EFFECTS OF INTENSIFIED HARVESTING ON RATES OF NITROGEN AND PHOSPHORUS REMOVAL FROM PINUS RADIATA AND EUCALYPTUS FORESTS IN AUSTRALIA AND NEW ZEALAND

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ABSTRACT

Intensive harvesting operations involving conversion of native forest to plantations, and use of short rotations and/or more complete utilisation of biomass will markedly increase both the rate of nutrient export from sites and the nutrient cost (weight of nutrient per unit of biomass) of biomass production. The nutrient cost is particularly high for young thinnings or when crown components of trees are removed, and is considerably greater for **Pinus radiata** D. Don than for **Eucalyptus**, especially for phosphorus and when tree rotations are longer than about 20 years. In addition to the direct removal of nutrients in biomass, significant losses of nutrients may occur as a result of harvesting and site preparation. Such losses are less predictable than removal in biomass, but can be quantitatively more important. Much more research is needed to assist in interpreting the significance of varying rates of nutrient removal to the long-term productivity of forest sites.

On most soils, emphasis should be placed on silvicultural systems which minimise both nutrient losses and any detrimental redistribution of nutrients on the site. In general, introduction of intensive harvesting involving removal of tree crowns and root systems would seem unsuited to the maintenance of productivity on most sites. It may be possible to maintain nutrient supplies by applying heavy rates of fertiliser, but maintenance of acceptable levels of soil organic matter may prove more difficult.

INTRODUCTION

Increasing demands for forest products and the development of new technologies have stimulated utilisation of biomass and shortening of rotations in forestry. Such strategies can markedly increase the rate of removal of nutrients from the forest site via both direct and indirect mechanisms (Raison & Crane 1981), and consequently lead to the important question "What management regime is required in order to sustain or improve forest productivity in the long term?"

The impact of intensive harvesting on nutrient cycling and productivity has received considerable attention outside Australia (e.g., Webber 1978; Leaf 1979) but only little here despite the fact that Australian soils are in general of low fertility and receive low natural inputs of nutrients. Nutrients are exported directly in harvested material, and other losses are associated with disturbance during harvesting, site preparation prior to planting, and absence of a closed-canopy stand.

DIRECT REMOVAL OF NUTRIENTS IN HARVESTED BIOMASS

The amount of nutrients exported, and their rate of removal in biomass from a forest depend on combinations of the rate and pattern of nutrient storage by the particular tree species, the length of tree rotation employed, and the degree of utilisation of biomass (including thinnings). The relative effects of these factors are well known for Northern Hemisphere forests (e.g., Malkonen 1976; Kimmins 1977; Leaf 1979), and some information for *P. radiata* and *Eucalyptus* is summarised here.

As stands age, a progressively greater proportion of the above-ground biomass is contained in the stem. For example, the biomass yield of an 8-year-old *P. radiata* stand would increase by 130% if the crown was included in the harvest (Table 1). In contrast, the comparative increase in biomass yield of the 29-year-old stand of *P. radiata* studied by B. Webber (unpubl. data) is only 18% (Table 2). In the latter stand, the 18% increased yield from whole-tree logging would result in about a 100% increase in the amount of nitrogen and phosphorus removed in biomass. An alternative strategy in which the branches are harvested but the foliage is left on site (defoliation treatment), would result in an increase of 49% in the amount of nitrogen, and 62% in the amount of phosphorus removed compared with a harvest in which only the stems were removed.

Since the bark may contain 25–50% of the nitrogen or phosphorus in the trunk of *P. radiata* and *Eucalyptus* trees (Attiwill 1980; Crane & Raison 1980; Feller 1980; Stewart *et al.* 1981; B. Webber, pers. comm.), harvesting systems which allow bark to be removed at the stump would significantly reduce the removal of nutrients during logging.

