EFFECTS OF FOREST FERTILISATION ON NUTRIENT LOSSES IN STREAMFLOW IN NEW ZEALAND

D. G. NEARY*
Forest Research Institute, New Zealand Forest Service, Rotorua
and
J. H. LEONARD
Technical Centre, N.Z. Forest Products Limited, Auckland

ABSTRACT

The effect on water quality of urea and superphosphate aerial topdressings of **Pinus radiata** stands was studied at five sites. Urea was applied at a rate of 500 kg/ha to 126 ha of the Mangotutu catchment near Kinleith. A total net loss of 95 kg N (0.33% of applied N) occurred during a 21 week period after aerial topdressing. Of this amount, 46.0 kg was lost during the first week by direct fall into the stream. Nitrate N reached a maximum of 1.18 mg/l some 44 days after application. A 73 ha catchment in Golden Downs S.F. received 540 kg/ha of superphosphate. Over a 189 day period only 1.2 kg of elemental P (less than 0.01% of that applied) left the catchment. The PO_4-P level peaked at .109 mg/l shortly after topdressing and was back to normal within several days. Two catchments in Tasman Forest, west of Nelson, received 200 kg/ha of urea and 400 kg/ha of superphosphate. The smaller (74 ha) catchment was entirely topdressed and exhibited much higher levels of N and P in streamflow (1.72 mg/l total P and 0.79 mg/l total N). The larger (478 ha) catchment received fertiliser on only 199 ha and its stream was not overflown. Total P and total N levels reached maxima of only 0.031 mg/l and 0.72 mg/l respectively. An 18 ha catchment in Tairua S.F. was topdressed with 1250 kg/ha of superphosphate. Despite a very high rise in PO_4-P concentration in streamflow to 51.87 mg/l, total loss of P was only about 0.06% of that applied. A similar amount of superphosphate applied to a 31 ha catchment in Riverhead S.F. produced a maximum stream concentration of 16.13 mg/l PO_4-P. Inputs of forest fertilisers can be kept low by using 20-m buffer strips along stream edges, topdressing during no-wind conditions, and using larger granule fertilisers dropped from low altitudes.

INTRODUCTION

Forest fertilisation has become a widely accepted silvicultural technique in production forestry. Historically, the role of fertilisers in forestry has developed from one of correcting nutrient deficiencies to one of increasing tree growth. Baule (1973) has pointed out the rapidly expanding nature of forest fertilisation throughout the world. This trend has also been very evident in New Zealand (Ballard and Will, 1978).

The increasing use of fertilisers in routine forest management operations has created

* Present address: U.S.D.A., Forest Service, Franklin NC 28734, U.S.A.

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concern amongst the general public and particularly conservation groups. Questions are being asked about the possible environmental effects of applying large amounts of fertiliser to forests. The range of these environmental questions has been reviewed by Weetman and Hill (1973). They concluded that there are two major effects of forest fertilisation which will continue to raise doubts in people's minds. These are: (1) the risks of water pollution and (2) general changes in the ecology of forest ecosystems.

The principal environmental concern regarding forest fertilisation will probably always be the effect on water quality. Aerial topdressing is a highly visible activity and thus is likely to attract public attention. Water quality has been subject to considerable publicity in recent years and has consequently become a political issue.

The purpose of this paper is to assess the impact of forest fertilisation on water quality and to examine its relative role as a contributor to eutrophication of fresh waters. This will be done by reviewing a number of overseas studies and by presenting the results of some recent New Zealand studies.

Fate of Fertilisers

Fertilisers are applied to the soil to provide additional sources of elements for tree growth. Losses of fertiliser from treated areas not only reduce the amounts available to the trees, but also provide nutrient sources which may have an effect on water quality. These losses can occur through direct fall of fertiliser into water, surface movement of dissolved or sediment-adsorbed ions, and leaching from the active rooting zone into underlying ground water.

Direct Inputs Into Water

Fertilisers are usually added to nurseries, seed orchards, or seedlings at time of planting by manual or tractor-mounted spreader systems. These methods provide precise control of distribution onto the soil. Application of fertiliser to established forest stands is generally done by means of aerial topdressing. This method is the most practical and economic means of spreading fertiliser over large areas of forest land. However, aerial topdressing introduces the hazard of fertiliser losses into water courses. These losses can occur from direct fall of large granules or drifting of finer material into water courses.

The amount of fertiliser entering waterways is dependent on a number of factors. These include the total surface area of stream courses within a topdressed area, the uniformity of fertiliser distribution, the size range of fertiliser particles, the height at which the fertiliser is dropped, the amount of wind, and the nominal application rate.

Overland Movement

Overland flow is a highly selective process in removing nutrients from a site. It transports fine soil particles and organic matter which are naturally high in nutrients such as nitrogen (N) and phosphorus (P). Sizeable quantities of fertiliser can be removed by this process. Most authorities agree that overland flow is the major mechanism for removing nutrients from agricultural lands (Metson, 1971), but this is a rare phenomenon in forests. Well-structured soils and deep humus layers which develop under stands of trees promote infiltration rather than overland flow. Fertiliser losses can occur where vehicle movements alter soil infiltration and runoff takes place. Another type of runoff loss occurs when fertiliser granules are washed out of ephemeral stream channels.

Leaching

Leaching losses from the soil are determined by a number of factors including the type of fertiliser used, the physical and chemical properties of the particular soils, the rate of nutrient uptake by plant roots and the rainfall pattern. Other things being equal, the main characteristic influencing leaching of fertilisers is the mobility of the individual ions formed by dissolution of solid fertiliser. Nitrogen and P fertilisers are quite different in this respect.

The most commonly used phosphorus fertiliser in New Zealand forestry is superphosphate (8-10% P), which consists mainly of water-soluble monocalcium phosphate (MCP). In the soil MCP reacts quickly to form less soluble precipitates of basic calcium phosphates and/or aluminium and iron phosphates. In addition, P left in solution may be strongly adsorbed onto various clay minerals and hydrous oxides found in most soils. Consequently there is usually very little movement of P from fertilisers into groundwater systems.

