Impact of Timber Harvest and Regeneration on Nutrition of the Jarrah and Karri Forests of South-West Western Australia

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Abstract

Full rotation length nutrient balances are estimated for karri (*Eucalyptus diversicolor* F. Muell.) and jarrah (*E. marginata* Donn ex Sm.) forests of the south-west of Western Australia. These balances take into account the storage, input and export of the six major nutrients (nitrogen, phosphorus, potassium, sulphur, calcium and magnesium) over rotation lengths of 100 years in karri and 120 years in jarrah. Although only approximate, these balances provide a useful framework for evaluating management impacts on the biological cycling of nutrients. Examination of the balances reveals that nutrient export at harvest is small in relation to nutrient storages and inputs over the whole rotation. Further research needs are identified and discussed.

INTRODUCTION

The concept of nutrient balance provides a systematic framework within which to evaluate impacts of management on forest nutrition. The nutrient balance is the net result of gains by and losses from the forest ecosystem over a given period. When related to the gross storage of nutrient in the ecosystem a simple indication of the likely importance of the nutrient balance can be gained. This can be used to guide research or modify management.

The usefulness of nutrient balance analysis is usually constrained by the availability of data. However, sufficient data are available for the karri (*Eucalyptus diversicolor* F. Muell.) and jarrah (*E. marginata* Donn ex Sm) to provide reasonable full rotation length estimates of nutrient balance for the major nutrients.

Therefore, this paper reviews the currently available data on karri and jarrah forest nutrition and assembles it into a nutrient balance context. Within this systematic framework the role of timber harvest and regeneration, fire and fertilizer application are discussed and research needs identified.

REVIEW OF CURRENT KNOWLEDGE

Balances are assembled for the six major nutrients (nitrogen, phosporus, potassium, sulphur, calcium and magnesium) for typical karri and jarrah forest sites (Table 1). The karri data come mainly from Hingston *et al.* (1979), and are for a pure karri stand on a red-earth categorized as White community type by Inions *et al.* (1990). The only jarrah data available are for the northern jarrah forest (Hingston *et al.* 1980/81, 1989): these data are the average of 13 yellow sandy lateritic gravel sites and are assumed to be representative of southern forest jarrah on similar soils. Both types are assumed to receive 1100 mm rainfall per year, and to have rotation lengths of 100 and 120 years respectively. Each balance includes a full harvest of sawlogs and chips, followed by regeneration.

Soil Nutrient Storage

The soil nutrient storage data in Table 1 are separated into available and total categories. In presenting this data Hingston *et al.* (1979), indicate that the criteria used to segregate the available and total categories have been developed for agricultural applications. For this purpose the available category includes only nutrients in readily extractable forms and at shallow depth (less than 1 m), and which have been found to be correlated with response to fertilizer in agricultural plants.