TABLE 1—Effect of degree of utilisation on yield of biomass, nutrient removal, and nutrient cost per unit of biomass harvested for young thinnings (**P. radiata** aged 8 years)*

	Harvest		Percentage increase
	Stemwood and bark (wood)	Full thinnings	
Biomass yield† (t/ha)	20.1	46.5	131
Nutrient removal			
Nitrogen (kg/ha)	26	127	388
Phosphorus (kg/ha)	4.8	20.3	323
Nutrient cost			
Nitrogen (g/t biomass)	1294	2731	111
Phosphorus (g/t biomass)	239	437	83

* Calculations based on data of Madgwick **et al.** (1978) and unpublished data of H. A. I. Madgwick, D. S. Jackson, and P. J. Knight.

† Removal of 963 stems/ha, mean d.b.h. 7.9 cm.

TABLE 2—Effect of degree of utilisation of biomass on nutrient removal and nutrient cost per unit of biomass harvested at clearfelling (**P. radiata** aged 29 years)*

	Stemwood and bark	Full tree	Defoliated full tree
Biomass yield (t/ha)	361	426 (18)†	418 (16)
Nutrient removal			
Nitrogen (kg/ha)	214	439 (103)	318 (49)
Phosphorus (kg/ha)	31	66 (114)	50 (62)
Nutrient cost			
Nitrogen (g/t biomass)	593	1031 (74)	761 (28)
Phosphorus (g/t biomass)	86	155 (80)	120 (40)

* Calculations based on unpublished data of B. Webber.

† Figures in parentheses are percentage increase over those for conventional logging (wood and bark removal).

The increase in nutrient removal associated with more intensive utilisation of biomass is relatively greater for young stands (compare Tables 1 and 2) because the foliage and bark contain a higher proportion of the nutrient content in young trees. Stems of young trees (thinnings) also contain a much larger amount of nutrient per unit of biomass than do older trees (Tables 1 and 3). Harvesting thinnings with the crown attached would increase the amount of nutrients removed by a factor of 3 or 4 in comparison to harvesting of stems alone (Table 1). Such a situation is equivalent to full-tree harvesting on very short rotations. The nutrient cost (weight of nutrient removed per unit weight of biomass harvested) ranges from 130 to 440 g/tonne for phosphorus and from 590 to 2730 g/tonne for nitrogen (Tables 1–3) depending on the age of the stand and the degree of utilisation of biomass.

The above conclusions are reinforced for *P. radiata* by the studies of Will (1964, 1968). In a 12-year-old stand, Will (1964) found that the stem constituted 80% of the above-ground mass, but contained only about 40% of the nitrogen and phosphorus

TABLE 3—Characteristics of harvested material from a stand of **P. radiata** of about Site Quality IV according to South Australian yield tables (after Crane & Raison 1980)

	Clearfelling	Thinings				Clearfelling
Age (years)	18	16	22	28	34	40
Harvested stems/ha	1682	1117	165	110	102	188
Mean d.b.h.o.b. (cm)	22	14	27	33	38	53
Merch. vol. (m^3/ha)	345	108	84	93	128	489
Weight wood (t/ha)	177	55	43	48	66	255
Stem phosphorus (kg/ha)	45.7	21.7	7.6	7.1	10.0	32.4
Phosphorus (g/t stemwood)	258	395	177	148	152	128

in the trees. For a forest grown on a rotation of 35 years without commercial thinning, Will (1968) estimated that 205 kg N/ha and 49 kg P/ha would be returned to the soil in slash (including thinnings).

Even with full-tree logging, a proportion of the biomass (e.g., broken branches, shed foliage) will remain on the site (McIntosh & Wright 1977). The removal of nutrients in harvested biomass is thus always less than that calculated as being present in the fractions to be harvested. However, the difference may be small – e.g., clear-felling and efficient removal of logs (wood + bark) from a 29-year-old *P. radiata* stand in New Zealand showed that more than 95% of the available trunk biomass can be removed (B. Webber, pers. comm.).