Nitrogen fertilisers used in forestry are usually applied in the forms of ammonium (NH_4^+) salts or urea which hydrolyses to NH_4^+. Positively charged NH_4^+ ions are readily adsorbed on to negatively charged sites of clay minerals and organic matter. Under suitable conditions of soil pH, aeration, moisture and temperature, adsorbed NH_4^+ is converted by bacteria to the nitrate (NO_3^-) form. The negatively charged NO_3^- ion is not adsorbed to any extent in the soil. Thus it is very susceptible to movement with soil water away from the active rooting zone. The NO_3^- form of N then becomes a source of enrichment for groundwater and ultimately surface water.

Literature Review

Nitrogen

Nitrogen is often associated with eutrophication of fresh waters and can pose a threat to drinking water quality. Its tolerance limit in drinking water has been set at 10.0 mg/l as NO_3^-N). High nitrate (NO_3^-) levels in drinking water cause the blood disease methaemoglobinemia, an anaemic condition resulting from the reaction of nitrite ions (NO_2^-) with haemoglobin. Infants are the most susceptible to this disease.

The majority of the North American literature regarding the effects of forest fertilisation on water quality deals with N (Table 1). Urea (46% N) is the most

TABLE 1—Studies on N outputs in streamflow following forest fertilisation

Reference	Location	Fertiliser	Rate kg/ha	N Budget Input	N Budget Output	Time days	Maximum NO_3-N mg/l
				—— kg/ha ——			
1. McCall (1970)	Washington	Urea	370	—	—		1.32
2. Klock (1971)	Washington	Urea	118	53.1	0.01	60	0.21
	Washington	$(NH_4)_2SO_4$	280	58.8	0.01	60	0.07
3. Tiedmann (1973)	Washington	Urea	78	35.1	3.28	365	0.33
4. Aubertin **et al.** (1973)	W. Virginia	Urea	560	257.6	51.20	365	17.10
5. Moore (1975)	Washington	Urea	492	224.1	0.44	210	0.04
	Washington	Urea	492	224.1	0.58	210	0.12
6. Meehan (1975)	Alaska	Urea	448	—	—	—	1.30
	Alaska	Urea	448	—	—	—	2.61
7. Fredrikson **et al.** (1975)	Oregon	Urea	498	229.1	0.38	365	0.18
8. Tamm (1975)	Sweden	Urea	337	—	—	—	0.50
	Sweden	NH_4NO_3	400	—	—	—	24.00

commonly used fertiliser, especially in areas such as the Pacific Northwest. Recent trends in Scandinavia have shown a definite swing towards a preference for ammonium nitrate.

Several studies in Washington State have documented low concentrations of NO_3-N and streamflow (McCall, 1970; Klock, 1971; Tiedemann, 1973). Moore (1975) summarised a study in which two catchments (49 and 67 ha) in mixed-aged Douglas fir were topdressed with 492 kg/ha of urea. Helicopters spread the fertiliser, keeping 60 m away from stream courses. Over a 7-month period after topdressing, both areas lost only 0.2-0.26% of applied N in streamflow; NO_3-N accounted for 52-68% of the output and reached a maximum concentration of 0.12 mg/l. Fredricksen *et al.* (1975) discussed a study in a 68 ha catchment of old growth conifers which was topdressed by helicopter with urea at 498 kg/ha. Total fertiliser N lost in streamflow in the first year amounted to only 0.4% of the applied N. About 92% of this loss occurred during rainy weather 4-6 weeks after topdressing.

The aerial topdressing by helicopter of a 30 ha hardwood forest catchment in West Virginia with 560 kg/ha of urea produced a sharp increase in N flux in streamflow (Aubertin *et al.,* 1973). No effort was made to avoid the stream course because of the small size of the perennial stream channel. A maximum NO_3-N level of 17.1 mg/l was noted during a storm 4 months after topdressing. Nitrate-N output climbed from 6.7 kg/ha during 12 months preceding fertilisation to 51.2 kg/ha (18% of applied N) over the following 12-month period.

Two streams in southeast Alaska were studied by Meehan *et al.* (1975) after topdressing of 607 ha of cutover land with urea at 448 kg/ha. The NH_4-N concentrations on one stream rose from less than 0.1 mg/l to 1.3 mg/l during topdressing, with a return to base levels within 1 month. Nitrate N levels rose in a similar fashion but did not recede for 14 months. The other stream showed no increase in NH_4-N, and had slightly higher NO_3-N levels which returned to baseline within 1 month.

Studies of forest fertilisation in Scandinavia have been discussed by Tamm (1975). Observations of streams flowing from two topdressed catchments showed that the use of NH_4NO_3 produced maximum total N and NO_3-N concentrations four and fifty times higher, respectively, than urea.

Phosphorus

Most of the reported studies on P inputs into fresh waters from aerial topdressing are from New Zealand. This reflects this country's high use of phosphatic fertilisers. There are few references in North American literature since P fertilisers have been in limited use only in the south-eastern U.S. (Sandford, 1975). Phosphorus is an element of concern to water quality because of its role in the eutrophication of fresh water, but poses no direct threat to drinking water.

A study of P movement and distribution was reported by White (1972). He examined four catchments at Taita with different vegetation. A grassland catchment (3.6 ha) received an initial topdressing of 1255 kg/ha of superphosphate (8-10% P) at establishment and biannual applications of 377 kg/ha. Soluble orthophosphate (PO_4-P) outputs from two storms in October 1971 were studied. Amounts leaving the fertilised area in streamflow were 2.4, 4.8, and 1.9 times greater than those of nearby native forest, exotic forest and scrub catchments, respectively.

McColl *et al.* (1975) noted that three nested agricultural catchments in Northland produced very small losses of P following topdressing with superphosphate. Applications totalling 1771 kg/ha over 2½ years produced additional outputs of 1.15, 0.90 and 0.50 kg for three catchments involved.

RECENT FOREST FERTILISATION STUDIES IN NEW ZEALAND

A number of studies have been conducted in New Zealand in the past 2 years to assess the contribution of forest fertilisation to the eutrophication of lakes and streams These have been undertaken by public and private forestry agencies to provide basic information on the magnitude of fertiliser inputs into fresh waters. Considerable speculation has been going on recently as to forestry's contribution to water quality problems in many areas of the country. These studies should provide a good base for making a scientific assessment of the effect of forest fertilisation on water quality.

