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Nutrient Losses from Forestry in the Lake Taupo Catchment

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Executive Summary

This report provides background information on fertiliser use and nutrient leaching for forests in the Taupo catchment area, with a focus on nitrogen. Soils of the Taupo catchment are formed dominantly from pumice. Radiata pine forests growing on pumice soils may be marginally deficient in nitrogen (N) and have been shown to respond to N at rates of up to 200 kg/ha when applied in conjunction with thinning operations. Currently the usual practice is not to apply N fertiliser to correct such marginal deficiencies, but this may change should economic conditions justify it. Nitrogen also may be applied after planting to promote early growth (at approximately 30 g/tree) or at any stage during the rotation to correct limited areas of severe deficiency. Nitrogen losses from leaching of undisturbed plantation forests are usually low (of the order of 2 kgN/ha) and similar to native forest, but harvesting can cause limited short-term increases in N leaching. Available information on N leaching after fertiliser application to pumice soils in the Taupo catchment is limited. Because of the lack of New Zealand studies, the question "what maximum amount of nitrogen over what period should be specified for forestry operations to prevent ongoing increases to surface or groundwater resources in the Lake Taupo catchment?" cannot be directly answered.

Until additional research is undertaken, and in order to follow a conservative approach to prevent leaching of N, the following points are suggested as useful guides in terms of increased fertiliser applications in forestry:

- Broadcast applications of N at any time should not exceed 200 kg/ha.
- Spot applications after planting should not exceed 30 g N/tree.
- Application during winter or other wet periods when soil water drainage is likely should be avoided.
- Except where plantations are severely deficient broadcast applications should be made in conjunction with thinning and pruning operations when N demand is high.
- Application decisions should be based on results of nutrient analysis of foliage.
- Mechanisms to prevent the direct discharge of fertiliser into surface water should be in place.
- Rapid revegetation of clearfelled areas should be promoted to minimise losses after harvest.

Introduction

Environment Waikato commissioned Ensis (formerly Forest Research) to:

"provide a report outlining the following information for the Lake Taupo catchment:

- Provide information on the types, timing and quantities of substances (nitrogen, phosphorous, trace elements) added to *Pinus radiata* forestry blocks through their lifetime of use for forestry and under standard forestry operations. General information is required across all additives but the nutrient of major concern, and therefore primary focus in the report, is nitrogen.
- For other plantation species currently, or likely to be grown in Taupo (eucalypts, Douglas fir), outline management differences from *Pinus radiata* that would affect nutrient losses.
- For the nutrients being added, outline predicted or actual measured leaching rates from forestry operations and comment on the significance of those rates relative to other land uses and impacts on groundwater and surface water resources."

The report was required to comment on whether fertiliser addition raised the amount of nitrogen leached below the root zone. A key issue to be addressed was "what maximum amount of nitrogen over what period should be specified for forestry operations to prevent ongoing increases to surface or groundwater resources in the Lake Taupo catchment?"

Fertiliser Use in Lake Taupo Catchment

In contrast to farming practice, fertilisers are not applied to forests in a routine manner in New Zealand, although there are many areas where growth responses to fertiliser, especially nitrogen (N), application might be obtained. The use of fertilisers including N in plantation forests in New Zealand began in the mid-1950s, but up to 1970 the amounts used were erratic (Will 1981). Between 1970 and 1980 there was a marked increase in fertiliser use and in Rotorua conservancy 1350 tonnes of N were applied in 1980 to an area of approximately 8 500 ha[1], largely to recently thinned pine stands and newly planted eucalypts (Will 1981). There are no published accounts showing statistics of fertiliser use on forests since then, but use had dropped substantially by the late 1980s and currently it is thought that little N is applied to forests in the Taupo catchment area.

