Extractable Soil Nitrogen Following Clear-cutting and Burning in a Beech Forest¹

M. J. PHILLIPS AND K. M. GOH²

ABSTRACT

Nitrogen (N) mineralization was monitored in the humus layer and soil in an undisturbed and harvested beech (*Nothofagus* spp.) forest in the West Coast of the South Island of New Zealand. To assess the effects of different harvesting regimes and intensities of burning on N mineralization, treatments applied were (i) *Podocarpus* spp. clear-cutting; (ii) *Podocarpus* spp. clear-cutting and prescribed burning; (iii) harvesting to chipwood standard (10-cm dbh); and (iv) chipwood logging and prescribed burning. Nitrate was found to be negligible in fresh and field-incubated humus and soil samples in the undisturbed beech forest. Ammonium predominated in both the humus layer and soil. Clear-cutting, and clear-cutting and burning increased $\text{NH}_4^+\text{-N}$. The burning effect was confined mainly to the humus layer.

Additional Index Words: harvesting regimes, burning intensities, N cycling, NO_3^- , NH_4^+ , field incubated soil samples, humus layer, *Nothofagus* spp.

Phillips, M.J., and K.M. Goh. 1985. Extractable soil nitrogen following clear-cutting and burning in a beech forest. *Soil Sci. Soc. Am. J.* 49:1563–1568.

MATERIALS AND METHODS

Study Site

The Larry's Creek study area (42° 20' S, 171° 50' E) was located 30-km north of Reefton on the West Coast of the South Island of New Zealand. The site was on remnants of a terrace that has been truncated and dissected into undulating topography. The elevation was 200 m on a south-west aspect with slopes avg 18%. Rainfall averaged approximately 1800-mm annually. Many terraces have been formed as a consequence of regional tectonic uplift and subsequent river incision. The oldest have been dissected further by streams. Our site was underlain by weakly to moderately weathered gravels containing clasts of granites, schists, sandstones, and siltstones. These were underlain by Cenozoic siltstone and sandstone. Four major soil classes were identified as: Yellow Brown earth (Inceptisol), Gley soil (Aquept); Humic Gley with thin Fe pan (Placiaquept); and Podzol (Spodic soil).

Approximately 95% of the forest cover was silver beech (*N. menziesii*) and red beech (*N. fusca*). Remaining species were predominantly podocarps mostly kahikatea (*Podocarpus dacrydioides*), miro (*P. ferrugineus*), matai (*P. specatus*), and rimu (*Dacrydium cupressinum*).

Experimental Design

Treatments

Harvesting treatments were applied in a completely randomized block design, consisting of three replications of high intensity burn, low intensity burn, and nonburning treatments. High intensity burns were obtained by burning the residues (e.g., leaves, branches, twigs, stems, litter) from clearcutting followed by harvesting only podocarp species (PL/B). Low intensity burns were obtained by burning the

residues from logging (i.e., materials <10-cm dbh) after harvesting to chipwood standard (10-cm dbh) (CL/B) treatments. Control nonburning treatments on each block consisted of podocarp logged (PL) and chipwood logged (CL) treatments. Each block contained four 0.08-ha plots with treatments assigned randomly within the block in a transect line running across the midslope. Also, one forested plot (F) was established 20-m above each of the major blocks. The plots were harvested in May 1976. All designated plots were burned in February 1977, and radiata pine seedlings were planted in July 1977.

Measurements

The field method for measuring soil N mineralization was based on the method described by Ellis (1974). Instead of using plastic vials, 4.0-cm diam nylon cloth tubes (0.045-mm aperture) were used for incubating litters and soil samples in the field. This allowed the free drainage of soil water which prevented water logging and anaerobic conditions. The nylon tubes also allowed better contact between the incubated core samples and the surrounding soil. Due to the free drainage of water, however, an unmeasured portion of the mineralized N was probably leached. Mineralized N was measured in the humus layer and at two soil depths (0–9 cm, 9–18 cm).

Four field fresh and incubated samples were obtained at each depth from random locations in each plot during each sampling period. To obtain each fresh sample and prepare one field incubated sample, individual soil cores were taken with a tubular probe (diam 4.0 cm). Litter or ash was first removed, then each core was divided into the different depths and placed separately into plastic bags and mixed. Visible plant roots and stones were removed. Each composite sample was divided into two; one for field incubation and the other as the fresh sample for analysis in the laboratory with no further incubation. This procedure was repeated for the other three cores.