Mangotutu Stream, Kinleith

Urea fertilisation of thinned *Pinus radiata* stands on the central North Island volcanic plateau is a management practice adopted in recent years by N.Z. Forest Products Limited to enhance the rate of growth. With such an operation there is the possibility of some runoff loss, and a study was therefore undertaken during October 1973 to April 1974 to examine N loss in streamwater from a 389 ha catchment in the vicinity of Kinleith (Leonard, 1977).

The catchment, 5 km long and 0.6 km wide, consists of rolling contours of yellow brown pumice soils that carry mainly stands of immature second crop established in 1954-1956. The understorey has typical native shrub hardwoods, ferns, blackberry, tutu, etc. Pumice roads, together with former logging dumps, comprise about 5% of the total area. A branch of the Mangotutu stream (baseflow 15-28 l/s) originates as two small springs 2.8 km from the base of the catchment and flows roughly in the middle along its main axis. The stream bed is mostly 0.5-2.0 m wide but over a few sections it widens further into marsh conditions.

Aerial application of urea took place between 2 and 5 October 1973. Leaving the upper two-thirds of the catchment as an unfertilised control, and making no attempt to avoid the perennial stream channel, granular urea was spread over the lower catchment (126 ha) at a rate of 230 kg N/ha (500 kg/ha of urea) in such a way that each flight path was covered twice. A stream length of 1.2 km was covered on the first day. Unfavourable winds extended the operation beyond the expected 1-2 days, but no rain fell during that period. Streamwater samples were collected at the base of the catchment for a period of 21 weeks from the start of fertilisation. Over the initial 6 weeks analyses were made for NO_3-N, nitrite nitrogen (NO_2-N), NH_4-N and organic N, on samples representing alternate 60-minute periods of flow. Thereafter frequency of analysis was reduced to an extent depending on flow and rain gauge readings in the catchment. Control samples were taken regularly at 12- or 24-hourly intervals from a point just above the fertilised zone.

High and low flow water samples taken over the 12-month period before fertilisation and from the unfertilised control zone after fertilisation established that concentration levels of NO_3-N, NO_2-N and NH_4-N were consistently below the detection limits of 0.01, 0.005, and 0.01 mg/l of N respectively. On one occasion, however, NO_3-N was just detectable and on another, NH_4-N. Organic N varied within the range 0.02-0.30 mg/l.

The pattern of fertilisation response at the base of the catchment covering the first 53 days after fertilisation through October and November is shown in Fig. 1. The first change was detected 3 hours after the start of the operation and fluctuating levels of organic N in the form of unhydrolysed urea (0.50-9.28 mg/l) continued for the 6 days of fine weather leading up to the first rainstorm. Thereafter, the main loss of N resulted from four rainstorms (7-54 mm) occurring within a period of 39 days. The transformation of urea into NH_4-N and then into NO_3-N is also reflected in the six storm responses shown, NO_3-N being the only species present after the third storm. Maximum flow, occurring during storm No. 3, was about four times the baseflow. Over the following 3 months there were 11 rainstorms (5-60 mm) and with two of them only slightly increased NO_3-N levels occurred. From the standpoint of water quality, the total discharge of N over the 4 months was four times the corresponding discharge from the unfertilised zone, and at no time did NO_3-N approach levels dangerous to health.

The total net loss of 95 kg N for the 21-week period is equivalent to 0.33% of the N applied as urea to the catchment and this is not a significant amount from the standpoint of operation efficiency. Of this, 46.0 kg (Table 2) was lost during the first 6 days' fine weather as direct fall-out into the stream and from overhanging trees and vegetation. A further 31.7 kg was lost in the first storm, and by the end of the third storm response on day 24 where all nitrogen species were represented, a total of 90.9 kg had been discharged. Thereafter storm responses were minor and only in the form of NO_3-N. In April 1974 a particularly heavy rainstorm (110 mm) took place, 6½ months after fertilisation and 7 weeks after discontinuing regular sampling, from which a final

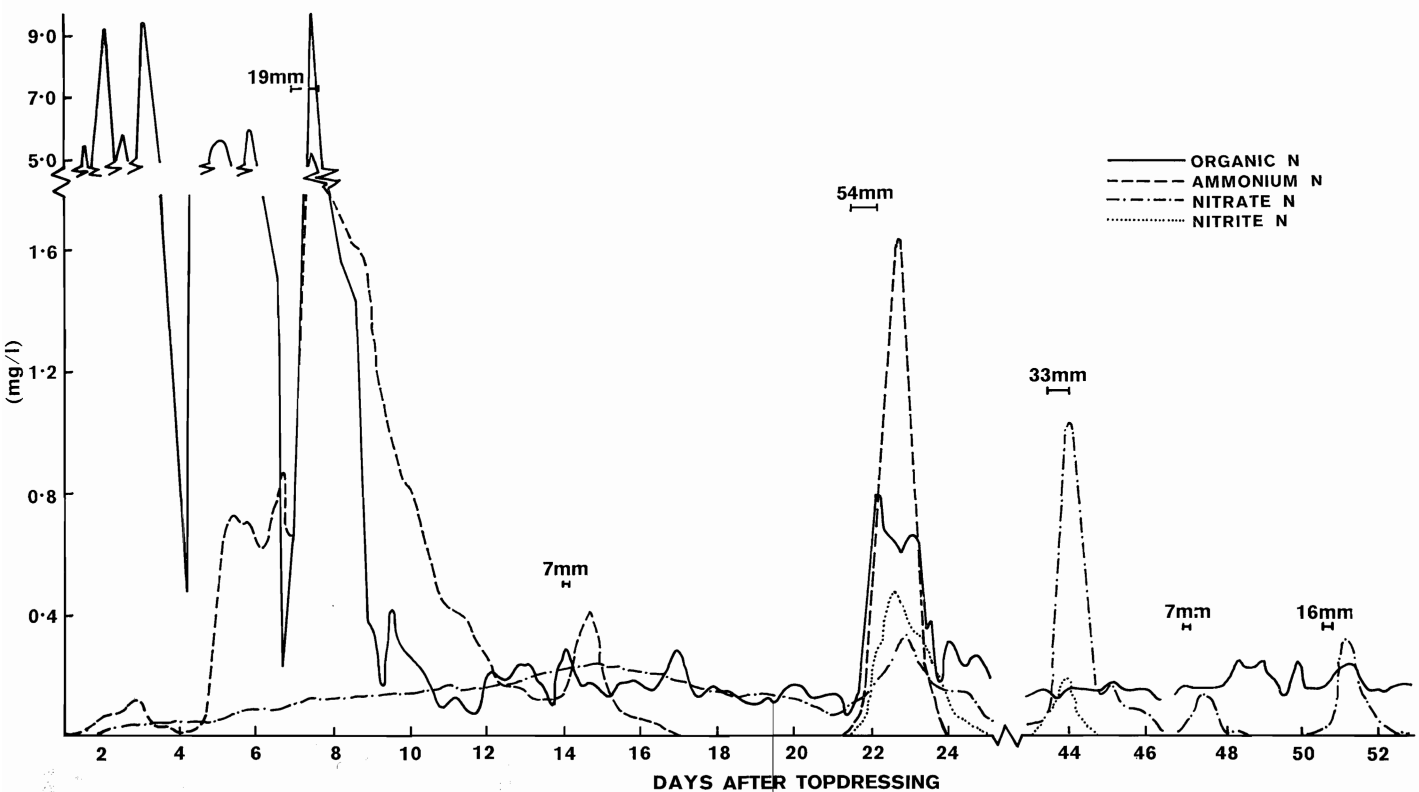
TABLE 2—Net discharge of N from a catchment fertilised with 29 tonnes of N as urea, from individual storms October 1973 — January 1974