It is possible that use of N fertiliser may increase in future if economic conditions justify its application. Further, a reduction in forest area, for example as a result of the current conversion of some forests to dairying, may see an increase in the use of N to sustain wood flows. The use of fertilisers in general may also increase as foresters become more cognisant of the need to replace nutrients removed in logs at harvest to sustain long-term productivity. Estimates of nutrients removed in radiata pine logs at harvest range between 128 and 337 kg nitrogen/ha, 22 and 38 kg phosphorus/ha, 168 and 439 kg potassium/ha, 126 and 237 kg calcium/ha and 63 and 107 kg magnesium/ha (Payn and Clinton 2005).

Nitrogen fertiliser trials

Forests are conservative in cycling N, but despite this many forests are deficient in N and worldwide N is considered to be the key nutrient limiting forest growth. Soils of the Taupo catchment are formed dominantly from pumice and there is good evidence that N fertiliser improves growth rates of radiata pine on pumice soils. An early study by Woollons and Will (1975) at Kinleith Forest showed responses of naturally regenerated

[1] This is an overestimate of the area to which N was applied as it includes areas to which small tonnages of phosphorus, potassium, magnesium and boron fertilisers were applied.

13-14 year-old stands to urea, provided they had been thinned. They suggested that two annual applications of 115 kg/ha of N was the most productive. Mead and Gadgil (1978) observed that at mid-rotation on central North Island soils tree volume responses to N at about 200 kgN/ha would often exceed 8m^3/ha/yr, and recommended 150-250 kgN/ha be applied when the tree canopy was developing. Their recommendation was based on trials that included both single and split applications of nitrogen. Hunter *et al*. (1985) reported results from a series of 10 trials on the pumice plateau (predominantly in Kaingaroa Forest) where tree age at fertiliser application varied from 4 to 20 years. They concluded that a large proportion of forests on pumice soils were responsive to N fertiliser, provided the stands had been recently thinned or pruned. Volume gains (projected to rotation end) appeared to be 35-50 m^3/ha for younger stands, and 15-30 m^3/ha for older stands. Finally West (1998) reported results from two trials in Kaingaroa and observed that while 200 kgN/ha improved growth in pruned and thinned plots it did not totally compensate for the basal area reduction due to thinning. His observation was that N application might reduce rotation length by two years.

Nitrogen response by radiata pine forests appears to plateau at about 200 kg/ha (Fig. 1, Hunter 1982, Hunter et al. 1985) and the normal recommendation is for aerial application of 200 kg N/ha in spring (Will 1985, Olykan 2002). Will (1985) states that responses can be obtained at other times of the year but maximum results can be expected in the spring when tree demands are high and losses due to volatilisation and leaching are likely to be low. On coastal sand dunes near Christchurch, however, Thomas and Mead (1992a) found no evidence for the superiority of applying N in any particular season to two-year-old radiata pine. With regard to leaching, Will's statement might be questioned especially if rainfall is high, as soil natural mineral N levels may be increasing in spring because of enhanced mineralisation of soil organic matter due to increasing soil temperatures.

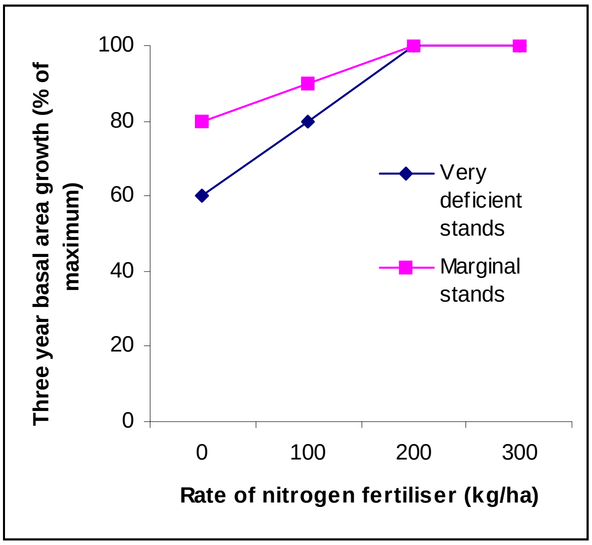

Figure 1: Response by radiata pine to different rates of nitrogen fertiliser (from Hunter et al. 1982)

Application of nitrogen fertiliser

The Institute of Forestry Handbook recommends N fertiliser application rates as shown in Table 1 (Mead 1995). Recommended rates of N for established stands range from 45 to 207 kg/ha. In addition to broadcast application to established stands, N may be applied at planting, usually in a spade slot beside the tree, particularly on deficient sites such as skid sites where topsoil has been removed. Even at high spot application rates, however (eg 28 g/tree, Table 1), per hectare application rates at planting are low (eg 28 kg/ha for a stocking of 1000 trees/ha).