Table 1
PROJECTED NUTRIENT BALANCES (kg ha⁻¹) FOR KARRI AND JARRAH FOREST

Component	Nitrogen karri	Nitrogen jarrah	Phosphorus karri	Phosphorus jarrah	Potassium karri	Potassium jarrah	Sulphur karri	Sulphur jarrah	Calcium karri	Calcium jarrah	Magnesium karri	Magnesium jarrah	Comments
Storage													Soil storages are for top 90 cm in karri and top 100 cm in jarrah for the size fraction <mm
soil total	NA	NA	1718[a]	725[b]	6214[a]	5861[b]	2906[a]	1296[b]	10224[a]	5508[b]	5346[a]	2200[b]	
soil available	7439[a]	1536[b]	54[a]	14[b]	471[a]	110[b]	260[a]	118[b]	3827[a]	11[b]	1027[a]	240[b]	
biomass	249[a]	327[b]	20[a]	14[b]	264[a]	311[b]	24[a]	60[b]	737[a]	353[b]	151[a]	182[b]	Excluding roots
litter	224[a]	48[b]	7[a]	2[b]	32[a]	8[b]	28[a]	8[b]	396[a]	90[b]	60[a]	20[b]	Litter age 6 years (since previous fire)
TOTAL	7912	1911	1799	755	6981	6290	3218	1482	15184	7137	6584	2642	
Inputs													For karri rotation of 100 years and jarrah rotation of 120 years
atmospheric	50[c]	60[c]	30[b]	36[b]	500[d]	600[d]	700[d]	840[d]	900[d]	1080[d]	700[d]	840[d]	
weathering	NA	NA	8[e]	8[e]	900[e]	1080[e]	NA	NA	600[e]	720[e]	200[e]	240[e]	Weathering 0.01 mm of new baseme rock per annum
fixation	1000[f,g]	1080[g,h,i]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
TOTAL	1050	1140	38	44	1400	1680	700	840	1500	1800	900	1080	
Outputs													Burning rotation 6 years in jarrah 9 years in karri
fire	1282	480	NA	NA	NA	NA	159	80	NA	NA	NA	NA	
drainage	nil	nil	nil	nil	185[j]	216[j]	422[j]	493[j]	528[j]	616[j]	1188[j]	1386[j]	204 t ha⁻¹ for karri 120 t ha⁻¹ for jarrah. Assumes total bark is taken in harvest
harvest	108[a]	101[b]	10[a]	4[b]	147[a]	90[b]	8[a]	19[b]	550[a]	62[b]	102[a]	34[b]	
TOTAL	1390	581	10	4	332	306	589	592	1078	678	1290	1420	
Balance: Inputs minus outputs	-340	559	28	40	1068	1374	111	248	422	1122	-390	-340	

Source

a. Hingston *et al.* (1979) single red earth site table III page 145
b. Hingston *et al.* means of 13 sites in northern jarrah
c. Bell and Barry (1980) and O'Connell (1985)
d. Hingston and Gailitis (1976)
e. Hingston (1977)
f. Grove and Malajczuk (1980)
g. O'Connell and Grove (1986)
h. Hingston *et al.* (1982)
i. Grove *et al.* (1980)
j. Loh *et al.* (1983)

It is likely that trees can utilize forms of nutrients not in the available category, albeit slowly, but in amounts which would be important over a full rotation (Crane 1978; Turner 1981). The lateritic jarrah forest soils have 50 per cent of gravel greater than 2 mm diameter in the top 1 m of the profile. Hingston *et al*, (1980/81) indicate that this fraction can contain as much or more nutrients than the fine earth (less than 2 mm) fraction, but, on the assumption that it is physically and chemically unavailable to roots, it has been excluded from consideration as a nutrient source for trees. However, physically isolated nutrients may be accessible to the long-term activity of micro-organisms symbiotically associated with tree roots.

The soils occupied by forests of the south-west of Western Australia, especially the jarrah forest, have unusually deep weathered profiles. Dell *et al*. (1983), suggest that the whole weathered profile, with depths averaging 20 m (Johnston *et al*. 1980), is exploited by roots. The phenomenon of salt storage arises from the near equivalence of rainfall and evapotranspiration. Under this regime the trace of oceanic salt in the rain accumulates as storage deep within the soil profile rather than being discharged into the drainage systems. Total soluble salt storage in the 1100 mm rainfall zone averages 7.5 x 104 kg ha^{-1} (Stokes *et al*. 1980). Some 10-15 per cent of this salt storage (10 000 kg ha^{-1}) comprises the soluble nutrient ions potassium, sulphate, magnesium and calcium (Loh *et al*. 1983). It is also likely that there are additional less soluble forms of these and other nutrients in the deep subsoil which may be available to tree roots.

Hingston *et al*. (1979) can therefore be strongly supported when they state that their data should not be considered an absolute measure of the proportion of nutrient capital which is available to forest plants. It should also be considered an underestimate of the size of both total and available storages.

Biomass and Litter Storage

The biomass and litter nutrient data are from Hingston *et al*. (1979) and Hingston *et al*. (1989).

The karri stand studied consisted of 36-year-old even-aged regeneration with 6-year-old understorey. It is the same site for which soil nutrient storage data were presented. The biomass included surface dead wood but excluded roots. However, some of the root nutrients would have been included in the soil nutrients. The biomass total at this site was 236 t ha^{-1}, of which 184 t was bolewood, 20 t bark, 20 t leaves and branches, 10 t understorey and 2 t was dead wood.

