NUTRIENT RELEASE BY WEATHERING: IMPLICATIONS FOR SUSTAINABLE HARVESTING OF *PINUS RADIATA* IN NEW ZEALAND SOILS

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ABSTRACT

Sustaining site productivity over multiple timber harvesting rotations requires an understanding of changes in the soil nutrient supply to the forest. To maintain soil fertility the amount of available limiting nutrients removed in each cropping cycle should be matched by inputs to the site. Weathering is one key source of nutrient inputs that has not been well quantified. Mineral weathering at six sites in New Zealand was examined where multiple-rotation forests were being studied to relate nutrient supply to nutrient removal with harvesting. Three sites were located in the North Island of New Zealand at Woodhill, Tarawera, and Kinleith Forests, and three were in the South Island at Golden Downs, Burnham, and Berwick Forests. Growth of *Pinus radiata* D. Don was used to estimate annual nutrient uptake rates. Weathering rates were determined using two methods: the PROFILE model with appropriate site data for all six sites, and leaching of soil columns from two sites. Annual weathering rates for calcium, magnesium, potassium, and phosphorus were 3–24, 3–10, 3–31, and 0.2–2.5 kg/ha respectively. Column-leaching estimates of weathering resulted in comparable weathering rates to that of PROFILE when used with a soil that had a consistent texture throughout the soil profile, as occurred at the Kinleith site. The Burnham soil had a fine texture over coarse and data did not compare well with the PROFILE estimates, probably due to irregular water flow in the soil column. PROFILE weathering rates appeared reasonable for all sites, indicating its usefulness for predicting nutrient supply by weathering over multiple rotations if sufficient soil and site data are available. Weathering rates calculated using PROFILE and leaching of nutrients from the O horizon suggest that both weathering and O horizon mineralisation are critical to sustainable production over multiple rotations. Without addition of fertiliser some nutrients may be depleted at current rotation lengths.

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Keywords: soil productivity; weathering; sustainable timber harvesting; forest soil.

INTRODUCTION

Plantation forestry is an important economic activity in New Zealand, generating in excess of NZ$2.8 billion in export revenue per annum, from approximately 1.7 million ha of land (NZMOF 2001). Plantations were established from the early 1900s onwards and, with a 30-year cropping cycle, some forests are into their third rotation. With such intensive and continuous forestry operations on the same site the question of how sustainable such operations are has to be raised. Long-term research was initiated in the 1980s to study changes in site quality under New Zealand plantations. A key component of this research is the need to understand changes in nutrient supply to the forest. To maintain a level of soil fertility (or site quality) and carbon storage the amount of limiting available nutrients removed in each cropping cycle should be matched by inputs to the site. Amounts removed are well quantified and vary depending on the volume of timber removed from the site (Payn *et al.* 1998). Nutrient inputs through fertiliser additions can be matched directly to removal rates to estimate maintenance fertiliser needs (Payn *et al.* 2000); however, these estimates can be affected by other components in the system such as atmospheric inputs and losses, mineral weathering rates, and leaching losses from the soil profile. Of these four components, mineral weathering is the least well quantified.

The importance of weathering to nutrient supply and site productivity has received more attention recently as the potential for phosphorus and base cation deficiencies to limit growth has been considered (Zabowski 1990; April & Newton 1992; Sverdrup & Rosen 1998). Weathering information is needed to develop a nutrient balance model to predict the effects of multiple rotations on soil nutrient supply. In this study we examined mineral weathering at six sites in New Zealand where multiple rotation forests were being studied to relate nutrient supply to nutrient removal with harvesting.

METHODS

During the late 1980s and early 1990s, a long-term site productivity research study was established at six different forest sites in New Zealand. Three sites were located in the North Island of New Zealand at Woodhill, Tarawera, and Kinleith Forests, and three in the South Island at Golden Downs, Burnham, and Berwick Forests (Fig. 1). Boles, foliage, and branches of trees from each forest were measured, sampled, and analysed to determine biomass pools prior to harvesting and then planting of the next rotation; soils at each site were also evaluated to supplement existing soil survey data (New Zealand Soil Bureau 1954, 1968a,b) (Fig. 2). Some background information on these sites is provided in Table 1.