To prepare for field incubation soil from the composite sample taken from the 9- to 18-cm soil depth was placed in the nylon tube and packed to a length of 9 cm. A constriction in the nylon tube was then made. The process was repeated for soil from the 0- to 9-cm depth. The remaining length of the tube (5–8 cm) was filled with the humus sample. The filled tube was placed into one of the sample collection holes and covered with approximately 4 cm of litter or ash. All samples were stored on ice for transportation to the laboratory. Field sampling began 1 d before burning (February 1977) and continued for 1 yr (February 1978). For the first 35 d after burning, samples were obtained at intervals of 3, 10, 11, and 14 d. Further samples were then collected at 30- to 60-d intervals.

Humus and soil (<2 mm) samples were extracted with 2 M KCl for 2 h on a shaker. An extractant/sample ratio of 10.1 (w/w) was used. Extracts were filtered through Whatman no. 32 paper. Ammonium N was determined by the phenol-hypochlorite method (Weatherburn, 1967). This method was compared with $\text{NH}_4^+\text{-N}$ determination by steam distillation. Results agreed closely between the methods, which indicated that the 2 M KCl was not extracting significant amounts of free amino acid N. Nitrate N was first reduced to NO_2^- by passing through a Cd column reductor and determined by Grasshoff's (1969) method. Results for $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ are expressed on an oven-dry basis. The amount of N mineralized between sampling periods was determined as the difference in exchangeable N between the incubated and fresh samples. Pretreatment differences in

¹ Contribution from Dep. of Soil Science, Lincoln College, Canterbury, New Zealand. Received 21 Sept. 1984. Approved 6 June 1985.

² Postgraduate Student and Reader, respectively, Lincoln College, New Zealand. Present address of Dr. Phillips: Soil Science Dep. Univ. of Florida, Gainesville, FL 32611.

Table 1. Nitrate-N concentration in humus and soil (0-9, 9-18 cm) in the standing beech forest and in the clearcut and clearcut logged/burned plots from 1977 to 1978.

Layer	Treatment									
	F		CL		CL/B		P		PL/B	
	Fresh†	Inc.‡	Fresh	Inc.	Fresh	Inc.	Fresh	Inc.	Fresh	Inc.
% of total										
Proportion of samples with detectable NO ₃ -N										
Humus	1.4	2.1	8	10	12	14	11	12	14	17
Soil (0-9 cm)	0.7	0.7	33	32	41	45	37	40	46	54
Soil (9-18 cm)	7.6	1.4	36	38	40	43	42	37	49	47
mg kg ⁻¹										
Mean NO ₃ -N concentration										
Humus	0.6	0.8	0.8	1.0	1.3	1.5	1.1	1.2	1.4	1.7
Soil (0-9 cm)	0.7	0.9	1.2	1.0	1.6	1.7	1.2	1.4	1.9	2.0
Soil (9-18 cm)	0.6	0.6	1.0	1.1	1.4	1.3	1.2	1.1	1.6	1.8
Maximum NO ₃ -N concentration										
Humus	0.8	1.0	1.4	3.1	4.9	4.3	3.7	2.6	5.6	5.1
Soil (0-9 cm)	1.3	1.3	2.6	3.0	9.6	8.8	2.9	3.8	12.4	9.3
Soil (9-18 cm)	1.2	1.2	3.2	2.8	7.1	7.4	2.8	2.4	7.5	8.6

† Total number of samples in each treatment = 144.

‡ Total number of samples in each treatment = 132.

Table 2. Humus and soil pH in the undisturbed beech forest and in the clearcut-logged and clear-cut logged and burned treatments at different biomass sampling periods.

Sampling period	Treatment	Humus		Soil (0-9 cm)	
		H ₂ O	CaCl ₂	H ₂ O	CaCl ₂
		pH			
Preburn	F	3.4a†	2.8a	--	--
	CL	4.0b	3.5b	--	--
	CL/B	3.8b	3.2b	--	--
	PL	3.9b	3.3b	--	--
	PL/B	3.9b	3.4b	--	--
Postburn	CL/B	4.1a	3.6a	--	--
	PL/B	4.4a	3.8a	--	--
Postburn (2 yr)	F	3.6a	3.1a	4.1 (0.4)‡	3.5 (0.4)
	CL	4.1b	3.6b	4.4 (0.5)	3.8 (0.4)
	CL/B	4.1bc	3.6b	4.3 (0.2)	3.7 (0.2)
	PL	4.2bc	3.7b	4.3 (0.4)	3.7 (0.3)
	PL/B	4.4c	3.9b	4.4 (0.4)	3.8 (0.4)

† Numbers within columns followed by the same letters are not significantly different at the 5% level by Duncan's New Multiple Range test for comparisons between treatments within a sampling period for the preburn and postburn sampling periods.