	Days	Rainstorm Events					
	1-6	1	2	3	4	5	6
Rain (mm)	0	19	7	54	33	7	16
Discharge (kg N)	46.0	31.7	1.3	11.9	3.0	0.2	0.4

sample collection was made. A brief net increase in NO_3-N to 0.34 mg/l showed that under such extreme conditions, some fertilisation response was still in evidence.

It is an open question as to how much of the catchment actually lost fertiliser N to the stream. There were not apparent tributaries to the main stream and only a relatively narrow strip on either side of the stream bed may have been involved. The lower catchment was fertilised along a stream length of 1970 m and at an application rate of 230 kg N/ha the net discharge is equivalent to the urea that would have fallen along this distance over a strip 2.1 m wide. The experiment deliberately included the stream and its environs as part of the fertilised area but by use of a buffer strip of about 20 m width on either side of the stream, net discharge might well have been reduced by at least the initial fall-out loss of 48%.

FIG. 1. CONCENTRATIONS OF N FORMS IN MANGOTUTU STREAM WATER AFTER TOPDRESSING WITH UREA, 2nd OCT. TO 21st NOV., 1973.



Compartment 224, Golden Downs S.F., Nelson

Compartment 224 (C-224) of Golden Downs S.F. was topdressed with 540 kg/ha of superphosphate in early 1976. The 73-ha compartment is located in the southwestern portion of the forest. It occupies the entire drainage area of a tributary to Donald Creek. The stream is ephemeral in nature, drying up during the summer. The compartment was planted with *Pinus radiata* in 1970. The main soil types are central yellow-brown earths which developed on Moutere Gravels.

Aerial topdressing occurred on 23 January 1976 and 4 February 1976. The upper 40% of the compartment was treated on the latter date. A fixed wing aircraft was used to spread the fertiliser. Direct fall of fertiliser into the stream was gauged using a series of buckets placed at 10-m intervals in the lower reaches of the catchment.

The output of P in stream flow was monitored at a temporary 120° V-notch weir, The plywood cutoff-wall weir was inserted in a suitable section of the stream 20-30 m above its confluence with Donald Creek. Water samples were collected prior to topdressing, during the spreading, and for 5 months afterwards. All samples were preserved, frozen, and air-freighted to Rotorua for analysis.

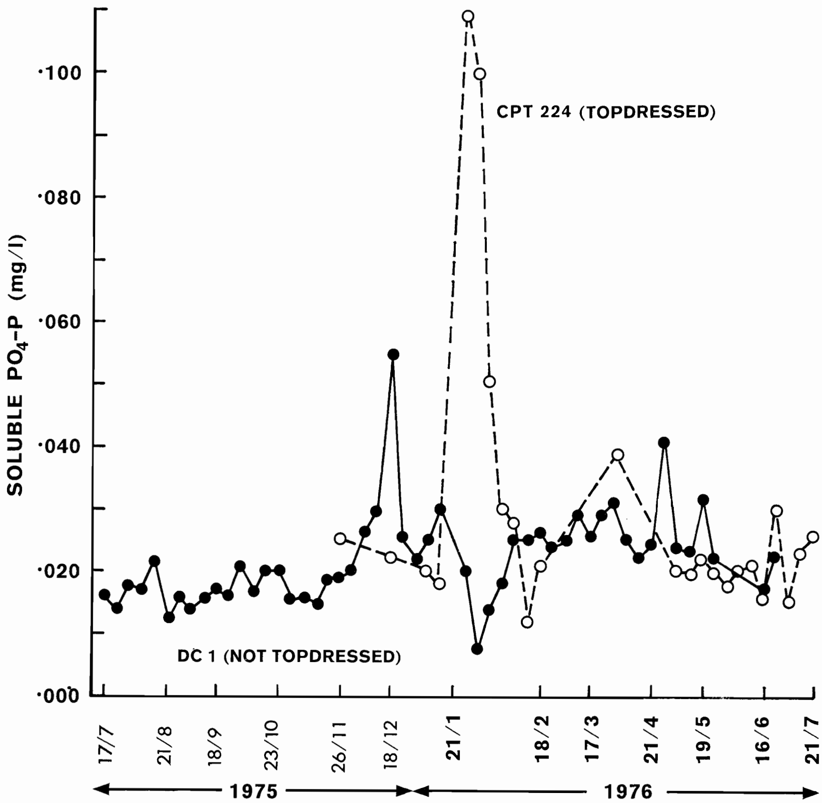
Only four samples were collected prior to the topdressing due to the late date in learning about plans for fertilising the compartment, and to zero flow which lasted for 4-6 weeks. These samples were thought to be reasonable estimates of baseline conditions since they compare favourably with chemical concentrations in water samples collected from the Donald Creek Hydrological Study. The Donald Creek catchments are in native beech forest and records date back to early 1975.