Table 1: Rates of nitrogen fertilisers recommended for radiata pine at planting and in established stands (after Mead 1995). Equivalent rates of elemental nitrogen are shown in parenthesis. Frequently used rates are shown in bold.

Type of fertiliser	At planting (gN/tree)	Established stands (kg N/ha)
Urea (46%N)	**25**-60 (11-28)	250-**450** (115-207)
Ammonium sulphate (21%N)	**50**-100 (10-21)	500-950 (105-200)
Diammonium phosphate (18%N)	40-**85 (7**-15**)**	250-**500 (**45-90**)**
Magnesium ammonium phosphate (18%N)	50 (9)	-

The decision on whether or not to apply N (or other fertilisers) is commonly based on results of nutrient analysis of foliage collected in late summer to early autumn. For radiata pine, foliar concentrations are evaluated in relation to diagnostic concentration ranges presented in Will (1985). Diagnostic ranges are also available for other species including Douglas fir and eucalyptus species.

For radiata pine it is normally recommended that N is applied in conjunction with thinning and pruning as responses are most likely when the canopy has been reduced and has the capacity (space) to expand again. Thinning and pruning operations are commonly undertaken at radiata pine plantation ages of 3-10 years, but late thinning may also be undertaken between the ages of 10-16 years (Mclaren 1993).

The above recommendations on rates and timing of application in relation to silvicultural operations are not restricted to pumice derived soils and are relevant to forests on most soils. Whereas marginal deficiency is likely to be quite common on pumice soils, severe deficiency (where visual symptoms of N deficiency are evident) tends to be restricted to certain types of soils low in organic matter such as sands (eg Woodhill Forest, Auckland; Santoft Forest, Manawatu). On pumice soils severe deficiency is likely to be restricted to limited areas, for example where topsoil has been removed on skid sites.

The utility of single versus split (or multiple) nitrogen applications has not been thoroughly examined in New Zealand. As noted above, from their study Woollons and Will (1975) suggested that two annual applications of 115 kg/ha of nitrogen in successive years was the most productive. However they did not compare single with split applications and it is possible that a single application of 230 kg/ha would have been as effective as a split application. For young (two-year-old) seedlings on coastal sand, Thomas and Mead (1992) found split applications of N resulted in reduced losses of fertiliser, probably from leaching, and suggested a that a split application strategy would be appropriate. Some overseas studies involving frequent N fertiliser application have shown the potential for multiple applications to greatly enhance forest productivity (Ballard 1984).

Inputs of N from other sources

In addition to fertiliser application, forests may receive N from atmospheric inputs and biological N-fixation, both of which may be considerable. Dyck (1982) estimated atmospheric inputs of approximately 120kg/ha over a 30-year rotation in Kaingaroa forest, and measured inputs of 6/ha/yr at the Purukohukohu Experimental Basin between Rotorua and Taupo (Dyck *et al*. 1987). Inputs from N-fixing species such as tree tutu, Maku lotus, gorse or broom may be of the order of 100-200kg/ha/yr for a few years in the period prior to their suppression by canopy closure (Gadgil 1982, Silvester *et al*. 1979, Watt *et al*. 2003).

Phosphorus and other fertilisers

Other than N, the key nutrients that might be limiting forest productivity in Taupo catchment are magnesium (Mg), and boron (B) on some coarse pumice soils (Will 1985). Soils from pumice are not normally deficient in phosphorus (P) for forest growth. Sources and rates of Mg and B, along with other nutrients applied to forests in New Zealand, are shown in Table 2.