‡ Data in parenthesis refers to standard deviation.

NH₄⁺-N concentrations between blocks were examined for homogeneity of variance using Bartlett's test.

Humus and soil pH were measured with a combination glass electrode using both distilled water and 0.1 M CaCl₂. An extractant/sample ratio of 10:1 and 2.5:1 was used for the humus and soil, respectively.

Moisture contents of fresh, incubated humus and soil samples were determined by oven-drying at 105°C for 24 h and expressed on oven-dry weight method. Forest floor temperature was determined by the sucrose inversion method (Jones and Court, 1980; Heng, 1980).

The data were analyzed using analysis of variance, Duncan's Multiple Range test, and *t*-test. These tests were performed using the Teddybear program (Wilson, 1976) on a Burroughs B6700 computer.

RESULTS AND DISCUSSION

Nitrate

No significant differences in variances were found between plots; therefore, statistical comparisons were

made between data obtained in the undisturbed beech forest and from the harvested plots.

Detectable NO₃⁻-N concentrations (≥ 0.1 mg kg⁻¹) are shown in Table 1. The low detection of NO₃⁻-N could be due to NO₃⁻-N being leached from the tubes with soil moisture. Nitrate was detected more frequently in the soil than in the humus layer in all treatments. Although some NO₃⁻ undoubtedly leached from the samples during moist periods, sizeable differences in KCl extractable NO₃⁻ could still be found between treatments. The mean and maximum NO₃⁻-N concentration, and the proportion of samples with detectable NO₃⁻-N in the humus and soil generally decreased in the order:

PL/B > CL/B > PL > CL > beech forest.

Within each treatment, there were no significant differences in NO₃⁻-N concentrations between field fresh and field incubated samples of humus and soil. Probably, this reflects the high mobility of NO₃⁻-N in the soil solution, rather than a lack of incubation effect.

In the undisturbed beech forest, NO₃⁻-N was negligible or undetected in fresh and incubated humus and soil samples (Table 1). Nitrification however, appeared to be enhanced by both clearcutting and clear-cutting and burning, although detectable NO₃⁻-N was generally found in less than half of all fresh and incubated humus and soil samples. Highest NO₃⁻-N was found in the burned plots within 60 to 90 d after burning. This was probably due to the nitrification of some of the abundant NH₄⁺-N present in the humus layer and soil during this period (Fig 1.) A significantly higher humus pH in burned plots (Table 2) may have promoted nitrification. Before burning, humus pH in the beech forest was 3.4 compared to a mean of 3.9 in the clearcut sites. Although low pH conditions have been reported to inhibit nitrification (Alexander, 1977), appreciable levels of NO₃⁻-N have been found in soils of pH 4.0 or less (Romell, 1932; Smith et al., 1968; Weber and Gainey, 1962). Removal of the forest canopy would eliminate inputs of water-soluble polyphenols to the humus and soil in throughfall and lit-

Table 3. Mean forest floor temperatures recorded at Larry's Creek.†

Sampling period	Forested site		Clearcut site		Burned site	
	$\bar{x}$ (°C)	CI	$\bar{x}$ (°C)	CI	$\bar{x}$ (°C)	CI
15 July 1976–17 Aug. 1976	6.9	(0.5)‡	7.5	(0.6)	--	--
18 Sep. 1976–18 Oct. 1976	8.5	(0.4)	9.8	(0.5)	--	--
19 Oct. 1976–29 Dec. 1976	13.1	(0.8)	15.1	(0.6)	--	--
3 Mar. 1977–3 Apr. 1977	13.3	(0.1)	14.6	(0.5)	15.6	(0.4)
4 Apr. 1977–4 Jun. 1977	9.2	(0.2)	9.4	(0.4)	9.2	(0.4)
5 June 1977–6 Aug. 1977	6.2	(0.2)	5.7	(1.0)	6.3	(0.7)
7 Aug. 1977–6 Oct. 1977	5.5	(0.1)	5.9	(0.2)	5.3	(0.4)
7 Oct. 1977–7 Jan. 1978	12.7	(1.1)	15.5	(0.4)	14.8	(1.0)
8 Jan. 1978–8 Apr. 1978	15.7	(0.1)	21.1	(0.6)	19.6	(1.2)
9 Apr. 1978–8 July 1978	13.8	(0.4)	13.8	(0.4)	13.9	(0.4)
9 July 1978–7 Oct. 1978	10.1	(0.1)	11.1	(0.4)	10.4	(0.4)

† Data obtained by Heng (1980) on the same plots.