The concentrations of PO_4-P in streamflow from C-224 and Donald Creek 1 (DC-1) are presented in Fig. 2. Application of superphosphate on 26 January 1976 caused P levels to increase by a factor of five times to 0.109 mg/l. Within 2 days this level was reduced by one half and by 2 weeks was back to normal. Although the upper 40% of C-224 was topdressed on 4 February 1976, there was no immediate rise in soluble PO_4-P. This was attributed to the lack of surface water flow in the upper reaches. The peak on 29 March 1976 was most likely due to flushing of ephemeral channels in the head of the catchment. The rise on 29 March was within the range of variation in DC-1.

If uniform distribution of the fertiliser is assumed, then based on amounts collected in buckets in the lower stream reaches the total direct fall could have been as high as 152 kg of superphosphate on the estimated 5632 m^2 of streambed above the sampling site. Using flow data from the weir, the estimated output of PO_4-P above baseline output was only 1.2 kg. In terms of superphosphate this would be 12 kg. The discrepancy between the flow calculated figure and the value determined by the bucket system is probably due to a number of factors. Direct fall into the stream could have been less upstream of the bucket monitoring site. Also, P adsorption on to particulate matter in the stream channel would reduce measured soluble P. McColl *et al.* (1975) noted this same phenomenon.

The overall effect of the superphosphate topdressing on water quality was very small. Soluble PO_4-P levels rose to five times antecedent values but returned to normal within several days. Loss of fertiliser in streamflow amounted to much less than 0.01% over a period of 185 days. A 50% increase in flow volume over the period of the study would have produced the same amount of additional P output. Topdressing of super-

FIG.2. SOLUBLE PO4 -P CONCENTRATIONS IN STREAMFLOW, Cpt 224 GOLDEN DOWNS S.F., AND DONALD CRK 1, BIG BUSH S.F.



phosphate does not represent a continuous source of P input into the catchment as fertiliser applications are done at intervals of 5-8 years. The small losses of superphosphate measured in C-224 did not represent any sort of a hazard to water quality.

Machine Gully, Tasman Forest, Nelson

A study of a combined urea-superphosphate topdressing was carried out in Tasman Forest (H. Baigent & Sons Ltd) east of Moteuka. Machine Gully is an elongated catchment of low relief draining north into Tasman Bay. The soils are central yellow-brown earths which have formed on lower portions of the Moutere gravels. The forested portion occupies 478 ha and includes the main gully and a smaller side catchment of 74 ha. The main stream flows through a wide swamp with no defined channel until it reaches farmland to the north, where it flows through drains bounded by pasture. The side stream flows through a tangled bottomland of blackberry, gorse and fern.

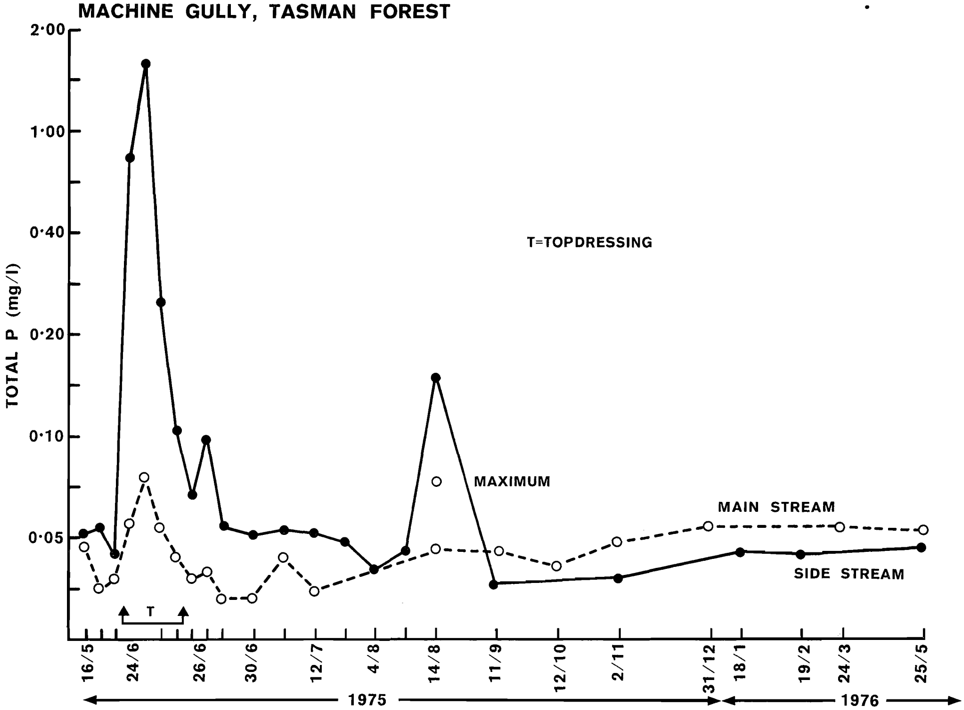
Urea and superphosphate were applied to 199 ha by fixed wing aircraft at rates of 200 and 400 kg/ha respectively. The superphosphate, supplemented with 5% borax, was applied on 24-25 June 1975 and the urea a day later. No attempts were made to avoid stream courses as the small stream channel was not discernible and the topdressed areas of the main gully did not include any of the swampy bottomland. Considerable drift of fine dust was evident during the superphosphate application.

Water sampling sites were set up on both streams prior to the topdressing. Manning S-4000 automatic water samplers were installed to give continuous discrete sampling. Problems developed with the side stream sampler so fewer samples were collected from July onwards. The side stream site was overflown by aircraft during topdressing runs, but the main stream sampling site was at least 200 m from the nearest fertiliser drop point. Samples were collected and analysed by the Cawthron Institute, Nelson.

The effect of direct fall of superphosphate into streams is shown in the graph of total P concentrations in both streams (Fig. 3). The side stream had a rapid rise in concentration to 1.72 mg/l the day of the topdressing. The main stream exhibited a far smaller rise (to .081 mg/l) since it was not overflown by the topdressing aircraft, and was affected only by drifting fertiliser. Total P concentrations in both streams returned to pre-topdressing levels within 2-3 days.