With stemwood harvesting in a stand of *P. radiata,* shortening rotations from 40 to 18 years increased the nutrient cost for phosphorus by 50% (Crane & Raison 1980). There can also be a marked interaction between the tree species grown and the length of rotation, which will affect the rate of nutrient export and the nutrient cost. This is shown by examining the pattern of phosphorus accumulation in stems of *P. radiata* and *Eucalyptus delegatensis* R.T. Bak. (Crane & Raison 1980). The nutrient cost decreases rapidly after about age 7 in eucalypts when heartwood formation commences, because heartwood has a very low concentration of phosphorus compared with sapwood (e.g., Hingston *et al.* 1979; Wise & Pitman 1981). Such effects are much less marked for *P. radiata* (i.e., heartwood formation does not commence until age 15–20, and phosphorus concentrations are higher in the heartwood of *P. radiata* than for eucalypts); as a consequence eucalypts form wood at a lower nutrient (phosphorus) cost, and this advantage increases with increasing length of the tree rotation (Crane & Raison 1980). For very young stands, the nutrient cost may be similar or in some instances higher for eucalypts than for *P. radiata* (Madgwick *et al.* 1981).

As with *P. radiata,* full-tree harvesting markedly increases the removal of nutrients from young plantations of *Eucalyptus globulus* Labill. (Table 4). The nutrient cost is significantly less for eucalypts than for *P. radiata* over a wide range of environmental conditions (Tables 1–4) (Crane & Raison 1980, and unpubl. data).

High soil fertility and fertiliser application will increase the rate of biomass production and often the storage of nutrients per unit of biomass formed (Table 4) (Will 1965; Snowdon & Waring 1974). Thus fertiliser application is likely to result in rapid rates of nutrient storage in biomass (including increased concentrations in stemwood) and greater nutrient cost per unit of biomass formed.

INDIRECT EFFECTS OF INTENSIVE HARVESTING

Effects on Nutrient Losses

Shortening of rotations increases the frequency of disturbance to the site by harvesting and site preparation. The proportion of time when the site is not fully occupied by a closed-canopy forest (which offers some protection to the soil) is also increased, exacerbating the effects of disturbance. Some methods of harvesting (e.g., removal of root systems) cause major disturbance to the site.

Harvesting and site preparation usually increase the loss of nutrients occurring via erosion, leaching, and transfer to the atmosphere (e.g., during burning) (*see* Sopper

TABLE 4—Effects of fertiliser and degree of utilisation of above-ground biomass on nutrient removal and nutrient cost per unit of biomass harvested (**E. globulus** plantation aged 9.5 years) (calculations based on data of Cromer **et al.** 1980)

	Harvest		Percentage increase
	Stemwood and bark	Full tree	
Without fertiliser			
Biomass yield (t/ha)	19.2 (wood)	31.2	63
Nutrient removal			
Nitrogen (kg/ha)	20	69	245
Phosphorus (kg/ha)	1.7	4.9	188
Nutrient cost			
Nitrogen (g/t biomass)	1042	2212	112
Phosphorus (g/t biomass)	89	157	76
*With fertiliser**			
Biomass yield (t/ha)	58.4 (wood)	83.3	43
Nutrient removal			
Nitrogen (kg/ha)	62	153	147
Phosphorus (kg/ha)	7.9	14.1	78
Nutrient cost			
Nitrogen (g/t biomass)	1062	1837	73
Phosphorus (g/t biomass)	135	169	25

* 200 kg N/ha and 90 kg P/ha

1975; Leaf 1979). In addition, undesirable redistribution of nutrients may occur (e.g., in windrows, Ballard 1978). The relative magnitude of nutrient loss (compared to nutrient removal in biomass) resulting from the above mechanisms is highly variable (*see* recent reviews by Webber 1978; Raison & Crane 1981), but may be very important with respect to erosion and losses to the atmosphere in slash fires (Raison 1980).

Much research on the indirect effects of forest harvesting on nutrient balance and cycling has been done in North America and Europe, but very little in Australia or New Zealand. The relevant research done in the latter regions is briefly reviewed here. In the only published study of leaching after clearfelling and slash burning of *P. radiata,* losses of nutrients were found to be slight on the central volcanic plateau of New Zealand (Dyck *et al.* 1981). Leaching of ions mobilised during harvesting and site preparation would be expected on sandy soils which are widely planted with *P. radiata* in Australia, but no studies of nutrient movement have as yet been reported.