For jarrah the data presented are the means for 13 sites on lateritic soils. No detailed breakdown of biomass and litter data was presented by Hingston *et al*. (1989). However, details were provided for one of the sites in Hingston *et al*. (1980/81) which had nutrient contents similar to the means of the bulked data and has therefore been taken as representative biomass breakdown data. Total biomass was 269 t ha^{-1}, of which 186 t was bolewood, 37 t bolebark, 41 t leaves and branches, and 5 t understorey. Dead fallen wood amounted to 130 t ha^{-1} but since this is a variable component of the nutrient store it has been excluded.

Nutrient Inputs

Estimates of the annual rates of nutrient input from the atmosphere, weathering and nitrogen fixation are available. These have been summed over a nominal rotation length (i.e. 100 years for karri, 120 for jarrah) to provide rotation length input estimates.

Atmospheric input can arrive as dry fallout or can be contained in rainfall. For the southern forests of Western Australia the major source of atmospheric input is oceanic. Input varies with rainfall and the following levels, appropriate to 1100 mm rainfall, have been used: 9 kg calcium, 7 kg magnesium, 7 kg sulphur and 5 kg potassium (Hingston and Gailitis 1976) 3.6 kg nitrogen (Bell and Barry 1980) and 0.3 kg phosphorus (Hingston *et al*. 1989).

As previously discussed it is likely that the entire depth of the weathered profile in the jarrah and karri forests is exploited by roots. Nutrients released from current weathering of the igneous basement rocks may therefore be available for uptake by roots. Hingston (1977) based his speculative estimates of nutrients released by weathering on an annual attrition of 0.01 mm thickness of rock over unit area i.e. 270 kg ha^{-1} annually.

Fixation of nitrogen in biomass is a major input, although it is difficult to quantify. Fixation occurs by symbiotic association of micro-organisms with plants, especially in the family Leguminosae, in the species *Macrozamia riedlei* and the genus *Allocasuarina*. Other non-symbiotic forms of nitrogen fixation also occur. The rate of fixation depends on the density, vigour and age of the fixing species. This in turn is linked to fire (especially to the role of fire in the regeneration of legume species), moisture availability and fertility. All of those factors may display great variation in time and space.

In parts of the karri forest the leguminous species *Bossiaea laidlawiana* is a dominating understorey component: it is capable of sustaining high levels of nitrogen fixation even in mature stands. Grove and Malajczuk (1980) observed fixation rates of 6-8 kg ha^{-1} annually at age 5-8 in regenerating forest and rates of 14 kg ha^{-1} annually in mature forest with 11-year-old understorey. This strong nitrogen-fixing capability is

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reflected in the competitive advantage of *B. laidlawiana* over the non-leguminous codominant understorey species *Trymalium spathulatum*. Biomass and nitrogen content data for growth of these species over time is presented in Table 2 from data in Grove and Malajczuk (1985).

Table 2
BIOMASS AND NITROGEN CONTENT OF KARRI UNDERSTOREY

Age (years)	Biomass t ha⁻¹		Nitrogen kg ha⁻¹	
4	2.1	1.3	14	4
8	17.5	12.7	103	30
11	23.7	12.3	129	24

a. B.l is *Bossiaea laidlawiana*
b. T.s is *Trymalium spathulatum*
(from: Grove and Malajczuk 1985)

O'Connell and Grove (1986) found that the environment within moist karri litter favours non-symbiotic fixation of nitrogen, and estimated rates of 2 kg ha⁻¹ annually.

To project a rotation length nutrient balance an annual nitrogen input of 10 kg ha⁻¹ has been assumed (Table 1). It is stressed that this integration over space and time must be considered very approximate.

In jarrah forest a greater diversity of legume species occurs and other non-legume nitrogen fixing species are also more numerous. The jarrah forest has also attracted more research work. Some discrepancy between nitrogen fixation rates for the same species has been reported by different workers. Hingston *et al*. (1982) reported rates of 7 kg ha⁻¹ for a dense young stand of *Acacia pulchella*, whereas Hansen *et al*. (1987) reported the same species averaging less than 1 kg ha⁻¹ annually over six years. The explanation for this discrepancy may be in part the difference in density, age and size of the stand but it may also reflect the capacity of jarrah forest legume species to opportunistically utilize soil nitrogen, or conversely, where conditions are favourable, to fix very large quantities of nitrogen. For example, in rehabilitated bauxite pits in the jarrah forest local legume species dominate the early stages of revegetation which, with generous application of phosphorus fertilizer, can produce up to 100 t of biomass and increase the nitrogen in the system by 207 kg ha⁻¹ annually over 5.5 years (Koch 1987). Nitrogen fixation rates averaging 6 kg ha⁻¹ annually have been reported for a stand of *Macrozamia reidlei* averaging 0.14 plants per metre (Grove *et al*. 1980).