A second peak in total P output occurred during a stormy period on 14-15 August 1975. A sample taken at 1500 hours on 14 August in the side stream had a concentration of 0.163 mg/l. A larger number of samples (13) were taken in the main stream. At 1500 h on the 14 August total P in this stream was only 0.045 mg/l. The peak level did not occur until 0300 h on 15 August when it reached 0.079 mg/l. Following the August storms total P levels decreased again and became quite stable. Samples collected on 27 May 1976 were very similar in content to those collected a year earlier on 16 May 1975.

FIG. 3 TOTAL P CONCENTRATIONS AFTER TOPDRESSING OF SUPERPHOSPHATE, MACHINE GULLY, TASMAN FOREST

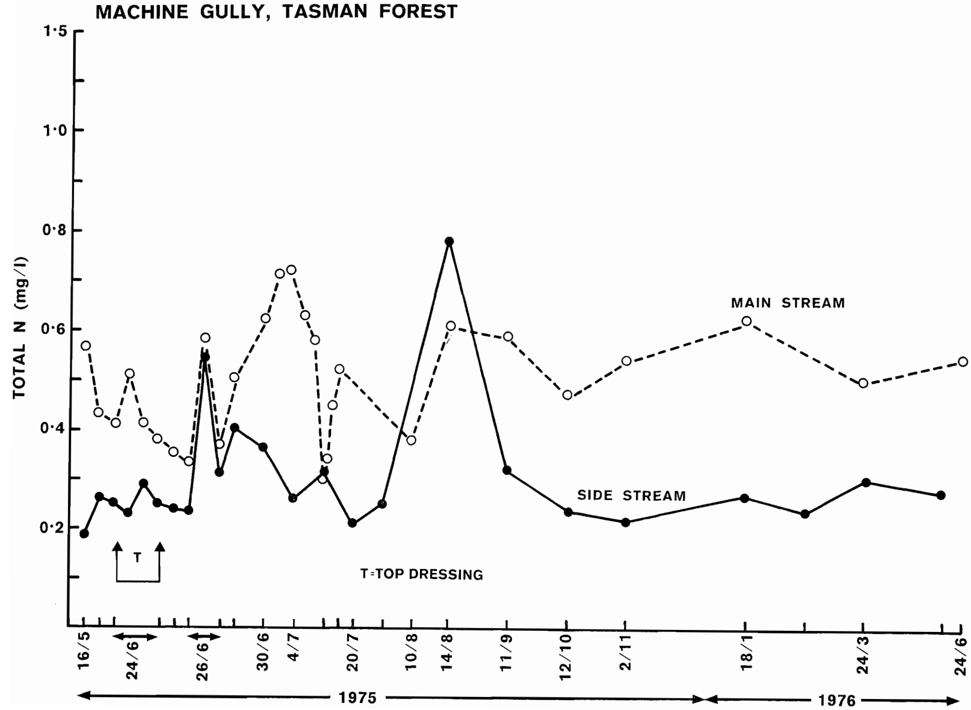


Total N concentrations in both the main stream and side stream throughout the period of the study are shown in Fig. 4. Total N tends to be high in these streams due to their swampy characteristics. Concentrations ranged from 0.32 to 0.56 mg/l in the main stream and .19 to .26 mg/l in the side stream during the pre-topdressing period. Applications of urea on 26 June 1975 caused distinct rises in total N levels in both streams.

The side stream total N concentrations rose from 0.24 mg/l on 25 June to 0.55 on the 26th as urea topdressing commenced. Total N levels dropped the next day to 0.31 mg/l, climbed again the following day, but were back to within the pre-topdressing range within 1 week. This first peak of total N was due to urea falling directly into the stream. A second and higher peak was measured during the same storm period that caused the total P levels to rise (Fig. 3). Total N concentration reached 0.79 mg/l at 1500 h on 14 August. This peak was probably due to a combination of NH_4-N and NO_3-N from hydrolysis of the urea, and expected increases resulting from storm flow. Since this stream was not sampled during storm conditions prior to topdressing, it is impossible to estimate the percentage of the 14 August total N peak caused by higher streamflow. After this peak, total N levels became quite stable.

The total N concentration rise in the main stream on the day of the topdressing closely paralleled that of the side stream. The maximum total N of 0.58 mg/l was not much higher than that on 16 May (0.56 mg/l), which was a pre-topdressing sampling date. A second rise in total N came over the period of 27 June to 10 July. Total N

FIG. 4 TOTAL N CONCENTRATIONS IN STREAMFLOW AFTER TOPDRESSING OF UREA, MACHINE GULLY, TASMAN FOREST



levels reached 0.72 mg/l on 5 July. Streamflow rate was about 15 l/s on 4 July, compared to 1 litre/s on the day of the topdressing. A third peak in total N occurred during the period of 14-15 August when flow rates rose to 60 l/s. At 1500 h on 14 August (same time as the side stream sample was taken) the total N concentration in the main stream was 0.61 mg/l. As with total P, the peak in total N occurred the following day. The maximum total N level was .37 mg/1 at 0900 h on 15 August. This was 6 hours behind the total P maximum. This rise in total N could have been due in part to flushing of NO_3-N released from urea after hydrolysis and nitrification. Since NO_3-N determinations were not done and no flows of this magnitude were sampled prior to the application of fertiliser, there is no way of estimating the contribution from the urea. Total N did not fluctuate appreciably after the mid-August rainy period.