‡ Data in parenthesis refer to 95% confidence interval (CI).

terfall. The presence of tannins and other polyphenols are known to inhibit nitrification (Rice and Pancholy, 1974). Removal of organic materials from forest floor during harvesting or site preparation also reduces the capacity of the soil to retain N (Vitousek and Matson, 1984).

Ammonium

Ammonium was the dominant mineral N form in the humus layer and soil. Seasonal trends in fresh humus and soil were found for all treatments (Fig. 1). Peak concentrations occurred in the fall (61.6 mg kg⁻¹ in humus, 11.5 mg kg⁻¹ in soils) and spring (46.0 mg kg⁻¹ in humus, 13.6 mg kg⁻¹ in soil). The peak levels of NH₄⁺-N generally corresponded to periods of litter-fall reported by Heng (1980) for the West Coast beech forests. The higher NH₄⁺-N levels in the spring probably reflected seasonal changes in microbial populations due to increased forest floor temperatures (Table 3). Heng (1980) reported high rates of CO₂ evolution for these sites in the spring months. Lowest NH₄⁺-N concentrations in the humus layer (17.6 mg kg⁻¹) were found in July when forest floor temperatures and biological activity were low. The NH₄⁺-N levels in field incubated humus and soil samples were generally higher, but followed a pattern similar to that found in the corresponding field fresh samples (Fig. 2).

The net change in NH₄⁺-N concentrations between sampling periods is a result of several processes (e.g., immobilization, leaching from the columns, in situ ammonification). In the undisturbed beech forest, increases in NH₄⁺-N occurred throughout most of the year (Fig. 3). Highest net accumulations of NH₄⁺-N (48.0 mg kg⁻¹ in humus, 10.5 mg kg⁻¹ in soil) occurred in spring (Fig. 3). This is to be expected as plant uptake would be greatest in the spring, thus increasing the relative differences in NH₄⁺-N levels between the fresh and corresponding incubated samples. Low NH₄⁺-N levels occurred in the winter months in the humus and soil, probably due to low soil temperature (Powers, 1980), microbial immobilization, denitrification, leaching, reducing litter input, or to a combination of these factors.

Nitrogen mineralization was not monitored in the clearcut plots until just before burning. Immediately after clearcutting, ammonification in the humus layer

Fig. 1. Seasonal pattern in mean NH₄⁺-N concentration in field fresh humus and fresh soil (0–9, 9–18 cm) in the standing forest and in the clearcut logged and clearcut logged/burned plots (small letters at each sampling period indicate results from Duncan's Multiple Range Tests; see Table 2 for abbreviations).

and soil would have increased above that in the undisturbed forest (Aref'yeva and Kolesnikov, 1964). After the initiation of sampling, the general pattern of ammonification in the fresh and incubated humus and

Fig. 2. Seasonal pattern in mean $\text{NH}_4^+\text{-N}$ concentration in field-incubated humus and soil (0-9, 9-18 cm) in the standing forest and in the clearcut logged and clearcut logged/burned plots (for explanation of abbreviations see Fig. 1).

soil samples in all clearcut plots was similar to that found in the undisturbed beech forest (Fig. 1 and 2). However, important differences in the levels of $\text{NH}_4^+\text{-N}$ were found. In the CL and PL treated plots, $\text{NH}_4^+\text{-N}$ concentrations in the fresh and incubated hu-

Fig. 3. Seasonal pattern in mean net $\text{NH}_4^+\text{-N}$ concentration in humus and soil (0-9, 9-18 cm) in the standing forest and in the clearcut logged/burned plots (for explanation of abbreviations see Fig. 1).

mus samples were lower than those found in the undisturbed beech forest throughout the study. The relative differences in humus $\text{NH}_4^+\text{-N}$ concentrations between those in the undisturbed beech forest and those in the CL and PL treated plots generally increased with time. Many of the differences were statistically significant. A similar effect was found in the soil, although the soil $\text{NH}_4^+\text{-N}$ levels were initially higher in the CL and PL treated plots (Fig. 1 and 2).