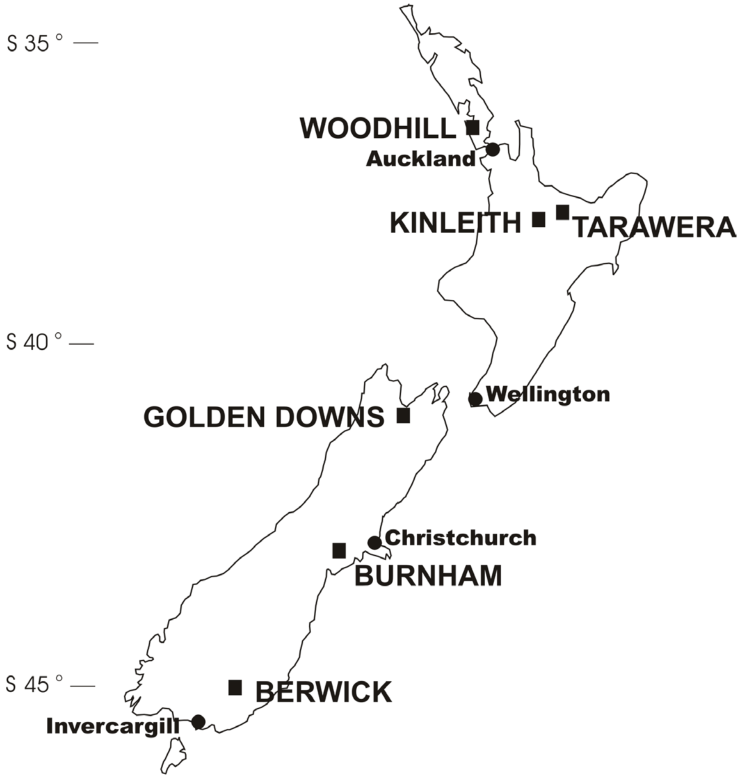

FIG. 1–Map of site locations.

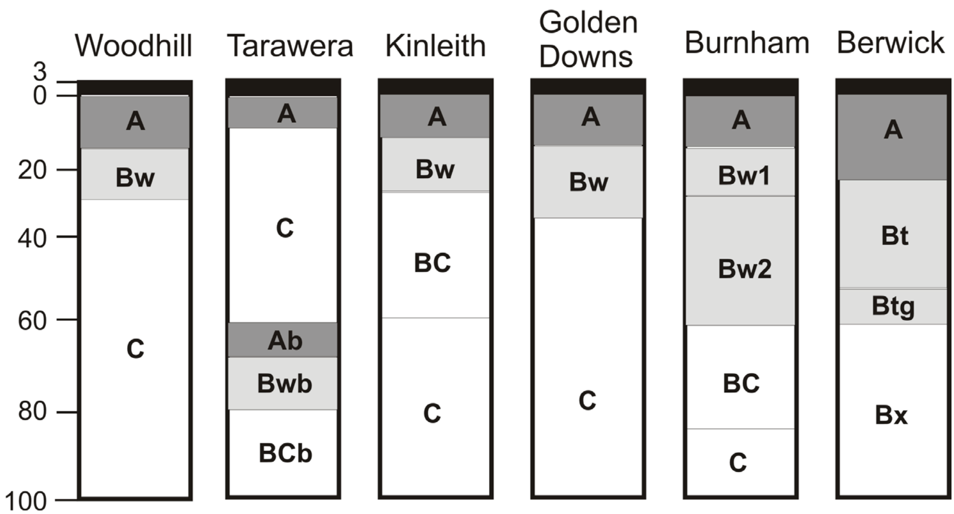

FIG. 2–Soil profiles of the six study sites, with depths in centimetres. The O horizon of each soil is shown in black.

TABLE 1–Site (including calculated throughfall and soil drainage) and soil characteristics for each of the long-term sustainability study sites.

	Woodhill	Tarawera	Kinleith	Golden Downs	Burnham	Berwick
Overstorey species	*Pinus radiata*	*Pinus radiata*	*Pinus radiata*	*Pinus nigra*	*Pinus radiata*	*Pinus radiata*
Elevation (m)	30	90	490	450	70	200
Age at time of harvest	42	27	26	45	32	31
Stocking (stems/ha)	270	288	270	750	666	204
Mean air temp. (°C)	14.3	14.0	13.2	10.4	11.5	10.3
Ann. precipitation (mm)	1330	1820	1420	1340	639	747
Throughfall* (mm)	997	1438	1078	1006	375	472
Drainage* (mm)	304	724	423	386	0	0
NZ Soil Series	Pinaki	Tarawera	Taupo	Spooner	Lismore	Waitahuna
NZ Soil Classification	Typic Sandy Recent	Buried-pumic Tephric Recent	Immature Orthic Pumic	Acidic Orthic Brown	Pallic Orthic Brown	Mottled Fragic Pallic
US Soil Order	Entisol	Andisol	Andisol	Inceptisol	Inceptisol	Alfisol
Soil texture	sand	silt loam over sand	sand	gravelly silt loam	silt loam	silt loam
Parent material	coastal sand dunes	tephra/pumice	tephra/pumice	highly weathered greywacke gravels	loess over outwash gravel	loess
Dominant soil minerals†	Q, F, M, C	G, F, K, B	G, F, V, B	Q, F, M, C, V, K	Q, F, M, C, V, K	Q, F, M, C, V

