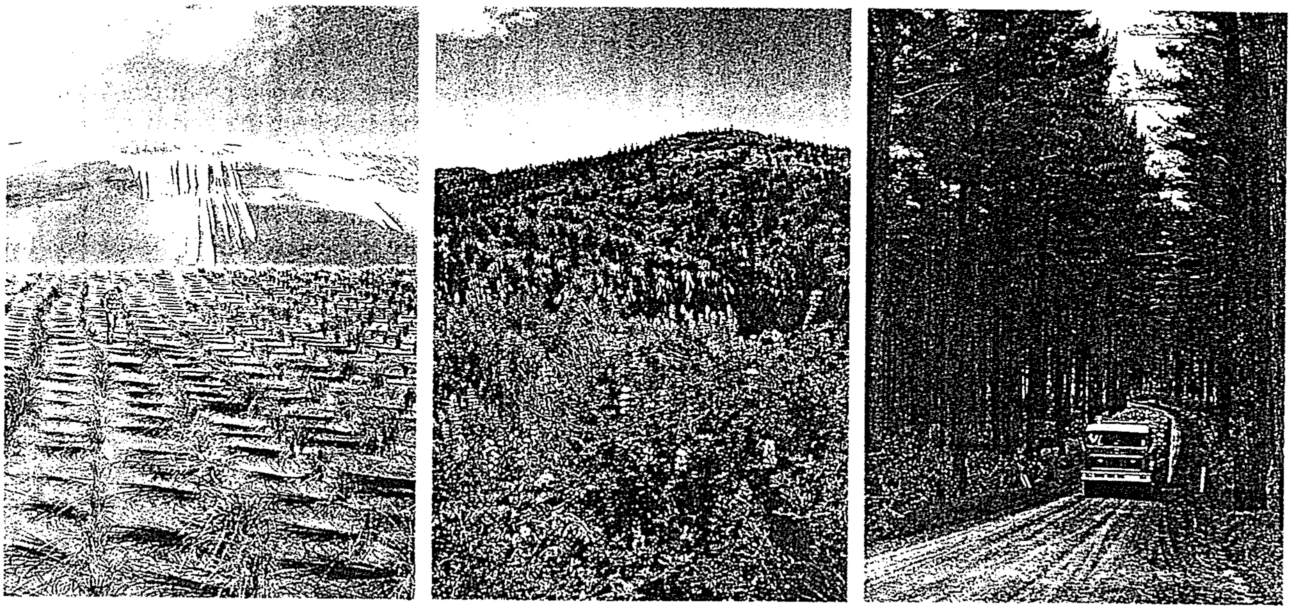
Region	Site Type	N (kg/ha)	P (kg/ha)	N:P ratio
VIC[a+]	not specified	250	50	5:1
S.A. south-east[b+]	not specified	166	26	6:1
S.A. central[b+]	not specified	74	41	1.8:1
W.A.[c+ #]	deep aeolian sands	30	26	1.2:1
	lateritic podsolics	60	52	1:1
	'Hills' ex-bush	120	104	1:1
NSW*	shale (Bondi S.F)	400	75	5:1
	shale (Carabost S.F.)	200	225	0.8:1
	granodiorite (Green Hills S.F.)	200	225	0.8:1
	quartzose-sand. (Penrose S.F.)	200	75	2.6:1

a Hopmans (pers. comm.); b S.A. Woods and Forestsl (1987); c W.A. Dept of C.A.L.M Forest Management Guide
+ operational prescritpions
# selection from the range of prescriptions being used
* optimum rates from post-first thinning fertiliser trials (Turner and Knott (1991)

WHAT'S NEW IN FOREST RESEARCH

No. 170 1988

Managing nitrogen in sand-dune forests



Stages in the establishment of a sand-dune forest. Left to right: sand planted with marram grass; lupins and young radiata pine; mature forest.

The concept of using radiata pine to stabilise sand dunes and protect valuable coastal farmland was adopted in New Zealand around the 1920s. Early efforts to establish seedlings on sand dunes met with failure: the harsh environment associated with the wind-driven, nitrogen-deficient sand killed the seedlings. However, by planting marram grass to stabilise the dunes and then sowing yellow tree lupin to add nitrogen (N) to the sand, forest managers so modified the environment that radiata pine seedlings survived and grew. In fact, the radiata pine forests that were established on sand dunes in the 1940s have become a valuable source of New Zealand's timber, exceeding the original purpose, which was to stabilise the dunes.

The success of these first crop stands is largely a result of the addition of N to the sand dunes by the lupins, at stand establishment and again whenever the stands have been thinned and lupins have regenerated. The Soils and Site Amendment group and the Tree Physiology and Stand Productivity group of FRI have been investigating whether productivity can be further increased in:

- first rotation stands, by inputs of N fertiliser
- second rotation stands, by conserving the logging debris, "slash", left on the site from the harvesting of the first crop.

Research efforts have also been directed at an issue critical to these studies: how trees use the available N for growth and productivity.

FOREST RESEARCH INSTITUTE
PRIVATE BAG, ROTORUA, NEW ZEALAND.

The trials for this research were in Woodhill Forest, a typical sand-dune forest located on the North Island's west coast, 70 km north of Auckland. Like most of New Zealand's mature sand-dune forests, it is a first crop forest that relied on marram grass and lupins for establishment and growth.