Substantial losses of nutrients (especially the readily volatile elements nitrogen and sulphur) can accompany slash fires used for site preparation (Harwood & Jackson 1975; Flinn *et al.* 1979; Webber 1978). Volatile losses of nitrogen during slash burns after clearfelling of *P. radiata* have been estimated at 420–920 kg N/ha (Flinn *et al.* 1979; Squire & Flinn 1981; Woods 1981). Such losses of nitrogen are likely to exceed the amounts contained in harvested biomass (e.g., Squire & Flinn 1981). Woods (1981) had evidence of a direct correlation between the amount of nitrogen lost during slash burning for site preparation and the decline in productivity measured in the second rotation of *P. radiata* in the south-east of South Australia. It is not surprising that alternative methods of site preparation (e.g., crushing of slash) are now being adopted in several forest regions of Australia.

There are no reports of the quantitative loss of nutrients by erosion after clearfelling and site preparation in either eucalypt forests or plantations of *P. radiata.* However, on impermeable soils on steep sites the rate of sediment export from forested areas can be significantly increased by clearfelling or hot fire (Burgess *et al.* 1980). Quantification of soil and associated nutrient losses resulting from erosion after management operations is urgently required since this mechanism of nutrient loss is potentially very significant (Raison & Crane 1981).

Effects of Thinning on Nutrient Cycling and on Rates of Nutrient Demand by Residual Trees

Thinning can dramatically affect nutrient distribution and cycling in a forest stand. Extraction of thinnings results in a significant removal of nutrients contained in this biomass (Tables 1, 3) especially if the crown components are also removed (Table 1). Thinning to waste thus would add a large amount of nutrients contained in slash to the forest floor – for *P. radiata* up to 60–70% of the nitrogen and other elements initially contained in standing biomass (Will 1968; Madgwick *et al.* 1977). The most common thinning practice involves removal of stems and return of canopy components to the forest floor. Decomposition of nutrient-rich foliage which is deposited is likely to be rapid and may provide a pulse of available nutrients for use by the residual trees. Madgwick *et al* (1977) showed that nutrient uptake and storage in crown components may be rapid after thinning of *P. radiata.*

Thinning operations disturb the litter layer, and can increase both litter temperatures and the rate of litter decomposition (Piene 1978). However, thinning of a 14-year-old stand of *P. radiata* in New Zealand had no effect on the rate of litter decomposition or the mineralisation of nitrogen from litter (Will *et al.* 1981). Gadgil & Gadgil (1978), who found that the rate of litter decomposition increased after clearfelling of *P. radiata,* suggested that release of saprophytic micro-organisms from competition with mycorrhizal fungi (associated with living roots) was responsible, rather than changes in microclimate.

After thinning, the photosynthetic rate of the residual stand is usually high as a result of better moisture conditions (Butcher 1977), and improved illumination and retention of foliage in the lower canopy (Brix 1981) create the potential for a higher rate of nutrient utilisation per tree in thinned stands, which results in a greater response to fertiliser than in unthinned stands of comparable age (Miller 1981). Fertiliser application combined with thinning increased needle mass per tree by 271% (compared to no treatment) in Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests in Canada (Brix 1981). In addition, the decomposition of roots left behind in the soil after thinning may temporarily immobilise nitrogen, resulting in a reduction in nitrogen availability (Cochran 1968).

Repeated use of harvesting machines is likely to adversely affect the physical characteristics of soils (producing compaction and/or erosion), injure existing roots, and decrease the production of new roots (Strand 1968; Oswald 1974). For example, Baneva (1980) reported that in a young (23-year-old) Norway spruce (*Picea abies* (L.) Karst.) stand in the Leningrad region, the amount of fine roots was less than half that in an unthinned stand 5 years after the thinning. The consequences of such changes to the productivity of sites have not generally been assessed in quantitative terms.