* as calculated
† Q = quartz, F= feldspars, M = micas, C = chlorite, G = volcanic glass, K = kaolinite, V = vermiculite, B = biotite

The PROFILE model (ver. 4.2) developed by Sverdrup and Warfvinge (Sverdrup & Warfvinge 1988a,b; Warfvinge & Sverdrup 1992) was used to determine weathering rates at all six sites. PROFILE simulates weathering using a steady-state, mass-balance approach, and details have been published by Sverdrup and Warfvinge. The model predicts weathering of calcium, magnesium, potassium, sodium, aluminium, silicon, and phosphorus. Jönsson *et al.* (1995) estimated that uncertainty in the PROFILE model was 15–20%. Physical properties and mineralogy were entered into the PROFILE program for each horizon of each soil. For three soils, mineralogy and some physical properties were not available for the actual soil and so data from similar local soils were used (the Golden Downs, Woodhill, and Berwick soils) (R. Parfitt, pers. comm.). For the volcanic soils, a model volcanic glass was used within the PROFILE model (H. Sverdrup, pers. comm.) with stochiometric composition of the glass altered to match the glass of the Tarawera and Kaharoa tephra deposits at Tarawera, and the Taupo tephra at Kinleith (Lowe *et al.* 1999; Stokes *et al.* 1992; Newnham *et al.* 1998). In addition to soil information, the model requires information on rainfall, runoff, and atmospheric deposition. Total precipitation at each site was divided into quantity of throughfall and drainage below the C horizon by subtracting calculated actual evaporation and calculated transpiration at each site (Peter Beets, pers. comm.). Elemental composition of rainfall at the six sites was taken from Nichol *et al.* (1997) using chemistry from the closest site measured relative to each study site, with the exception of Woodhill. Woodhill is a coastal site and rainfall chemistry was used from the only coastal site where rainfall chemistry was available. A summary of basic information about each soil used in the model is given in Table 1.

For comparison with modelled results, bulk soil samples were collected by horizon from two of these sites — Kinleith and Burnham Forests (the Taupo and Lismore soil series; a Vitrand and Ustochrept respectively, in the USDA soil classification). Horizon depths were also recorded so that an accurate soil profile could be reconstructed in columns. Half of the soil had detectable roots removed and was treated at 20°C for 4 hours with hydrogen peroxide to remove readily oxidisable organic matter (600 cm^3 soil in 300 ml distilled water with 50 ml of 30% H_2O_2 incrementally added, followed by draining and rinsing in distilled water). The remaining soil was not treated in order to allow a comparison between weathering and total leaching losses.

For weathering rates of B and C horizons, three replicate columns (75-mm-diameter PVC tubing) were packed with soil of the appropriate horizon to recreate a 1-m soil profile depth without the A horizon. The A horizon was not included in the columns used to measure weathering as the organic matter could not be removed readily from the mineral soil. Columns were tamped to mimic natural soil bulk density as they were packed. Column temperature was maintained at 15°C to approximate typical soil field temperatures and columns were kept in a dark room. Columns were then leached with a 1-mM solution of oxalic acid to simulate the concentration of organic acids entering the mineral soil profile from the litter layer. Oxalic acid was used as it is a present in forest soils and is a known weathering agent (Cromack *et al.* 1979; Jones 1998). Leaching was done three times per week, with the volume of solution added equal to 10 cm of rainfall. After an initial rinse, the columns were leached 14 times. Leachate solution concentrations were subsequently plotted to determine when the elemental concentrations were stable. This final concentration was assumed equal to soil weathering inputs to the soil solution, and was multiplied by the annual quantity of water moving through the soil (total precipitation minus interception) to give a weathering rate.