The nitrogen cycle

In any ecosystem, N is continually being recycled by natural processes. Nitrogen enters the cycle in precipitation and by biological fixation from the atmosphere (Fig. 1). In the coastal sand-dune forests, N additions in precipitation are about 4 kg/ha/yr, far less than the amount required for tree growth. Bacteria present in the soil invade the roots of lupins and, by a complicated chemical process known as N-fixation, absorb N from the air at a rate of up to 160 kg/ha/yr. As parts of the lupin plants die and decompose, this N is released back into the soil. Most of this N is taken up by plants for growth, but when there is more N available than is taken up, the excess is leached to groundwater. Within the tree, most N is in the foliage, with lesser amounts in other components. Tree N is returned to the soil in dead leaves, roots, stems, and branches. The dead plant material, or litter, is slowly decomposed and the N that is released is recycled back to the tree. The availability of N depends on the rate of the slowest process in the N cycle.

Manipulating nitrogen inputs

Scientists have been monitoring the productivity of radiata pine stands in Woodhill Forest which have been receiving experimentally controlled inputs of N. Each stand received one of four treatments (listed in order of increasing N input):

(1) Control treatment. Lupins sown, then crushed at tree planting, and further lupin regrowth excluded. No fertiliser added.

(2) Lupin management as for (1) except that lupin regrowth encouraged after tree planting. No fertiliser added.

(3) Lupins excluded as for (1). Nitrogen fertiliser added twice yearly for 10 years.

(4) Normal lupin management. Nitrogen fertiliser added as for treatment (3).

Differences in productivity between the treatments became evident when the trees were 7 years old, and progressively increased (Fig. 2). By age 17, the most productive stands were clearly those that had received the greatest N input, from lupins and fertiliser (i.e., the fourth treatment). These stands had accumulated nearly twice as much stem dry matter as the least productive stands, a result of a sustained increase in their productivity after age 10 – despite the fact that fertiliser application had ceased 7 years ago.

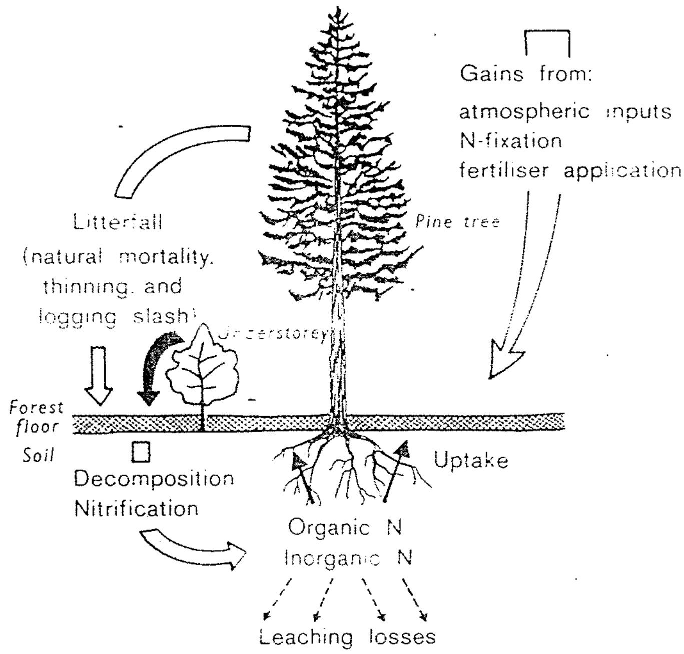


FIG. 1 — The nitrogen cycle

These trends in stemwood productivity can be explained by the data from this and another study on N accumulation of first rotation stands of unthinned radiata pine that had received normal lupin management (*see* Fig.3; Fig. 4, "lupin"). Stand N rapidly rose as a result of N-fixation by the lupins which had developed prolifically from seed or from sprouts produced by the crushed plants. The radiata pine trees, planted when the lupins were crushed, used this readily available N for growth. By about 6 years after planting, the canopy had closed over, supressing the lupin understorey. With the N-fixing lupin supressed, further increases in ecosystem N ceased. However, an important change in the distribution of N within the ecosystem then occurred.

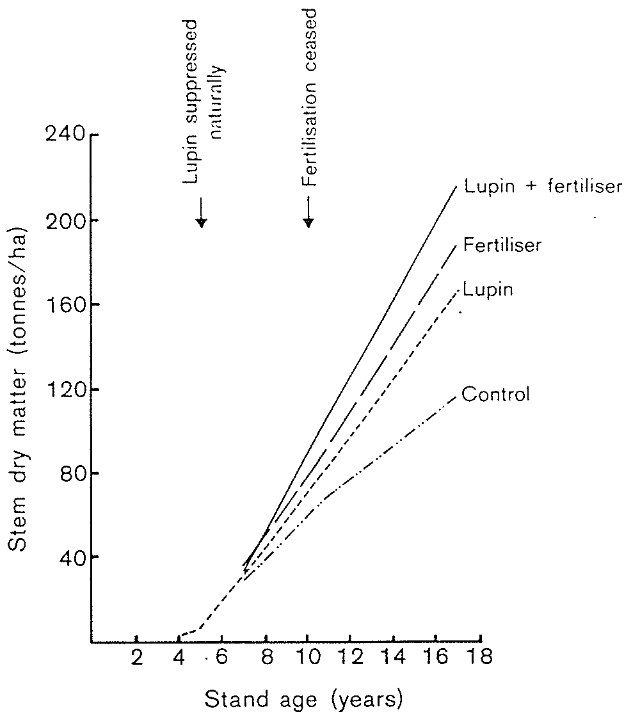


FIG. 2 — The effect of N input on the productivity of unthinned radiata pine, planted at 2200 stems/ha