IMPLICATIONS OF INCREASED REMOVAL OF NUTRIENTS IN BIOMASS

Leaf (1979) provided a valuable discussion of the implications of nutrient removal in biomass for future productivity of forest sites, but there exists no simple method of assessing the significance of such nutrient losses. A detailed discussion of these aspects is beyond the scope of this paper but general statements, relevant particularly to the Australian forest environment, can be made:

(a) Australian soils are often low in reserves of both total and plant-utilisable nutrients, and those reserves are likely to be only slowly available to subsequent crops of trees. The widespread marked response of *P. radiata* to fertiliser (Waring 1981) supports this conclusion. Natural inputs of nutrients (e.g., by nitrogen-fixation, in rainfall, from weathering) will be very low in plantations of *P. radiata* and are insignificant in relation to the rates of nutrient demand by trees grown for production forestry (B. Webber, unpubl. data).

(b) Responses to fertiliser are the rule (Waring 1981) and fertiliser application is likely to be essential (Webber 1978) to maintain productivity of subsequent rotations; *P. radiata* places a much greater demand on the soil for nutrients than does the native vegetation which it has frequently replaced (Crane & Raison 1980).

(c) Nutrient removals should not be compared with total reserves of nutrients in the soil as a basis for assessing the significance of harvesting. In general, inputs of nutrients should aim to maintain (or improve) the nutrient-supplying capacity of the soil. Thus, more nutrients generally need to be added than are removed in biomass because of the low efficiency of recovery of applied (fertiliser) nutrients by trees (often <30% for nitrogen (Ballard 1979), maybe less for phosphorus on Australian soils which frequently have a high phosphorus-fixation capacity). Economic analyses of the costs of replacing nutrients removed in biomass which do not take account of these factors (e.g., Wise & Pitman 1981) can be serious underestimates.

(d) Maintenance of organic matter will be a critical factor on many Australian soils (*see* Squire & Flinn 1981). Organic matter is an important determinant of physical, chemical, and biological properties of the soil which control the long-term supply of nutrients and water to tree root systems. Organic matter is much more difficult to manipulate than inorganic nutrients.

CONCLUSIONS

The direct export of nutrients in biomass is markedly increased by shortening tree rotations and by removal of canopy components at any stage of the rotation. While such increases are significant, they are also reasonably predictable for a range of environments and forest management options (Miller *et al.* 1980). Much research is still needed to quantify the indirect losses of nutrients associated with harvesting and regeneration (e.g., via erosion, leaching, and gaseous transfers), and to assess the significance of total nutrient losses to the long-term productivity of forest sites.

The following strategies appear important in assisting the maintenance of long-term nutrient supply in short-rotation forestry programmes on poorer (Australian) soils:

(a) Leaving nutrient-rich biomass (fine branches and foliage) on the site, not harvesting root systems on most sites, removal of bark from tree trunks and its retention on the site where possible;

(b) Use of conservative site-preparation procedures which minimise disturbance and loss of nutrients and organic matter from slash, litter layers, and surface soil (e.g., retention of slash where possible, avoidance of redistribution of topsoil during windrowing, planning of vehicle traffic, and use of procedures which minimise the overland flow of water);

(c) Efficient use of fertilisers based on an understanding of patterns of tree requirements and fate of applied nutrients (Ballard 1979);

(d) The possible use of legumes (either inter-cropped or during a fallow period between rotations) to assist in the maintenance of soil organic matter and nitrogen economy;

(e) Use of tree stock selected for their low nutrient demand (Forrest & Ovington 1971; White & Harvey 1979).

The efficient application of all these strategies depends on an improved understanding of the factors (not just nutritional) controlling the productivity of forest stands under a range of environmental conditions. The factors involved will be quite variable, as will the strategies needed to maintain adequate long-term rates of nutrient supply under short-rotation forest cropping. To date such studies have concentrated mostly on the more inherently fertile soils. Increased research effort is now needed on relatively infertile soils (e.g., in Australia) where the effects of intensive harvesting on subsequent productivity are likely to be more marked, and the maintenance of stable highly productive plantations remains a continuing challenge for forest managers.

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