Like N, the decision on whether or not to apply Mg and B fertilisers may be based on results of nutrient analysis of foliage, but observation of visual symptoms may be used as symptoms of deficiency of both nutrients are quite distinctive. It is recommended that Mg be applied at 100 kg/ha, and B at 6-8kg/ha. Boron would normally be applied to younger (less than age 10 years) rather than older stands. While symptoms of Mg deficiency are relatively common, response to fertiliser is slow and Mg is rarely applied.

Species other than radiata pine

Little is known of the fertiliser requirements of species other than radiata pine likely to be grown in the Taupo catchment area. Douglas fir appears to behave rather similar soil fertility requirements to radiata pine and so can be assumed to have similar fertiliser requirements. Two groups of species, eucalypts and cypresses, may, however have greater nutrient demand. Cypress species are more "site demanding" than radiata pine, that is they prefer and are currently grown on more fertile soils. If the area of cypresses expands into areas currently dominated by radiata pine plantations, then it may be expected that fertiliser use, especially of N, would increase. The same would be expected for eucalyptus species grown as short-rotation high-productivity crops where nutrient removals at harvest are likely to be greater than for conventionally grown radiata pine crops.

Table 2: Sources and rates of non-nitrogenous fertilizers recommended for radiata pine. The most commonly used rates and fertilisers are given in italics. From Mead 1995.

	Nutrient %				Rate of fertilizer	
Fertilizer	**N**	**P**	**K**	**Other nutrients**	**At planting (g/tree)**	**Established stands (kg/ha)**
Superphosphate	0	9	0	20Ca;11S	60-*100*-*180*	300-*800*-1200
Triple super	0	20	0	14 Ca; 2S	40-*90*	150-*400*-600
Rock phosphates	0	11-16	0	32-38Ca	*	-
*PARR phosphate***	0	17	0	20Ca	50-100	200-*400*-*500*
Potassium chloride	0	0	50		*25*-50	*100*-200
Potassium sulphate	0	0	40	17S	50	125-250
Epsom salts	0	0	0	10Mg; 13S	-	500-1500
Kieserite	0	0	0	18Mg; 23S	-	250-800
Dolomite	0	0	0	11Mg; 24Ca	-	500-1500
Calcined magnesite	0	0	0	50-55Mg	-	100-*200*-300
Copper sulphate	0	0	0	25Cu; 13S	-	20-40
Copper oxychloride	0	0	0	57Cu	-	*9*
Zinc sulphate	0	0	0	36Zn; 18S	-	10-30
Borax***	0	0	0	11B	4	20-40-80
Ulexite	0	0	0	12-13B	4	20-*50*-*70*
Na borates	0	0	0	13-22B	-	Variable
Colmanite	0	0	0	16B	4	25-*50*-70

* Rock phosphate, perhaps in mixture with super, can be band or broadcast applied at establishment at 500-1000 kg/ha.
** PARR is partially acidulated reactive rock phosphate.
*** Sometimes added as boronated superphosphate.

Leaching of Nitrogen and Other Nutrients from Plantation Forests

Nutrient export from catchments

Unlike intensive pastoral farming and cropping, forests are conservative in cycling N and little is lost through leaching. Nitrogen is returned to the soil from the canopy as diffuse litterfall in organic form and is only slowly mineralised and made available for plant uptake, mainly as ammonium-N. This contrasts with pastoral farming where N is returned mainly in concentrated urine patches which becomes available for leaching after conversion to nitrate. Thus, in an early lysimeter study with unfertilised radiata pine growing in pumice soil, Knight and Will (1977) found no leaching loss of inorganic N over a seven year period during establishment and canopy closure phases. For the same period losses of K, Ca and Mg (4.2, 5.7, and 1.6 kg/ha/yr respectively) were recorded.