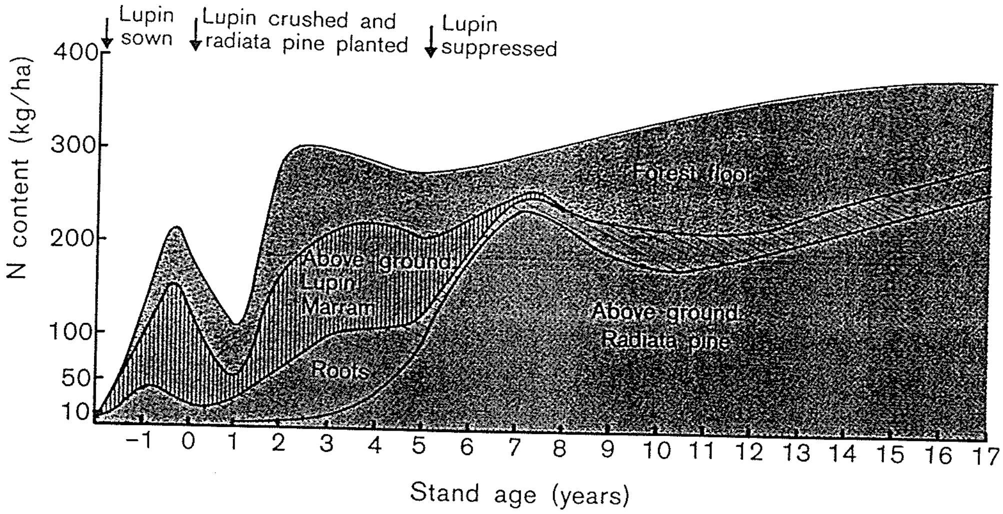


FIG. 3 (left) — The accumulation of N in the various components of a radiata pine stand with normal lupin management.

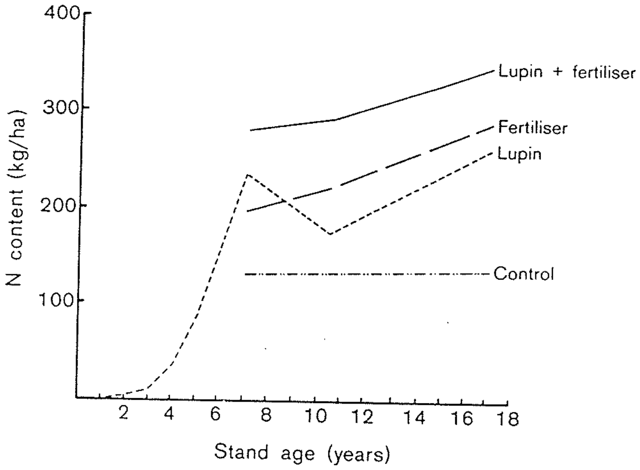


FIG. 4 (below left) — Nitrogen in radiata pine trees (above-ground parts) in four treatments, remeasured at different stand ages.

With most of the tree N in the foliage, the needlefall that began at age 7 resulted in a decrease in the trees' N content and a corresponding increase of N in forest floor. In contrast to lupin litter, the N in the pine litter was not readily available and remained in the forest floor for 3–4 years. During this period the N supply to the trees was insufficient for rapid rates of leaf growth, and consequently needlefall showed a decline. At about age 10, the N content of the trees began to increase again as the N in the pine litter became available.

Stands that had received fertiliser for the first 10 years after planting (i.e., those receiving treatments 3 and 4) did not show the drop in tree N between ages 7 and 10 that had occurred in the no-fertiliser stands because of needlefall (Fig. 4). Why? Fertilisers had provided the extra N to maintain high rates of leaf growth and needlefall. The combined effect of fertilisers and lupin management was that the accumulation of N in the above-ground components was greatest in the lupin/fertiliser stands and least in the control stands. Other studies have shown that these treatment effects are also present in the N accumulation of the forest floor, and the amount of N cycled can be expected to increase in this way too. Clearly, in this study, growth rates reflect the effect of past levels of N inputs on rates of litterfall and N cycling.

Nitrogen levels at harvesting

Nitrogen accumulation and distribution in a mature stand of radiata pine were measured at Woodhill Forest after one rotation. Samples of tree components were weighed and their N content determined. The understorey, forest floor, and soil also were sampled and analysed for N content. The results were extrapolated to the entire stand. At the start of the rotation the bare sand had contained virtually no N. However after one rotation of radiata pine, almost 1000 kg/ha of N had accumulated in the ecosystem (Fig. 5), most of which was in the forest floor and in "unusable" parts of the tree left on site as slash. Measurements of N just after various harvesting and site preparation techniques indicated that when only logs were removed, less than 15% of the N capital of the site was lost, whereas when logging debris and the forest floor were displaced by operations such as windrowing up to 80% of the accumulated N was removed (Fig. 6).

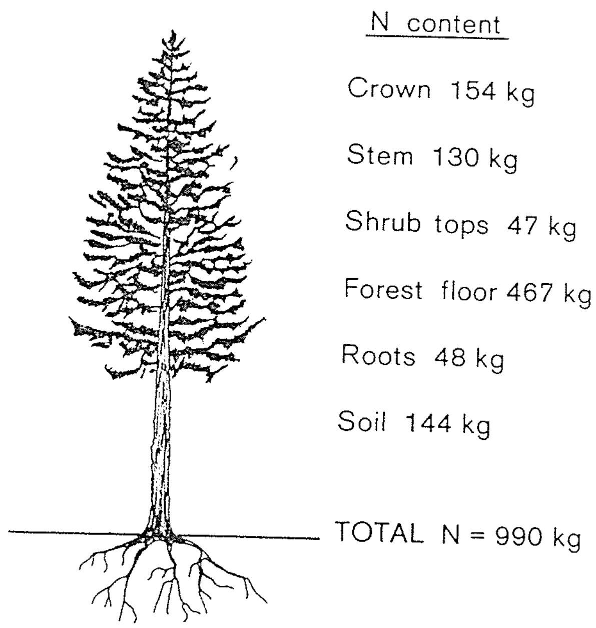


FIG. 5 — N distribution in 1 ha of a mature radiata pine forest

Woodhill Forest staff were interested in knowing if stand productivity would be increased by conserving rather than pushing aside the N contained in the logging debris and forest floor. A trial has been set up to address this question and, in particular, the relationship between harvesting and site preparation techniques, N availability, and tree growth. The trial is a long-term study, and the most important results will be collected at its conclusion when the trees are harvested. Preliminary results show that the availability of N and tree growth rates are lowest in plots where the forest floor has been removed, and that this apparent decline in productivity can be fully compensated for by the application of N fertilisers. In practice, lupins are a cheaper source of N than fertiliser, and management to ensure their presence should be encouraged to compensate for N losses at harvesting.