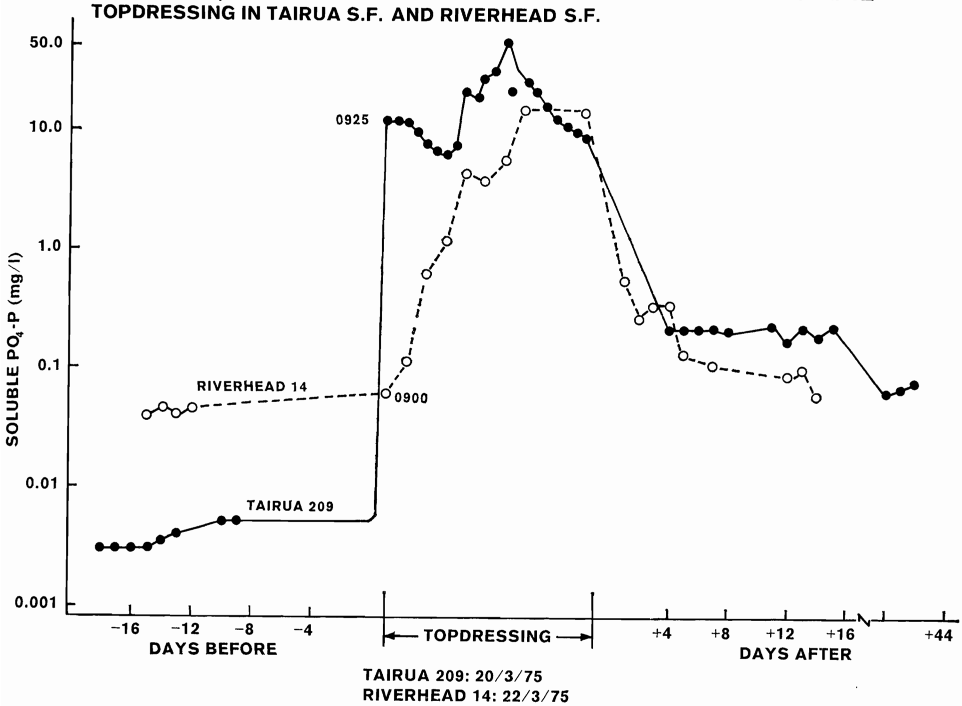
The effect of the application of urea and superphosphate on the water quality of the Machine Gully streams was quite small. Overall losses of N and P from the two catchments could not be accurately assessed since continuous flow data was not available during the entire study period. Total P concentrations were the highest in the side stream during topdressing. This rise accounted for an output of about 60 g of P (.6 kg of superphosphate) during the 72 hours following topdressing. Output of P was calculated from an estimated flow rate of 1 litre/s during the period of 24-26 June. Far less P came out of the main catchment in streamflow. Except for another rise in total P 2 months later, there was no detectable elevation in concentration of either stream over a period of 1 year. The main stream had three successive concentration peaks of increasing magnitude over a 2-month period. The first was associated with topdressing and the second two with storm events. There appeared to be no significant long-term rise in total N in either stream. The maximum total N concentration occurred in the main stream. Losses of N in streamflow would probably be less than 0.1% of that applied.

Cpt 209 Tairua S.F., Coromandel

A topdressing operation in Compartment 209 (C-209) of Tairua S.F. was monitored for a short period in March and April of 1975 to obtain some preliminary data on fertiliser losses in streamflow. An 18-ha portion of C-209 containing a 6-year-old ***Pinus radiata*** stand was selected for the study. Soils are mainly yellow-brown loams derived from volcanic parent material. Water samples were collected at a culvert carrying streamflow from the study area. Superphosphate was applied on 20 March 1975 at a rate of 1250 kg/ha using a fixed-wing aircraft. No stream avoidance measures were taken as the water course was too small and very difficult to identify from the air.

Pre-topdressing water samples in C-209 averaged less than 0.005 mg/l soluble PO_4-P (Fig. 5). Application of fertiliser started on the morning of 20 March before water samples were collected. Soluble PO_4-P levels jumped to over 10 mg/l. A drop in P concentration occurred during a lull in flight operations. With a resumption in topdressing reactive PO_4-P climbed again. The maximum of 51.87 mg/l occurred shortly after a "direct hit" was scored on the sampling station. The bulk of one plane-load came down all around in a rain of granules and choking dust. Soluble PO_4-P concentrations fell off again, dropping to 8.5 mg/l by the end of the day. Sampling resumed 4 days later. By then P levels were down to about 0.250 mg/l. Water samples

FIG. 5 SOLUBLE PO_4-P CONCENTRATIONS IN STREAMFLOW AFTER SUPERPHOSPHATE TOPDRESSING IN TAIRUA S.F. AND RIVERHEAD S.F.



collected 40 days after the topdressing (0.060 mg/l) were still not down to pre-topdressing levels.

Flow was measured at the C-209 collection point to determine the quantity of P lost in streamflow. At a flow rate of 1 litre/s total output of reactive PO_4-P over the 2-week period following topdressing was just over 1.2 kg (equivalent to 12 kg of superphosphate). This represented slightly less than 0.06% of the elemental P applied.

To put these losses into perspective, a look at estimated PO_4-P outputs is necessary. At a flow rate of 1 litre/s and a concentration of 0.005 mg/l, the PO_4-P output on a yearly basis would be 0.16 kg. The mean flow rate is probably more like 2 l/s which would give an output of 0.32 kg/yr, thus the PO_4-P output in the first 2 weeks following topdressing was about four times the normal yearly output. If a fertiliser cycle of 7-8 years is taken into account, then the topdressing increased P output by about 50%.

Extrapolation of results from small catchments like this to larger basins is difficult as McColl *et al.* (1975) have shown. Relative losses of fertiliser from larger catchments are likely to be smaller due to two factors. First, the stream surface area represents a smaller proportion of a large basin. Secondly, the areas contributing to the quick flow portion of storm flow are a smaller fraction of the catchment in large basins.

Compartment 14, Riverhead S.F., North Auckland

A 31 ha portion of Compartment 14 (C-14), Riverhead S.F., was studied during an aerial topdressing of superphosphate in March, 1975. This compartment planted with

Pinus radiata in 1970, had supported a previous crop of pines. The soils are strongly leached and weathered northern yellow-brown earths. In 1959, superphosphate at 627 kg/ha was applied. The 1975 topdressing was applied by fixed-wing aircraft at a rate of 1250 kg/ha. No precautions were taken to avoid overflying the stream.

The catchment stream is a tributary of the Rangitopuni Stream, along the eastern boundary of Riverhead S.F. Orientation of the catchment is east-west with a maximum relief of 70 m. Water samples were collected from a stream draining out of C-14 at a point where it leaves the forest. The samples were preserved with $HgCl_2$, frozen, and shipped to the Forest Research Institute for analysis.