Pines established on ex-pasture sites may suppress nitrate (NO_3) formation (Cooper 1986, Davis 2001), possibly as a result of competition for ammonium by pines (leaving little for nitrifying bacteria), and various studies have indicated greater loss of N and/or P from pasture than pine forest catchments (for review see Mclaren 1996). Larned *et al.* (2004) found that at a national level dissolved N and P concentrations in pastoral and urban surface water classes were 2-7 times higher than in native and plantation forest classes, and that water quality in the native and plantation forest classes did not differ significantly. Estimates of annual loadings of N to surface waters (Parliamentary Commissioner for the Environment 2004) from non point sources suggest agriculture contributes ~100,000 tonnes per annum, natural forests ~15,000 tonnes per annum and plantations ~7000 tonnes per annum. These equate to approximately 8, 4 and 2 kg $N.ha^{-1}.yr^{-1}$ respectively, demonstrating the low impact nature of plantations comparative to agriculture (Payn and Clinton 2005). According to Hamilton (2005), for the central volcanic plateau, annual N export rates may be around 10-16 kg/ha for sheep and beef farms, 30-70 kg/ha for dairy farms and 1.5-3 kg/ha for areas uninfluenced by pastoral land use (or geothermal activity). In localised situations influenced by geothermal activity where N inputs may be very high for prolonged periods, however, N export rates from forests may be similar to those of agricultural systems for at least part of the forest rotation (Parfitt *et al*. 2002)

Nutrient export from pine catchments varies over time, however, and may in some instances exceed that from pasture catchments. Cooper *et al.* (1987) found greater concentrations[2] of NO_3 in streamwater from pine forest than in streamwater from an adjoining pasture catchment, while concentrations from native forest were higher than from pine forest (Table 3). Concentrations of total and dissolved reactive P followed the order pasture > pine > native forest, consistent with the input of P fertiliser to the pasture (Table 3). Cooper *et al*. (1987) suggested that the lower concentrations of NO_3^- in streamwater from the pasture catchment were due to NO_3^- stripping by in-stream vegetation, which was not present or of reduced extent under forest because of shading. While NO_3^- was higher in forested streams, total N export was higher in streamwater from pasture than from native forest, which in turn was higher in streamwater from pine, in the ratio 9:3:1, because of much greater export of particulate-N from the pasture catchment during storm events (Cooper and Thomsen 1988).

[2] Nutrient concentrations given in mg/l may be multiplied by (annual precipitation x 0.01) to give an estimate of leaching rates (kg nutrient/ha/yr). These approximations assume drainage = rainfall and hence are gross overestimates. For forest in areas where rainfall is around 1500 mm a closer approximation can be obtained by multiplying the nutrient concentration by (annual precipitation x 0.01 x 0.3) which assumes drainage = one third of the annual precipitation.

Table 3: Nutrient concentrations (mg/l) in streamwater emanating from adjoining catchments with different land use at Purukohukohu experimental basin, central North Island. Pine was planted into pasture in 1973. Values are monthly means for the 14-year period 1972-1986. Soils are from volcanic ash, rainfall is approximately 1550 mm. Data are from Cooper *et al*. 1987.

	Total P	Dissolved reactive P	NH_4-N	NO_3-N
Pasture	0.031	0.012	0.012	0.013
Pine	0.018	0.008	0.011	0.176
Native forest	0.013	0.003	0.010	0.805

Influence of harvesting and vegetation management

Harvesting may lead to increased leaching loss of N from forests as N uptake is disrupted and decomposition is accelerated. Dyck *et al.* (1981) reported elevated concentrations of nutrients in leachate collected in suction cups at soil depths of 1 m after harvesting operations, but the effect was short lived (Table 4). For NO_3 the elevated levels persisted up to three years after logging. Nitrate leached to the lower soil in the first and second years after logging and burning was estimated to be less than 15 kg/ha (Dyck 1982).

Table 4: Impact of logging (1976) and burning (1977) operations on lysimeter leachate concentrations (mg/l) in P. radiata forest on volcanic ash soil, Kaingaroa. Herbicide was used to control weed growth. Leachate was collected at 100 cm, except for P (45 cm). Rainfall is approximately 1400 mm. Data are from Dyck *et al*. (1981).