Implications

Results from this research, and from other studies being conducted elsewhere in New Zealand, have indicated the areas in which changes of management and harvesting practices should result in better productivity. In general terms, managers should aim to:

(1) make the N contained in logging debris and forest floor material available to the next rotation;

(2) increase N inputs by increasing the rate of N fixation; and

(3) improve the efficiency of fertiliser use by a stand.

For example, at Woodhill Forest, stemwood production could be increased by more than 30% during the second rotation if the N added during the first rotation by lupins was managed appropriately. Such a gain is too large to overlook while pursuing other management objectives.

The best means of accomplishing the above aims are currently under study. Baseline information is required on all the major soil types used for forestry in New Zealand, to determine the long- and short-term consequences of N addition, harvesting, and site preparation. The FRI is currently the leader of one of the International Energy Agency's Bioenergy projects, with the purpose of predicting the consequences of site preparation and harvesting on site productivity.

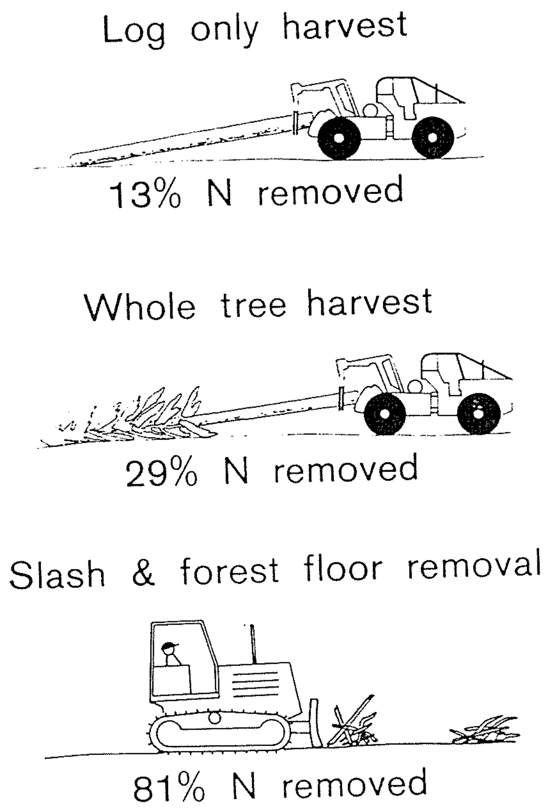


FIG. 6—Nitrogen removed by different harvesting practices

The project involves scientists from New Zealand, Canada, Sweden, the United Kingdom, and the United States who undertake related research and share results. Such international collaboration offers a cost-effective means of relating soil, climate, management practices, and productivity.

Summary

Managers of sand-dune forests generally are aware that without added N, either by lupins or fertiliser, the growth of radiata pine is poor. Added N is taken up by the trees, lost in needlefall, and accumulated and recycled in the forest floor. Managing this N, and the N in the logging debris and forest floor litter left on the site by better harvesting practices, may increase productivity. Existing practices may not be optimising tree growth.

This article is based on the work of:

P.N Beets, W.J. Dyck, and R.L. Gadgil
Ministry of Forestry
Forest Research Institute
Private Bag
ROTORUA

ISSN 0110-1048

PRINTED BY HOLMES PRINTING, ROTORUA - 1988

Reprint 2499
ODC 416.16:174.7
Pinus radiata:424.7

Upper Mid-Crown Yellowing (UN in *Pinus radiata* forests

Appendix 4

P.N. Beets*, T.W. Payn*, E.J. Jokela†

Abstract

Upper Mid-Crown Yellowing is a condition of radiata pine in which needles in the sub-apical zone of the upper crown become yellow tipped with age, needle retention is low, and crown dieback occurs.

Many factors have been suggested as possible causes of UMCY; however, ecological, physiological, and chemical evidence suggests that a nutritional imbalance involving magnesium and potassium is the most likely cause. Magnesium deficiency in young stands and UMCY in older stands occur because the effective supply of magnesium is too low to meet the needs of radiata pine. Expected changes in the relative supplies of soil Mg and K suggest that the incidence and severity of UMCY is likely to increase in the future; however monitoring of the severity of UMCY on a national scale has been inadequate to confirm this.

The available evidence suggests that deficiency symptoms appear more severely in genotypes with a predisposition to accumulate low amounts of magnesium and high amounts of potassium in their foliage. Radiata pine has an inherently low capacity to accumulate magnesium in its foliage in comparison with other species, and variation within radiata pine is also large. Foliar chemistry data from seedling trees, clones, and radiata families show that within-stand variation in foliar Mg arises from genetic differences in tree nutritional characteristics. Based on the evidence linking UMCY to nutritional traits, the heritability of UMCY is likely to be high but family differences in UMCY (narrow sense heritability) need to be determined.