No data on the nitrogen input from *Allocasuarina* are available. Non-symbiotic fixation in litter is less than 1 kg ha⁻¹ annually (O'Connell and Grove 1986).

For the projected nutrient balance in jarrah forest an annual average input of 9 kg nitrogen has been assumed (Table 1). As for karri such a projection over space and time must be regarded as very approximate.

Nutrient Export

Export of nutrients can occur through fire, drainage and harvesting.

Losses of both nitrogen and sulphur occur during fire. Some loss of phosphorus and other nutrients may also occur but this is not well documented. Litter and understorey biomass contain the nutrient storages most vulnerable to fire. Fire can range from intense wildfire to low intensity controlled burns used for reducing fire hazard. The consumption of fuels varies greatly within a burnt area. These factors make the estimation of average losses owing to fire extremely difficult. There may also be a net loss of nutrients in ash which is redistributed locally or regionally by turbulence during fire. Evans *et al*. (1976) reported that up to 4 per cent of ash may be transported over long distances in smoke plumes; the other 96 per cent is redistributed nearby.

Losses of nitrogen during fire in eucalypt forest have been measured by Raison *et al*. (1985). They found losses ranged from 50 - 75 per cent of the nitrogen in the burnt fuel. The losses of sulphur may be smaller in proportion (Raison *et al*. 1984) but a factor of 50 per cent is used for both nutrients for low intensity prescribed burns and 75 per cent for the karri regeneration burn.

The burning regime for karri forest includes the initial regeneration burn followed after age 20 by regular prescribed fires on a 9-year cycle to give some nine fires over the nominal 100 year rotation. The regeneration burn is assumed to consume all biomass and litter not harvested (although this would rarely happen). The nitrogen storage is 473 kg (biomass plus litter) less 108 kg (harvested bolewood), 75 per cent (i.e. 274 kg) of which is lost. Similarly for sulphur there is 52 kg (biomass + litter) less 8 kg (bolewood), 75 per cent (i.e. 33 kg) of which is lost. The loss owing to prescribed burning is 1008 kg nitrogen (50 per cent of 224 kg nitrogen in litter x 9 burns) and 126 kg sulphur (50 per cent of 28 kg sulphur in litter x 9 burns). The total losses are 1282 kg nitrogen and 159 kg sulphur (Table 1).

In jarrah the burning regime does not include an intensive regeneration burn, and prescribed burns are on a 6-year cycle giving 20 burns over a 120 year rotation. Total losses of nitrogen are 480 kg (50 per cent of 48 kg for 20 fires). For sulphur, losses are 80 kg (50 per cent of 8 kg for 20 fires).

These estimates are conservative in that no allowance is made for possible combustion of green biomass, especially the understorey where fine fractions (leaves and twigs) contain a disproportionate amount of nutrients and are readily burnt (Grove and Malajczuk 1985). On the other hand, prescribed burns do not always consume the entire litter layer. The fine layer near to mineral soil contains two thirds of the nitrogen and sulphur (O'Connell 1989) and is the fraction most likely to escape complete combustion. Also spring burns leave a mosaic of unburnt patches throughout the forest.

Drainage losses are considered to include output in streamflow only. Deep leaching of nutrients does not remove them from the root zone in karri and jarrah forest soils so that leached nutrients remain in the available storage category. Losses are estimated using streamflow salt concentration data from Loh *et al.* (1983), and streamflow volume data from the Steering Committee for Research on Land Use and Water Supply (1987). It is assumed that streamflow volume and salt concentration are increased for 10 years after harvest from 10 per cent to 20 per cent of rainfall and 200 to 300 mg L^{-1} respectively. It was assumed that no losses of nitrogen or phosphorus occur in streamflow.