Reactive PO_4-P in the C-14 stream was initially about 10 times higher than Tairua C-209 (Fig. 5). The mean pre-topdressing concentration was 0.043 mg/l. Levels of soluble PO_4-P rose more slowly in this situation than at Tairua. This was most likely due to a lower rate of direct fall near the sampling point. The peak concentration of PO_4-P (16.13 mg/l) occurred later in the day at Riverhead than at the Tairua site probably due to a longer time of travel to the sampling point. Sampling was continued the next day, by which time PO_4-P levels were considerably reduced. Phosphorus concentrations continued to recede, reaching baseline levels 13 days after topdressing.

Flow data from the C-14 stream were not available so no quantitative measure of P output could be calculated. The Riverhead study showed that considerable increases in stream soluble PO_4-P can occur during topdressing from direct fall into the water. However, the increases are normally only transitory.

ROLE OF FOREST FERTILISATION IN EUTROPHICATION

The relative role of forest fertilisation in contributing to the eutrophication of fresh waters can easily be appreciated by examining nutrient inputs into a lake from various sources. We shall use a hypothetical basin modelled after the Lake Rotorua catchment (Fish, 1975). The N and P inputs into the lake in this model originate from aerial topdressing, rainfall, microbial fixation and urban sewage.

The model assumes a basin area of 50 500 ha with a composition of 40% grassland agriculture, 40% exotic production forests, and 4% urban. The lake (16% of the basin) receives drainage waters from all other areas.

Over an evaluation period of 8 years, all forest areas receive one topdressing of 1000 kg/ha superphosphate and 500 kg/ha of urea. The grassland areas receive yearly applications of 300 kg/ha superphosphate. Additions of N occur as fixation but are treated in the model as if applied as a topdressing. Annual fixation of N in grass/clover pasture in New Zealand has been estimated to average 200 kg/ha. Loss of N from intensively managed pastures, through leaching, can be as high as 25% (Ball *et al.*, 1977), but in this model is taken as a lower level used for losses from applied N fertiliser. Fertiliser losses in streamflow are assumed to be 3% with no stream buffer strips and 0.5% with buffer strips (Moore, 1974).

The urban area, with a population of 50 000 produces 22.5×10^3 m^3/day of sewage effluent (450 litre/person. day). The N and P contents of the effluent are considered to average 25.8 and 4.2 g/m^3, respectively (Fish, 1975).

Rainfall and dry atmospheric fallout inputs into the lake are estimated at 1.9×10^3 kg P/yr and 18.9×10^3 kg N/yr (Fish, 1976).

Normal streamflow inputs into the lake are calculated using an annual flow of 212 284 m^3 from a catchment area of 20 200 ha (40% of the basin) and PO_4-P (.069 g/m^3), NO_3-N (.040 g/m^3), and NH_4-N (.03 g/m^3) data from Fish (1975).

Inputs of N and P during the 8 year period are shown in Table 3. With an all-out forest fertilisation programme (i.e., 500 kg/ha urea and 1000 kg/ha superphosphate) and no use of buffer strips, inputs into the lake from forest fertilisers would account for only 4.6% of N and 9.9% of P inputs. The use of buffer strips and other protection features could easily reduce losses from forest topdressing to 0.5% of the amount applied. This is a conservative figure in that losses could be less than 0.1%. In case of the reduction of losses to 0.5%, N and P inputs into the lake from forest fertilisation would drop to 1.1 and 2.3%, respectively. Thus very little practical reduction in the nutrient loading of the lake could be achieved by restricting the aerial topdressing of production forests.

TABLE 3—Sources of N and P inputs (tonnes, and % of total) into a hypothetical lake over an 8-year period

	3% Loss of Fertiliser				0.5% Loss of Fertiliser			
	N Input		P Input		N Input		P Input	
	t	%	t	%	t	%	t	%
Streamflow[1]	73.0	2.4	117.2	19.1	73.0	3.5	117.2	26.6
Rainfall and Dry Atmospheric Fallout	151.2	5.0	15.2	2.5	151.2	7.2	15.2	3.5
Grassland Fertiliser	969.6	32.0	145.4	23.7	161.6	7.7	24.2	5.4
Production Forestry Fertiliser	139.4	4.6	60.6	9.9	23.2	1.1	10.1	2.3
Urban Sewage	1695.1	56.0	274.6	44.8	1695.1	80.6	274.6	62.2
Total	3028.3	100.0	613.0	100.0	2104.1	100.0	441.3	100.0

[1] N and P Inputs represent PO_4-P and NO_3-N/NH_4-N only.

While forest fertilisation contributes very little nutrient loading in relation to other sources, there is no justification for allowing complacency to develop. Every effort should be made to minimise the impact of topdressing on water quality. It is in the best interest of the forestry profession to maintain a high level of self regulation in regard to environmental considerations.

CONCLUSIONS

At current and projected levels of usage, fertilisers are not creating a nutrient problem in streams draining forest lands. Most overseas work has dealt with N fertilisers. Increased outputs of N in streamflow following aerial topdressing have ranged from 0.1 to 50.4 kg/ha.yr; most of these studies have reported losses of 1.0 kg/ha.yr or less. Nutrient loadings in streams from forest fertilisation normally represent much less than 0.5% of applied fertiliser. Since normal outputs from undisturbed forests range from 3 to 15 kg/ha.yr for N and 0.03 to 1.0 kg/ha.yr for P, additions from forest fertilisation should not increase the annual outputs greatly.

Several studies in New Zealand on fertiliser inputs into streams after aerial topdressing in forests have recently been completed. These have included both urea and superphosphate applications. The main source of fertiliser losses has been direct fall of granules or dust into streams. Further reductions in the current low levels of streamflow fertiliser losses could be obtained by:

1. Avoiding overflying streams by using 20-m clearly-marked buffer strips on both sides of water courses.
2. Topdressing streamside areas during periods of no wind, or in the situation where wind exists:
   (a) Dropping fertiliser from lower altitudes with helicopters,
   (b) Using fertilisers with low dust content and large granule size.

The key factor preventing nutrient loss in streamflow is the use of adequate buffer strips. North American experience in fertilisation operations where buffer strips are inadequate or not used indicates that the total loss of applied fertiliser in streamflow could be 2-3% or more. Buffer strips along main streams and tributaries should ensure that losses are kept below 0.5%.

Aerial topdressing will continue to be an important tool in forest management. It is also quite compatible with the goal of maintaining good water quality in streams draining production forest lands.

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