Research is under way to survey the incidence and severity of UMCY, and its association with site and management factors. The effects of UMCY on individual tree and stand growth and yield are being determined, to assess the cost of UMCY. Trials are being established to determine if UMCY can be economically treated by fertilisation with magnesium. The heritability of UMCY, and the extent breeding for tolerance to UMCY impacts on growth and form are being investigated. Soil tests to predict Mg deficiency, and plant tests to screen for tolerance to UMCY are being examined.

Introduction

Typified by yellow needles in the upper crown followed by needle loss and various degrees of crown dieback (Beets *et al.* 1991), UMCY is only easily visible from above the canopy of New Zealand's older *Pinus radiata* D. Don stands. UMCY is difficult to observe from the ground because the affected zone is easily masked by healthy branches lower in the crown, but UMCY has been increasingly recorded by Forest Health Observers following adoption of aerial surveillance methods in 1982 (P. Gadgil, pers. comm.). Concern about UMCY subsequently increased, and a major effort is being initiated to identify the causes of UMCY and to find solutions.

Reports by forest health officers indicate that UMCY is widespread throughout New Zealand, with the possible exception of Northland. Many reasons have been suggested, singly or in combination, to explain UMCY, among these being physical damage from possums, wind, snow, and land subsidence, needle pathogens such as *Cyclaneusma* species, root diseases such as *Armillaria* species, site limitations such as poor drainage, and nutrient deficiency.

An example of severe Upper Mid-Crown Yellowing in *Pinus radiata*, New Zealand.

In this article we present our views regarding the following questions:

Is UMCY a new phenomenon?
Is magnesium deficiency the underlying cause?
Is it exacerbated by one or more of the other reasons postulated?
Is the condition really on the increase and if so why?
Is there a loss in yield associated with UMCY?

We also examine steps that are being taken to develop cost-effective solutions.

Historical perspective

UMCY has been of concern to foresters and researchers for several decades. Records indicate that UMCY was evident at least 15 years ago. UMCY may have been evident in radiata pine stands at Kaingaroa Forest in the 1930s (Birch 1933). Graham Will used the term "upper mid-crown yellowing" almost three decades ago to describe magnesium deficiency in radiata pine (Will 1966).

Magnesium deficiency is the most likely cause of UMCY because both conditions have many features in common (Beets *et al.* 1991):

1) The yellowing of needles found in the UMCY zone is symptomatic of magnesium deficiency. Both UMCY and magnesium deficiency lead to the development of a tree crown with a symmetrical sub-apical zone with low needle retention and yellow-tipped or completely yellow needles, resulting from retranslocation of magnesium out of older needles during the spring growth phase.

2) Foliar magnesium concentrations decrease with height up the tree and would explain why the UMCY zone is sub-apical.

3) Magnesium deficiency symptoms in young stands and UMCY in old stands both show marked tree to tree variation, and records of the same trees over many years show a progression between the two conditions.

4) Magnesium deficiency and UMCY are both common in radiata pine but magnesium deficiency and UMCY are rarely found in other species at Kaingaroa.

5) Young stands with marginal magnesium deficiency symp-

* *Dr Peter Beets, and Dr Tim Payn, Scientists, New Zealand Forest Research Institute, Private Bag, Rotorua.*
† *Dr Eric Jokela, Associate Professor, Department of Forestry, The University of Florida, USA.*

toms are found adjacent to old stands with UMCY.

6) Stands with magnesium deficiency usually respond slowly to Mg fertiliser and early indications are that the same is true for UMCY, though few attempts have been made to treat UMCY affected stands.

The nutritional imbalance hypothesis

Tree nutrition research has established that radiata pine has a low capacity to accumulate magnesium in its foliage in comparison with other species (Will 1961). Radiata pine is a coastal species within its natural range, where it is typically exposed to salt spray under low rainfall conditions (Forde 1966) – conditions under which magnesium can be expected to accumulate in the soil. The ecological literature has highlighted the importance of Mg exclusion as an important plant adaptation for survival on high magnesium (serpentine) soils (Lyon *et al.* 1971). It is also well known that magnesium uptake is inhibited following application of potassium fertiliser (Grunes *et al.* 1992). Interestingly, radiata pine growing on coastal dunes at Woodhill are free of UMCY and foliar magnesium concentration at that site are two to three fold greater than radiata growing in central North Island stands.

In addition to species differences, large within-species differences in UMCY are evident among adjacent radiata pine trees growing on sites where UMCY occurs (see photograph). UMCY is known to be highly variable among clones, suggesting that some genotypes are predisposed to UMCY (Beets and Jokela in preparation). Within-stand variation in foliar Mg and other nutrients in radiata pine is known to be large (Mead and Will 1976), but the cause of this variation was not known until clonal tests with rooted cuttings grown on a range of sites showed that clonal effects exceed environmental (microsite) effects on a range of soils (Burdon 1976, Knight 1978). In other words, both UMCY and foliar nutrient concentrations vary among clones. UMCY is also associated with clones earlier shown to have low foliar Mg. This link is based on only six clones, but is supported by a series of photographs taken over a ten-year period from the top of the meteorological tower at Puruki which showed that young seedling trees showing marginal magnesium deficiency symptoms subsequently developed UMCY.

Acceptance of evidence from clones was confounded by the fact that clones propagated as grafts in seed-orchard stands can show graft incompatibility symptoms, not unlike UMCY. Mortality from delayed graft incompatibility was of sufficient concern in seed orchards that clones were subsequently propagated as rooted cuttings. The appearance of symptoms similar to graft incompatibility in some of the rooted cuttings was unexpected. These symptoms were at that time ascribed to poor rooting, because cuttings taken from old trees were known to have various ageing characteristics and a reduced capacity to produce roots compared to cuttings from juvenile pines. However, in 18-year-old stands at Puruki, where rooted cuttings (with a physiological age believed to be around five years at time of planting) are growing in mixture with seedling trees, foliar nutrient concentrations of seedlings were similar to aged cuttings. Furthermore, seedling trees were no less prone to UMCY than trees propagated as cuttings, and UMCY in seedling trees was also associated with low foliar Mg (Beets *et al.* 1991).