Year	Treatment	NH_4-N	NO_3-N	K	Ca	Mg	PO_4-P
1977	Control	0.008	0.066	1.65	1.14	0.67	0.006
	Logged	0.020	0.599	1.70	1.16	1.74	0.037
	Logged+burned	0.008	1.188	1.64	0.97	1.30	0.013
1978	Control	0.015	0.021	1.14	1.02	0.55	T[1]
	Logged	0.013	0.795	1.73	0.80	0.74	0.038
	Logged+burned	0.011	0.871	1.22	0.64	0.77	T
1979	Control	0.011	0.010	2.59	1.61	0.98	T
	Logged	0.012	0.542	2.32	0.73	0.52	T
	Logged+burned	0.010	0.024	1.42	0.55	0.62	T

[1] Trace (<0.010 mg/l)

Normally leaching losses after harvest are small and short lived since revegetation of cutovers by "weeds", which take up N that might be otherwise leached, is rapid. If revegetation is prevented, however, losses can be higher. For example, increased concentrations of NO_3-N were measured in suction cups after above ground vegetation was removed from trenched treeless plots (simulating harvesting) in Kaingaroa forest (Dyck *et al.* 1983). After 21 months soil-water NO_3-N concentrations had risen to a maximum of 9.4 mg/l compared to 2.0 mg/l in an adjacent logged but unweeded area. Concentrations in unlogged controls were 0.002 mg/l. Again, the increase in trenched and weeded plots appeared short-lived with concentrations declining to 4 mg/l at the close of the study (24 months after treatment).

In contrast to other studies, Parfitt *et al*. (2002) found harvesting reduced catchment NO_3-N loss, from 28 kg/ha/yr to less than 1kg/ha/yr, after two years on a pumice soil of high natural N status at the Purukohukohu experimental basin site. The reduction was attributed to N uptake by weeds (especially grass) that invaded the site after harvest, as well as enhanced microbial activity and incorporation of N into microbial biomass. Cation (K, Ca, and Mg) concentrations appeared to decrease at the same time as NO_3-N in lysimeters, but not in streamwater. The leaching loss of NO_3-N of 28 kg/ha/yr was measured in 1996, just prior to harvest, and was greater than values reported for the same area earlier for 1982-83 of <1 kg/ha (Cooper 1986) and 1985-86 of 5-13 kg/ha (Dyck *et al.* 1987). Together the studies indicate a trend of increasing losses of NO_3-N with time, as the forest matured and required less N from soil N pools. The leaching loss of 28 kg/ha/yr is abnormally high for plantation forests and is considered to be due to the presence ammonium emitting steam vents in the area, which presumably contribute to the high natural N status of the site.

Nutrient losses from species other than radiata pine

Nutrient losses from eucalypt or Douglas fir plantations are unlikely to be greater than from radiata pine. Dyck *et al*. (1983) compared NO_3-N losses from undisturbed and disturbed forest ecosystems (radiata pine, Douglas fir, *Eucalyptus saligna*) and gorse on pumice soils in central North Island (average rainfall = 1500 mm). Nitrate concentrations measured in suction cup solutions at 60-80 cm depth in undisturbed forest were low (0.006-0.272 mg/l) compared to gorse, which fixes atmospheric N (Table 5). Trenching of treeless plots and weed removal, simulating clearfelling and continued weed control, resulted in substantial increases in solution NO_3^- concentrations in radiata pine and Douglas fir, but not *E. saligna*. However increases after actual clearfelling (radiata pine), or clearfelling and burning (Douglas fir) were much reduced and short lived, probably because of rapid revegetation of the sites after the harvesting operations were completed.

Table 5: Average nitrate concentrations in suction cup solutions from undisturbed forest and gorse on pumice soils. Data are from Dyck et al. (1983).