Net accumulations of $\text{NH}_4^+\text{-N}$ in the humus layer in the CL and PL treated plots during the fall months were not significantly different from those in the undisturbed beech forest (Fig. 3). In the soil, these differences generally were statistically significant with higher $\text{NH}_4^+\text{-N}$ levels in the clearcut plots. This probably reflected a continued decrease in the quantity of easily mineralizable N substances in the clearcut plots

or increased amount of leaching from columns in the clearcut plots.

Increases in soil NH_4^+ -N concentrations after burning have been observed in other studies (Christensen, 1973; DeBano et al., 1979; Dunn et al., 1979). In the present study, prescribed burning had a short-term but significant impact on NH_4^+ -N concentrations in the humus layer, but little measurable effect on soil NH_4^+ -N concentrations (Fig. 1). The minimal effect on soil NH_4^+ -N levels was probably because both burning treatments were of light to moderate intensity (unpublished data).

Ammonium N concentrations in the fresh and incubated soil samples in the CL/B and PL/B treated plots generally were higher than those in the CL and PL treated plots for approximately 60 d after burning (Fig. 1 and 2). Not all of the differences were statistically significant.

Large increases in NH_4^+ -N concentrations were found in fresh and incubated humus samples 3-d after burning (Fig. 1 and 2). This could have resulted from direct inputs from the ash layer, as NH_4^+ -N has been reported to be a major N component in ash (Christensen, 1973). The thermal decomposition of amino components in the humus is another possibility (Russell et al., 1974). Ammonium N concentrations continued to increase, reaching maximum values in the fresh humus from 21-d (CL/B = 82.7 mg kg^{-1} , PL/B = 97.5 mg kg^{-1}) to 35-d (CL/B = 89.4 mg kg^{-1}) after burning (Fig. 2). For the incubated humus samples, the maximum values (CL/B = 118 mg kg^{-1} , PL/B = 129 mg kg^{-1}) were found at 35 d after burning (Fig. 2). Throughout these 35 d, NH_4^+ -N concentrations in the fresh and incubated humus samples in the CL/B and PL/B treated plots were significantly higher than those found in the beech forest and the CL and PL treated plots.

The continued increase in NH_4^+ -N concentrations for the first 35-d after burning suggests a rapid increase in the population of ammonifying organisms, possibly due to the elimination of other competing organisms for the same substrate. Burning has been shown to favor bacteria rather than fungi (Jones and Richards, 1977; 1978). Miller et al. (1955) reported that bacterial populations reached a peak within a month after light to moderate burns in New Zealand hill country, and then reverted to their initial preburn levels. A similar effect probably occurred at Larry's Creek.

Humus NH_4^+ -N concentrations returned close to those found in the CL and PL treated plots in <120 d after burning (Fig. 1).

Results from regression analysis indicated no significant correlations between NH_4^+ -N concentrations and moisture content in fresh humus and soil samples. No regression analysis was done for temperature. However, multiple linear regression analysis by Heng (1980) revealed no significant relationship between NH_4^+ -N concentration and both moisture content and forest floor temperatures in both hard beech and radiata pine forests. The spatial variation in such factors as litterfall, competition for the NH_4^+ -N ion, total N, substrate quality, and polyphenol content could mask or reduce the ability to measure effects of temperature and moisture on NH_4^+ -N dynamics.

CONCLUSIONS

Results presented showed that NH_4^+ -N was the dominant inorganic N form retained in the humus layer and soil. The NH_4^+ -N levels increased immediately after burning and were affected by site disturbance (e.g., clearcutting). Burning substantially increased NH_4^+ -N levels in the humus and to a lesser extent in the soil for approximately 120 d after burning. Trends of extractable NO_3^- -N concentrations reflected those of NH_4^+ -N in the topsoil. The enhanced NH_4^+ -N production is likely to effect increases in NO_3^- -N in the soil solution which may lead to increased fluxes of NO_3^- -N through the soil profile in the field. This aspect remains to be investigated.

ACKNOWLEDGMENTS

We wish to thank the Forest Research Institute, New Zealand Forest Service and the Lincoln College Research Committee for providing research funds and assistance and to Drs. D. J. Mead and G. M. Will for their encouragement and assistance.