Nutrient Balances

Table 1 indicates that harvesting losses are a small part of rotation length nutrient balance in both karri and jarrah production forests and are of no particular concern. The negative balances indicated for nitrogen and magnesium in karri, and magnesium in jarrah warrant further discussion.

In the case of the nitrogen balance in karri the available soil storage is probably enough to sustain productivity for several 100 year rotations. In the case of the negative magnesium balance in karri and jarrah, the available storage does not cover the deficit and a steep decline in productivity might be predicted.

Wise management of the nitrogen balance would demand that gains to the ecosystem should be arranged to comfortably cover losses owing to volatilization in fire. This matter has been analysed by O'Connell (1989). He suggests a lengthening of the prescribed burning cycle (from 9 to 13 years) and a lessening of fire intensity to protect the nutrient-rich lower layer of the litter from complete combustion. However, such a solution increases the risk of wild fire, which may not be acceptable. Another course explored by Grove (1988) is to enhance fixation by fertilization with phosphorus. He found that phosphorus application increased legume biomass and enhanced the competitive advantage of legumes over other understorey species, the reverse of what occurred with application of nitrogen fertilizer. These observations suggest an equilibrium between legumes/non-legumes and nitrogen/phosphorus in the ecosystem, which may be naturally self-correcting. As the soil nitrogen store is depleted a relative increase in the vigour of legumes occurs to correct the balance.

The negative magnesium balances indicated in Table 1 arise from inaccurate estimation of drainage losses rather than real nutrient imbalance. This occurred because fixed annual losses for two periods during the rotation were integrated to give a whole rotation loss. It is inappropriate to do this since large losses would not be sustained with the progressive depletion of the soil store. It is also clear that the total soil store is larger than that given for the upper 1 m of the soil profile in Table 1. This subsoil store could sustain considerable losses after disturbance to the water balance, analagous to those observed for salt, but losses would diminish steeply once the effect of the water balance disturbance had passed (Steering Committee for Research on Land Use and Water Supply 1987). The subsoil store may also be accessible to tree roots and so be involved in biological cycling. A more obvious reason why magnesium nutrition presents no concern is that total biomass requirement is well provided for by input from rainfall (Table 1).

Scope For Fertilizer Application

Attiwill (1979) has defined three phases of forest growth for eucalypts.

1   The establishment of photosynthetic and metabolic transport systems up to canopy closure. The rate of nutrient requirement during this stage is relatively high.

2   The heartwood formation stage, during which some nutrients are immobilized in heartwood, but large quantities of mobile nutrients (nitrogen, phosphorus, potassium) are remobilized during heartwood formation. Nutrient demands are reduced during this phase.

3   The maintenance phase during which forest mass is more or less stable, and nutrient cycling both internally and through the litter layer maintains the nutrient requirements of the trees.

Thus, it is during the first two of these stages that nutrient requirements are greatest. However, in a managed forest in which thinning occurs, it may be possible to increase growth rates during the third phase, as thinning effectively converts the forest back to the first phase where the photosynthetic and transport systems of the forest are not fully developed.

Abbott and Loneragan (1986) have reviewed the impact of fertilizer application on the growth of jarrah. Responses to nitrogen and phosphorus by jarrah seedlings grown in pots have been extensively documented. However, evidence of fertilizer responses by jarrah in the lignotuberous stage in the forest is lacking. Increased growth rates in pole stands of jarrah have been documented following the application of nitrogen, or nitrogen in combination with phosphorus and potassium, the responses being greatest in thinned stands (Kimber unpublished, quoted by Abbott and Loneragan 1986). The greater response in thinned stands is consistent with the hypothesis that if other non-nutritional factors (in this case water) are constraining growth, then responses to fertilizer will be limited. Currently no operational fertilization is carried out in the jarrah forest. However, considering the inherent infertility of the soils of the jarrah forest, there may be scope to improve the growth rate of jarrah, particularly in the higher rainfall areas, either during the early stages of growth or following thinning.