Ecosystem	Location	Age (yr)	Stocking (sph)	Soil	Average NO_3^--N (mg/l)	Leaching (kg/ha/yr)
Radiata pine	Kaingaroa forest	20	250	Silty sand	0.006	0.03
Douglas fir	Kaingaroa forest	56	200	Sand	0.272	1.2
E. saligna	Rotoehu forest	18	100	Coarse sand	0.080	0.36
Gorse	Rangitaiki	20	Dense	Sand	5.100	22.9

Influence of fertiliser application

There have been few studies of nutrient leaching following fertiliser application to forest in New Zealand. In a lysimeter study, Worsnop and Will (1980) found in a Taupo silty sand soil at Kaingaroa that no loss of ^{15}N from ^{15}N labelled urea applied (at 200 kg N/ha) occurred for three years after the fertiliser application (Table 6). No change in the leaching rate of other nutrients was recorded. The proportion of applied N in the litter and top 30 cm of soil dropped to 60% after 4 weeks and later stabilised at 50%, the authors suggesting that tree uptake accounted for much of the loss.

Table 6: Rainfall (mm) and nutrient losses (kg/ha/yr) before (1967-73) and after application of urea in 1975 to thinned 13-year old Pinus radiata forest, Kaingaroa. Data are from Worsnop and Will (1980).

Year	Rainfall	NH_4-N	NO_3-N	P	K	Mg	Ca	Na
1967-73	1500	Nil	Nil	0.007	4.2	1.6	5.7	12.5
1975	1578	<0.001	<0.001	<0.001	6.5	4.0	10.5	20.4
1976	1468	0.005	0.006	Nil	3.3	1.5	6.0	11.2
1977	1299	0.005	0.002	Nil	3.0	1.5	6.4	10.9

Clinton and Mead (1994) applied 330 kg/ha of N (ammonium 44%, nitrate 56%) in 11 monthly applications to 4-year-old radiata pine growing in bare ground, rank pasture, and simulated grazed pasture on a silt loam soil in Canterbury. One of the applications was labelled with ^{15}N. In the dry environment no leaching would have occurred and total system recovery of ^{15}N in soil and plant material was high (71-107%). All of the ^{15}N labelled NO_3 was recovered and the small losses of ^{15}N labelled ammonium were attributed to denitrification.

Nitrogen leaching may occur more readily on sands. Thomas and Mead (1992b) applied ^{15}N-labelled urea (150 kgN/ha) to 2-year-old seedlings on bare coastal sand in Canterbury in either single or split applications. For the single application 30% was lost below the main rooting zone through leaching, but when split into 3 applications of 50 kg/ha more N was retained in the soil and no N was detected below the root zone at 80 cm depth.

At Woodhill Forest (rainfall = 1330 mm) Smith *et al*. (1994) compared nitrate leaching (in suction cups at 60 cm depth) following harvest of a 42-year-old stand, in the presence and absence of urea application. In unfertilised plots NO_3 concentrations increased from less than 1 mg/l at harvest to peak at 5mg/l after 20-30 weeks, before declining to pre-harvest levels by 80 weeks after harvest. An exception occurred in a treatment where double the amount of slash was present, where levels peaked at 15 mg/l, although levels again declined to pre-harvest levels by 80 weeks. Where urea was added (200kg/ha/yr in quarterly additions of 50 kg/ha for 2 years) NO_3 concentrations had increased by 20 weeks, and remained at elevated levels of 2-25 mg/l in most treatments throughout the monitoring period to 120 weeks after harvest. In operational situations N is not applied as broadcast applications to seedlings, but both experiments show the potential of sands to leach N after fertiliser application.

Unless precautions are taken, fertiliser may directly enter stream channels during aerial topdressing operations. Leonard (1977) monitored streamwater N concentrations from a 389 ha catchment on the volcanic plateau planted in radiata pine, of which one third had been topdressed with 230 kgN/ha as urea. There was no attempt to avoid the stream channel. He measured a net stream loss due to fertilisation of 95 kg N (0.74 kg/ha, 0.33% of the total applied) during the first four months after application. Nearly half (48%) was lost during the first six days of fine weather, which the author attributed largely to fertiliser landing directly in the stream channel. He suggested using a buffer strip of 20 m wide on either side of the stream to prevent direct entry of N into the channel. Additional studies with both urea and superphosphate are reported in Neary and Leonard (1978), who, in addition to recommending using 20 m wide buffers, suggested topdressing during no-wind conditions, and using larger granule fertilisers dropped from lower altitudes to reduce direct entry of fertilisers into stream channels.