Heritability of nutritional traits

A study involving three-year-old control-pollinated radiata pine families established on contrasting soils (coastal dune at Aupouri, inland clay at Maramarua, and inland volcanic ash at Kaingaroa), has shown that significant family differences in foliar nutrient concentrations (including Mg, K, Zn and other nutrients) are evident at an early age. The narrow sense heritability was estimated to be around 0.3 for Mg (Beets and Jokela, in preparation). Family mean Mg levels differed by up to 40% at the coastal site, indicating that genetic factors override environmental factors (resulting from atmospheric deposition of Mg on the needles), in accounting for total variation in foliar Mg levels.

Based on the evidence linking UMCY to nutritional traits, it seems reasonable to assume that the heritability of UMCY is high. However, the key question regarding the heritability and genetic correlations of UMCY, foliar nutrient levels, and growth remains unanswered.

Testing the nutritional imbalance hypothesis

A study of 17 physiologically aged seed orchard clones, each represented by four rooted cuttings, was made to test if the known clonal differences in UMCY were correlated with clonal differences in foliar Mg. With the lack of conclusive proof from fertiliser studies, it was also important to establish if Mg was the cause of UMCY. In this respect, we acknowledge that low foliar magnesium levels in the UMCY zone could conceivably be a symptom of UMCY rather than a cause. Furthermore, we also accept that poor rooting and other agencies related to non-genetic factors could affect foliar nutrient levels in some clones. The sampling design therefore aimed to test:

1) If UMCY was correlated with foliar Mg and other nutrients.
2) If the expected gradient in foliar magnesium with height was larger in clones exhibiting UMCY compared to tolerant clones.
3) If foliar, nutrient levels, resulting from poor rooting was a contributing factor to UMCY.

Foliar nutrient levels and UMCY both showed differences among clones and were inter-correlated. Figure 1 (from Beets and Jokela, in preparation) illustrates the highly significant relationship between the clone mean UMCY score and clone mean foliar Mg concentration in the upper crown. Data from the lower

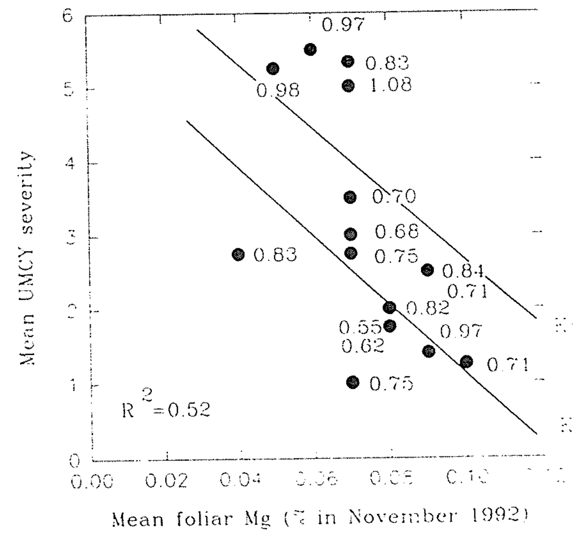


Figure 1: Relationship between clonal mean Upper Mid-Crown Yellowing (UMCY) score, foliar magnesium (Mg) concentration (% needle dry weight basis), and foliar potassium (K) concentration in 17 radiata pine clones. One-year-old needles were collected in November 1992 from the standard sampling position in the upper crown, UMCY was scored, and the four individual trees/clone analysed for nutrient content. Potassium concentration is shown next to the plotted symbol.

crown position showed a similar trend but at higher foliar Mg concentrations, because Mg in these clones decreased by a factor of two with height. The Mg concentration gradient with height was found to be similar in all clones irrespective of their susceptibility to UMCY.

At low foliar Mg levels, high UMCY scores occur in clones that accumulated potassium (in Figure 1 foliar K is given next to the plotted symbol) and nitrogen in foliage. UMCY was previously found to be associated with low foliar Mg and high K in a study using seedling trees at Puruki, but the implications of high foliar K were not appreciated at that time (Beets *et al.* 1991).

Observations indicate that poor rooting resulting from water-logged soil conditions or fungal attack, and disruption of phloem transport resulting from stem girdling were associated with low foliar concentrations of N, P, K, Ca and Mg (G. Will, pers. comm.). Active uptake and translocation of nutrients requires an energy source, and the transport of carbohydrates to the roots via the phloem is therefore essential. Poor rooting is unlikely to be the underlying cause of UMCY because only foliar Mg and Ca concentrations were low.

Given that seedling trees showed marked variation in foliar nutrient concentrations, and that clonal tests indicated that the effect of microsite variation on foliar nutrients is small, we conclude that within-stand variation in UMCY was largely determined by genetic differences in tree nutritional characteristics.

An imbalance in K and Mg nutrition has been demonstrated in the seed orchard clones and seedling trees at Puruki. An assessment of nutrient balances at more sites should reveal if this finding is generally applicable.

Role of other factors in UMCY

Possum damage is frequently associated with UMCY, but we rejected this as an underlying cause. Magnesium enters the branch via the xylem and exits via the phloem (bark), so ring-barking by possums would effectively limit Mg transport back out of the branch. Magnesium deficiency symptoms must then precede possum damage. The fact that UMCY can be predicted using foliar chemistry data from the healthy lower crown position also positively excludes upper crown damage (possum chewing, snow damage, wind) as a contributing factor. However, small branches can be bent by possums, possibly interrupting xylem transport, but leaving phloem transport unaffected. The yellowing sometimes associated with this damage should not be confused with UMCY, which affects major branches.