Seedling karri respond to nitrogen and phosphorus both in pots (Loneragan and Loneragan 1964) and in the field (Christensen 1974). Nitrogen and phosphorus are applied at planting to all karri seedlings planted in areas regenerated following clearfelling. Responses to nitrogen and phosphorus and a large positive interaction between nitrogen and phosphorus have been demonstrated for karri during the developmental stage of the forest (Attiwill's first growth phase) by Grove (1988). Although the response by karri to application of fertilizer following thinning has been studied in two separate experiments (Inions 1990), the design of these experiments precludes any definite conclusions being made about the possibility of the responses to nitrogen and phosporus being commercially significant. It is likely that wood production can be significantly increased by applying nitrogen and phosporus fertilizer to karri during the establishment and development phases, and following thinning.

CURRENT FERTILIZER RESEARCH IN JARRAH AND KARRI FORESTS

Departmental research into the nutrition of these forests consists of two projects examining the interaction between stand density (thinning) and fertilizer response. The experiments in the jarrah and karri forests have commenced and involve the monitoring of forest growth and tree and soil water relationships.

ADDITIONAL RESEARCH REQUIREMENTS

The major areas where insufficient information exists are:

1   Quantification of fertilizer response during the early growth of jarrah (from lignotuber to pole stages and karri seedlings to canopy closure).

2   Extension of the later age fertilizer experiments in jarrah and karri forests to a greater range of sites so that the range of responses to fertilization can be determined (i.e. determine the impact of climate, soil type and stand development on fertilizer response).

3   An understanding of the processes of nutrient cycling and the impact of fertilization on these processes in both the jarrah and karri forests. This would enable the development of efficient fertilization practices.

4   Determine the impact of fertilization on fuel loads in forests.

5   Determine the impact of fertilization on the occurrence of herbivorous and wood boring insects.

6   Determine whether the natural processes of regulation of the nitrogen economy in karri under prescribed burning are adequate to maintain the nitrogen status of the forest and whether it can be improved with phosphorus fertilization.

REFERENCES

Abbott, I. and Loneragan, O. (1986). Ecology of jarrah (*Eucalyptus marginata*) in the northern jarrah forest of Western Australia. Department of Conservation and Land Management, Bulletin No 1.

Attiwill, P.M. (1979). Nutrient cycling in a *Eucalyptus obliqua* (L'Herit.) forest. III Growth, biomass and net primary production. *Australian Journal of Botany* 27, 439-458.

Bell, D.T. and Barry, S.J. (1980). Nitrogen economy in jarrah forest catchments. In: *Managing nitrogen economies of natural and man-made forest ecosystems*. R.A. Rummery and F.J. Hingston (eds) CSIRO Div. Land Resources Management, Perth, Western Australia. pp 28-46.

Christensen, P. (1974). Responses of open-rooted karri (*Eucalyptus diversicolor*) seedlings to nitrogen and phosphorus fertilizer. Forests Department of Western Australia, Research Paper 12.

Crane, W.J.B. (1978). Phosphorus stability in eucalypt forest. *Australian Forestry* 41, 133-158.

Dell, B., Bartle. J.R. and Tacey, W.H. (1983). Root occupation and root channels of jarrah forest subsoils. *Australian Journal of Botany.* **31**, 615-627.

Evans, L.F., King, N.K., McArthur, D.A., Packham, D.R. and Stephens E.T. (1976). Further studies of the nature of bush-fire smoke. Technical Paper No. 2. Div. Applied Organic Chemistry, CSIRO, Australia.

Grove, T.S. (1988). Growth responses of trees and understorey to applied nitrogen and phosphorus in karri forests. *Forest Ecology and Management.* **23**, 87-103.

Grove, T.S. and Malajczuk, N. (1980). Nitrogen inputs to *E. marginata* and *E. diversicolor* forests. In: *Managing nitrogen economies of natural and man made forest ecosystems.* R.A. Rummery and F.J Hingston (eds) CSIRO Div. Land Resource Management, Perth, Western Australia pp. 179-188.

Grove, T.S. and Malajczuk, N. (1985). Nutrient accumulation by trees and understorey shrubs in an age series of *E. diversicolor.* *Forest Ecology and Management* **11**, 75-95.

Grove, T.S., O'Connell, A.M. and Malajczuk, N. (1980). Effects of fire on the growth, nutrient content and rate of nitrogen fixation of the Cycad *Macrozamia riedlei.* *Australian Journal of Botany* **28**, 271-281.