Maximum Nitrogen Fertiliser Amount

Because of the lack of New Zealand studies, the question "what maximum amount of nitrogen over what period should be specified for forestry operations to prevent ongoing increases to surface or groundwater resources in the Lake Taupo catchment?"

cannot be directly answered. Overseas work indicates forests differ in their response to N addition. For example a Massachusets USA forest stand received more than 1020 kg/ha N before significant N leaching occurred (Magill *et al*. 2000), whereas addition of 25 kg/ha resulted in increased N leaching from a forest in Vermont (Kahl *et al*. 1993). Binkley and Hogberg (1997) reviewed results from a number of Swedish N fertilisation experiments, to determine whether forests were N saturated as a result of atmospheric pollution. Annual atmospheric N inputs in southern Sweden amount to 25 kg/ha and decline to 15 kg/ha in central Sweden and 4 kg/ha in the north. Thirty year N inputs at these (Swedish) rates range from 120 to 750 kg/ha. From results of N leaching studies Binkley and Hogberg (1997) concluded that some forests along the south-western coast may be near N saturation (i.e. where outputs approached inputs), but a large proportion of forests in the same region were far from saturation. Under ambient deposition rates, forest soil leaching losses in Sweden were typically less than 5 kg/ha/yr, although rates as high as 25 kg/ha/yr have been reported.

While N-leaching from most forests generally remains low despite decades of atmospheric inputs, this may not hold when forests are harvested. At a fertiliser trial in central Sweden (atmospheric inputs 15kg/ha/yr) cumulative N fertiliser additions ranged from 0-1800 kg/ha over a 20-year period. No increased leaching of N was observed up to 1440 kg/ha; at 1800 kg/ha N leaching increased from 2 (control) to 4 kg/ha. For 3 years after clearfelling N leaching remained at background levels up to 720 kg/N/ha, but higher rates resulted in up to 17 kg/ha/yr of N leaching.

It is not completely understood what factors control differences in N leaching response to fertiliser application. Factors such as land-use history, soil N pool size, species composition, stand age, and length of growing season are likely to be important because they influence the balance between availability and demand (Reuth *et al*. 2003). Nitrogen leaching from N fertilised actively growing radiata pine forests should be low because of low atmospheric inputs and high N demand, and this suggestion is supported by the results of Worsnop and Will (1980) above. However, as elevated N leaching (although limited and of short duration) can occur following harvest, a cautionary approach should be taken to specification of maximum N application rates. From the information available it would seem unlikely that the current recommended practice of applying 200 kg/ha of N at thinning when foliar N concentrations are less than satisfactory for optimum growth (or of the same amount at any stage when concentrations indicate deficiency) would result in ongoing increases in N leaching. However, further research is required to confirm appropriate N application practices for promoting tree growth that do not lead to increased N leaching.

Until that additional research is undertaken, and in order to follow a conservative approach to prevent loss of N, the following points are suggested as useful guides in terms of increased fertiliser applications in forestry:

- Broadcast applications of N at any time should not exceed 200 kg/ha.
- Spot applications after planting should not exceed 30 g N/tree (or 60 g urea/tree).
- Application during winter or other wet periods when soil water drainage is likely should be avoided.
- Except where plantations are severely deficient broadcast applications should be made in conjunction with thinning and pruning operations when N demand is high.
- Application decisions should be based on results of nutrient analysis of foliage.
- Mechanisms to prevent the direct discharge of fertiliser into surface water should be in place (eg separation distances between application areas and waterways, topdressing only during no-wind conditions, and using granule fertiliser dropped from low altitude).
- Rapid revegetation of clearfelled areas should be promoted to minimise losses after harvest.

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