The supposition that infection by *Armillaria* species results in UMCY seems plausible. However, *Armillaria* results in root rot, so the uptake of nutrients in addition to Mg would be expected to be reduced. As already stated, trees with UMCY, while having low Mg and Ca concentrations, have significantly higher foliar K and N concentrations than unaffected trees. Like magnesium, K uptake is highly clonal. *Armillaria* while found at only low levels in the seed orchard study reported here (Mark Self, pers. comm.), was neither clonal nor associated with UMCY at this site. We conclude that sub-lethal infection of radiata pine by *Armillaria* species is not the primary explanation for UMCY, though it may be implicated in more general health problems (perhaps including Mg) at some sites.

Yellowing associated with infection by *Cyclaneusma* fungus can be confused with UMCY, because both conditions are particularly evident in spring, but the *Cyclaneusma* fungus is not the cause of UMCY. *Cyclaneusma* normally affects the older needles at the base of tree crowns, but under some environmental conditions it can affect all needle age-classes over the entire length of the crown. In such extreme cases UMCY is difficult to distinguish from *Cyclaneusma* and the presence of UMCY at a site is then best confirmed by examining surrounding trees that are not heavily affected with this fungus or by using foliar analysis.

Abiotic factors complicate the picture, because low plant availability of magnesium can be the result of rapid loss of Mg from the rooting zone through leaching. For example, coastal inputs of Mg will not always prevent UMCY. In spite of soil organic matter content and cation exchange capacity being low, coastal inputs of magnesium of around 8-10 kg/ha/year (>240 kg Mg over a 30-year rotation) are sufficient to meet the needs of radiata pine at Woodhill Forest because evapotranspiration rates closely match precipitation, and leaching losses are therefore low (Jackson *et al.* 1983). In contrast, similar rates of magnesium input would be insufficient in Westland because rainfall far exceeds evapotranspiration and leaching losses would be high. It is well known that variations in water supply are associated with variations in foliar nutrient concentrations, but the effect of moisture supply on nutrient balances does not appear to have been explored.

In summary, magnesium deficiency in young stands and UMCY in older stands occur because the effective supply of magnesium is too low to meet the needs of radiata pine. The available evidence suggests that deficiency symptoms appear more severely in genotypes with a predisposition to accumulate low amounts of magnesium and high amounts of potassium. Upper crown vigour is low in trees with UMCY. Recovery from physical damage and disease may be poor in trees with UMCY, though this is untested.

Between-tree variation in Upper Mid-Crown Yellowing severity at an UMCY prone site. The yellow-tipped needles in the UMCY zone are typical of magnesium deficiency. UMCY symptoms are evident in genotypes with a predisposition to accumulate low amounts of magnesium and high amounts of potassium in their foliage.

Magnesium deficiency symptoms have generally been ignored

Mg deficiency has largely been ignored in the past for various reasons. Widespread deficiency symptoms in young radiata pine in Kaingaroa Forest were particularly evident during the drought of 1963, but it was thought that the symptoms disappeared once tree roots penetrated into Mg supplies contained in buried topsoil (Will 1966). Because magnesium deficiency symptoms become less evident from the ground with increasing tree size, the progression to UMCY may have gone largely unnoticed. Forest managers have generally been aware of magnesium deficiency in their forests but have only recently become aware of the true extent of UMCY.

Current foliage sampling practices for Mg may not be adequate. It is easier to sample foliage lower in the crown where critical Mg concentrations are unlikely, even though concentrations can be critically low in the upper crown. Alternative sampling times and needle age classes may be more appropriate (Mead and Will 1976). In addition, year-to-year variation in foliar Mg is large in radiata (and other species), average Mg concentration in radiata pine (expressed on needle dry weight basis) at Puruki ranging between 0.076 (in 1985) and 0.107% (in 1990). Variation among trees in a stand is also high for Mg compared to other nutrients. Sampling of a limited number of trees in a limited number of years is unlikely to provide an adequate picture of the nutritional health of stands. With these difficulties it is not surprising that Mg deficiency was considered to be a transient condition, spring yellowing, and was largely ignored.

Relationship between UMCY and growth rate

UMCY occurs in some of the most productive stands of radiata pine in New Zealand, where rapid tree growth may lead to the dilution of magnesium in some of the dominant and co-dominant trees in the stand. Magnesium is an essential nutrient in many important processes, for example, photosynthesis (as part of the chlorophyll molecule), protein synthesis (where its role is vital), and activation of enzymes (essential for the transport of carbohydrates), and these processes are disrupted when Mg supply is low (Marschner 1986). Dieback is one result of magnesium deficiency (Hunter *et al.* 1986), and UMCY is apparently an expression of magnesium deficiency in older-aged trees. Poor shoot growth in the upper crown results in the localised accumulation of nitrogen in the UMCY zone, which indicates a failure to achieve full growth potential. High nitrogen is believed to be a symptom of UMCY. Nitrogen accumulation in shoots has been reported in agricultural crops that are deficient in Mg (Marschner 1986).

Predictions of growth loss resulting from UMCY were estimated using a leaf-area-based model (Beets 1982), which suggest that a growth reduction of around 10% could be ascribed to UMCY when half the crop trees in the stand are affected. A 10% loss in growth potential will be difficult to measure directly. No well-designed trials are available for assessing the effect of UMCY on productivity on a unit area basis. Realistic productivity targets are essential to determine if productivity is being forfeited. UMCY clearly does matter, but predictions of growth loss need to be validated. Even if growth losses associated with UMCY are of no economic consequence, at this stage UMCY should not be ignored.