Hansen, P.A., Pate, J.S., Hansen, A. and Bell, D.T. (1987). Nitrogen economy of post-fire stands of shrubs legumes in jarrah (*Eucalyptus marginata* Donn ex Sm.) forest of SW Australia. *Journal of Experimental Botany* **38**, 26-41.

Hingston, F.J. (1977). Sources and sinks of nutrients in forest ecosystems. In: *Nutrient cycling in indigenous forest ecosystems.* CSIRO Div. Land Resources Management Perth 41-55.

Hingston, F.J., Dimmock, G.M. and Turton, A.G. (1980/81). Nutrient distribution in a jarrah (*E. marginata* Donn ex Sm) ecosystem in the south-west of Western Australia. *Forest Ecology and Management* **3**, 183-207.

Hingston, F.J. and Gailitis, V. (1976). The geographic variation of salt precipitated over Western Australia. *Australian Journal of Soil Research* **14**, 319-335.

Hingston, F.J., Malajczuk, N. and Grove, T.S. (1982). Acetylene reduction (N^2 - fixation) by jarrah forest legumes following fire and phosphate application. *Journal of Applied Ecology* **19**, 631-645.

Hingston, F.J., O'Connell A.M. and Grove, T.S. (1989). Nutrient cycling in the jarrah forest. In: B. Dell, J.J. Havel and N. Malajczuk (eds) *The jarrah forest: A complex Mediterranean ecosystem.* Kluwer Academic Publishers, Dordrecht, Netherlands pp 155-177.

Hingston, F.J., Turton, A.G. and Dimmock, G.M. (1979). Nutrient distribution in karri (*Eucalyptus diversicolor* F.Muell) ecosystems in south west Western Australia. *Forest Ecology and Management* **2**, 133-158.

Inions, G., Wardell-Johnson, G and Annels, A. (1990). Classification of sites in karri regeneration II. Floristic attributes. *Forest Ecology and Management* **32**, 135-154.

Johnston, C.D., McAuthur, W.M. and Peck, A.J. (1980). Distribution of salts in soils of the Manjimup Woodchip Licence Area, Western Australia. CSIRO Land Resources Management Technical Paper 5.

Koch, J.M. (1987). Nitrogen accumulation in a rehabilitated bauxite mined area in the Darling Range Western Australia. *Australian Forest Research* **17**, 59-72

Loh, I.C., Ventriss H.B. and Collins P.D.K. (1983). Water resources quality in Western Australia. In: *Water quality its significance in Western Australia.* Proc Water Research Foundation Seminar Perth.

Loneragan, O.W. and Loneragan, J.F. (1964). Ashbed and nutrients in the growth of seedlings of karri (*Eucalyptus diversicolor* F. Muell.) *Journal of the Royal Society of Western Australia* **47**(3) 75-80.

O'Connell, A.M. (1989). Nutrient accumulation in and release from the litter layer of karri (*Eucalyptus diversicolor*) forests of south western Australia. *Forest Ecology and Management.* **26**, 95-111.

O'Connell, A.M. and Grove, T.S. (1986). Seasonal variation in acetylene reduction in the litter layer of eucalypt forest in south Western Australia. *Soil Biol Biochem.* **19**, 135-142.

Raison, R.J., Khanna, P.K. and Woods, P.V. (1985). Transfer of elements to the atmosphere during low intensity prescribed fires in three Australian subalpine eucalypt forests. *Canadian Journal of Forest Research* **15**, 657-664.

Raison, R.J., Woods, P.V. and Khanna, P.K. (1984). Dynamics of fine fuels in recurrently burnt eucalypt forests. *Australian Forestry* **46**, 294-302.

Steering Committee for Research on Land Use and Water Supply (1987). The impact of logging on the water resources of the Southern Forests, Western Australia. Water Authority of Western Australia Report No WH 41.

Stokes, R.A., Stone, K.A. and Loh, I.C. (1980). Summary of soil salt storage characteristics in the northern Darling Range. Water Resources Branch, Public Works Department of Western Australia Technical Report WRB 94.

Turner, J. (1981). Nutrient supply in relation to immobilization in biomass and nutrient removal in harvesting. In: *Productivity in Perpetuity,* proceedings Australian Forest Nutrition Workshop. CSIRO Melbourne pp 263-275.

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