REFERENCES

- Adams, J.A., and G. Mew. 1975. Soils of the Inangahua Depression, South Island, New Zealand. Part II. Soil chemistry and forestry appraisal. N.Z. Soil Survey Rep. 17:39-78.
- Alexander, M. 1977. Introduction to soil microbiology. John Wiley and Sons Inc., New York.
- Aref'yeva, Z.N., and B.P. Kolesnikov. 1964. Dynamics of ammonia and nitrate nitrogen in forest soils of the Transurals at high and low temperatures. Soviet Soil Sci. (Engl. Transl.) 3:246-260.
- Christensen N.L. 1973. Fire and nitrogen cycle in California chaparral. Science 181:66-67.
- DeBano, L.F., G.E. Eberlein, and P.H. Dunn. 1979. Effects of burning on chaparral soils. I. Soil nitrogen. Soil Sci. Soc. Am. J. 43:504-509.
- Dunn, P.H., L.F. DeBano, and G.E. Eberlein. 1979. Effects of burning on chaparral soils. II. Soil microbes and nitrogen mineralization. Soil Sci. Soc. Am. J. 43:509-514.
- Ellis, R.C. 1974. The seasonal pattern of nitrogen and carbon mineralization in forest and pasture soils in southern Ontario. Can. J. Soil Sci. 54:15-28.
- Grasshoff, K. 1969. A simultaneous multiple channel system for nutrient analysis in seawater with analog and digital data record. p. 133-150. In Advances in automated analysis. Technicon International Congress 1969, vol. II. Industrial Analysis, New York.
- Heng, S. 1980. The addition, decomposition and accumulation of organic matter in some native *Nothofagus* spp. forests and radiata plantations in the South Island of New Zealand, Ph.D. diss., Univ. of Canterbury, New Zealand.
- Jones, R.J.A., and M.N. Court. 1980. The measurement of mean temperatures in plant and soil studies by the sucrose inversion method. Plant Soil 54:15-31.
- Jones, J.M., and B.N. Richards. 1977. Changes in the microbiology of eucalypt forest soils following reforestation with exotic pines. Aust. For. Res. 7:229-240.
- Jones, J.M., and B.N. Richards. 1978. Fungal development and the transformation of N-labelled amino- and ammonium-nitrogen in forest soils under several management regimes. Soil Biol. Biochem. 10:161-168.
- Likens, G.E., F.H. Bormann, N.M. Johnson, D.W. Fisher, and R.S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed ecosystem. Ecol. Monogr. 40:23-47.
- Miller, R.B., J.D. Stout, and K.E. Lee. 1955. Biological and chemical changes following scrub burning on a New Zealand soil. N.Z. J. Sci. Tech. 37:190-313.
- Powers, R.F. 1980. Mineralizable soil nitrogen as an index of nitrogen availability to forest trees. Soil Sci. Soc. Am. Proc. 44:1314-1320.
- Rice, E.L., and S.K. Pancholy. 1974. Inhibition of nitrification by climax ecosystems. III. Inhibitors other than tannins. Am. J. Bot. 61:1095-1103.
- Romell, L.G. 1932. Mull and duff as biotic equilibria. Soil Sci. 34:161-168.

- Russell, J.D., A.R. Fraser, J.R. Watson, and J.W. Parsons. 1974. Thermal decomposition of protein in soil organic matter. *Geoderma* 11:63-66.
- Smith, W., F.H. Bormann, and G.E. Likens. 1968. Response of chemoautotrophic nitrifiers to forest cutting. *Soil Sci.* 106:471-473.
- Vitousek, P.M., and P.A. Matson. 1984. Mechanism of nitrogen retention in forest ecosystems: A field experiment. *Science* 225:51-52.
- Vitousek, P.M., J.R. Gosz, C.C. Grier, J.M. Melillo, W.A. Reiners, and R.L. Todd. 1979. Nitrate losses from disturbed ecosystems. *Science* 204:469-474.
- Weatherburn, M.W. 1967. Phenol-hypochlorite reaction for determination of ammonia. *Anal. Chem.* 39:971-974.
- Weber, D.F., and P.L. Gainey. 1962. Relative sensitivity of nitrifying organisms to hydrogen ions in soils and in solutions. *Soil Sci.* 94:138-145.
- Wilson, J.B. 1976. Teddybear statistical program. Tech. Rep. T5, 2nd ed. University of Otago Computing Center, Dunedin, New Zealand.