UMCY is likely to be on the increase

The severity of UMCY is likely to be on the increase in the future because: 1) Future growth rates (per unit area) are known or are suspected to be increasing (through for example tree breeding, elevated $C0_2$, and altered cultural practices) and consequently tree demands for Mg relative to supply will likely increase; 2) Magnesium fertiliser is rarely applied on forest sites; 3) Radiata plantations are increasingly being planted on ex-pasture sites which have been somewhat depleted of their native supplies of Mg, have often been fertilised with potassic superphosphate, and have high nitrogen fertility owing to use of legumes – factors which jointly accelerate growth rates and raise the site K/Mg supply ratio; 4) The number of rotations is increasing and intensive harvesting is known to affect magnesium supply more so than potassium supply on volcanic soils (Will and Knight 1968) and perhaps others.

Forest health records show that UMCY has been increasingly reported in recent years. In part this has come about because of an increased awareness of UMCY. Forest Health Officers usually report the distribution of UMCY nationally, but not national trends in UMCY severity. (D. Kershaw, pers. comm.) Magnesium deficiency and UMCY may have increased for reasons stated earlier, but quantification of the condition on a national scale has been inadequate to confirm this.

Toward a solution to UMCY

Information is required on the distribution, incidence and severity of UMCY, and the environmental factors contributing to variation. The current and potential costs to forest management of UMCY also need to be determined. The inheritance of UMCY and associated foliar nutrient levels needs to be researched, to provide a basis for facilitating early evaluation of progeny tests for breeding for tolerance to UMCY. As a basis for initiating any breeding work the following studies would be desirable: 1) Determining the capacity of major soil types to continue to provide particular nutrients under intensive management; 2) Assessing nutritional management alternatives (e.g. oversowing with legumes in the case of N, and fertilisation for other nutrients) for maintaining and enhancing productivity. Radiata pine tolerance to a range of nutrient conditions could be improved, but it would be more effective if focused on those nutrients which are difficult to manage through manipulating site conditions. Better matching of nutrient supply with demand will be crucial in the case of magnesium.

These needs are encapsulated in the following research objectives recently formulated by the Upper Mid-Crown Yellowing Research Group comprising NZFRI researchers and forest managers from a number of companies. This group is open to involvement by interested parties. (Contact Tim Payne.)

Research Aims:

- To determine the distribution, incidence and severity of UMCY, and its association with site (soil type, climate) and management factors (rotation number, site preparation, fertilisation history).
- To predict the effects of UMCY on individual tree and stand growth and yield, and determine the "cost" of UMCY.
- To determine if UMCY can be economically treated by fertilisation with magnesium.
- To determine the heritability of UMCY score and whether it is genetically correlated with other traits (like foliar nutrient level), and then predict gains in volume growth which will result from selection for UMCY.
- To develop soil tests to predict Mg deficiency, and plant tests to screen for tolerance to UMCY tolerance.
- To develop methods for better matching nutrient supply with demand by the tree crop.

Literature

Beets, P.N., 1982. Modelling dry matter accumulation in a managed stand of *Pinus radiata*. PhD Thesis, Univ. of Georgia, Athens GA, USA.

Beets, P.N., S. Carson, M. Dick, A. Singh, M. Skinner, I. Hunter, 1991. Mid-crown yellowing – on the increase. What's New In Forest Research No. 206. Ministry of Forestry, Forest Research Institute, Rotorua.

Birch, T.C., 1933. Report on diseases of pines in the pumice country (Nov., 1932) and supplement (Dec., 1933), Unpublished.

Burdon, R.D., 1976. Foliar macronutrient concentrations and foliage retention in radiata pine clones on four sites. New Zealand Journal of Forestry Science 5: 250-9.

Forde, M.B., 1966. *Pinus radiata* in California. The New Zealand Journal of Forestry 2:20-42.

Grunes, D.L., J.W. Huang, F.W. Smith, P.K. Joo, D.A. Hewes, 1992. Potassium effects on minerals and organic acids in three cool-season grasses. Journal of Plant Nutrition 15:1007-1025.

Hunter I.R., J.M. Prince, J.D. Graham, G.M. Nicholson, 1986. Growth and nutrition of *Pinus radiata* on rhyolitic tephra as affected by magnesium fertiliser. New Zealand Journal of Forestry Science 16:152-65.

Jackson, D.S., E.A. Jackson, H.H. Gifford, 1983. Soil water in deep Pinaki sands: Some interactions with thinned and fertilised *Pinus radiata*. New Zealand Journal of Forestry Science 13: 183-96.

Knight, P.J., 1978. Foliar concentrations of ten mineral elements in nine *Pinus radiata* clones during a 15-month period. New Zealand Journal of Forestry Science 8:351-68.

Lyon, G.L., P.J. Peterson, R.R. Brooks, G.W. Butler, 1971. Calcium, magnesium and trace elements in a New Zealand serpentine flora. Journal of Ecology 59:421-429.

Marschner, H., 1986: Mineral Nutrition of Higher Plants. Academic Press, London.

Mead, D.J., G.M. Will, 1976: Seasonal and between-tree variation in the nutrient levels of *Pinus radiata* foliage. New Zealand Journal of Forestry Science 6:3-13.

Will, G.M., 1961: Magnesium deficiency in pine seedlings growing in pumice soil nurseries. New Zealand Journal of Agricultural Research 4:151-160.

Will, G.M., 1966. Magnesium deficiency: The cause of spring needle-tip chlorosis in young pines on pumice soils. New Zealand Journal of Forestry II: 88-94.

Will, G.M., P.J. Knight, 1968. Pumice soils as a medium for tree growth. II. Pot trial evaluation of nutrient supply. New Zealand Journal of Forestry 13: 50-65.