In addition, three replicate columns were set up with untreated mineral soil (including the A horizon but not the O horizon) for leaching with 1 mM oxalic acid to simulate leachable nutrients. By assuming that exchange sites are in equilibrium, these columns should approximate leachable plus available nutrients as no plant uptake was occurring. In conjunction with weathering data, the following equation can be used to determine if the soil is mineralising and losing nutrients or immobilising and storing nutrients:

$$\text{(mineralisation + weathering)} - \text{(immobilisation + adsorption)} = \text{leachable + available nutrients} \quad [1]$$

To include the mineralisation of nutrients from the O horizon, separate funnels (10.3 cm diameter) of O horizon (filled to the appropriate depth of intact O horizon from each site) were set up and leached with 10 cm of distilled water for 14 leachings identical to the mineral soil columns. Three replicates of O horizon were monitored.

Initially weekly solution analyses were done, then additional samples were analysed near the end of the leaching sequence to ensure a steady state concentration. Solutions were analysed using a Perkin-Elmer ICP-OES* (model 3000DV) for aluminium, boron, calcium, potassium, magnesium, sodium, phosphorus, sulphur, and silicon.

The nutrient demands of *Pinus radiata* at each site were estimated to compare weathering and decomposition releases of nutrients with demand. The total nutrient demand per year was estimated using total above-ground biomass (measured prior to harvesting) in conjunction with nutrient analysis of biomass components. Biomass of each component was multiplied by the concentration and summed to determine total above-ground nutrient storage. Only at the Woodhill site was below-ground biomass measured and root sample analysis done. Therefore, root biomass at the other sites was estimated using the method of Jackson & Chittenden

* ICP-OES, inductively coupled plasma-optical emission spectrometer

(1981) and multiplied by the Woodhill root nutrient analysis. Nutrient demand per year was subsequently estimated by dividing total stand nutrient content by the age of the stand.

RESULTS AND DISCUSSION

Weathering

Using column leaching to determine weathering rates from two of the sites provided an opportunity to verify the results of the PROFILE model. Column leaching at both the Kinleith and Burnham sites showed the expected exponential decrease in concentration with successive leaching for most elements (*see* Fig. 3 for calcium, magnesium, potassium, and silicon). The exponential decrease of the curves is probably due to the initial disturbance of the soil by creation of the columns, causing high losses of ions initially with the disturbance effect diminishing over time. Thus, the basal asymptote indicates a stable release rate of elements from the columns where organic matter has been removed. Leaching curves of other elements showed a similar pattern or were flat lines suggesting little effect of disturbance.

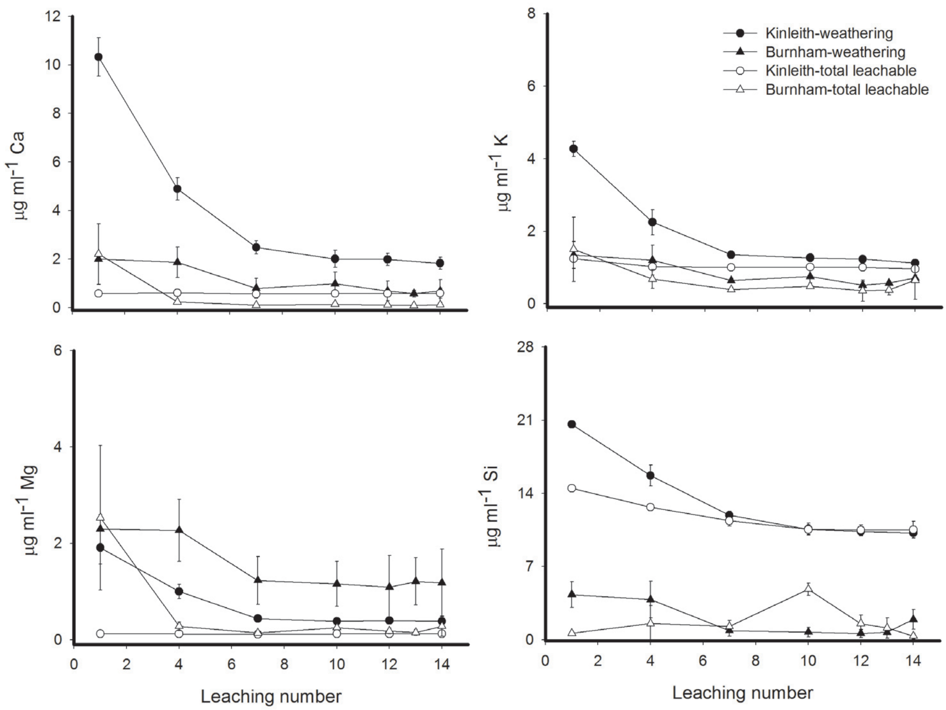

FIG. 3–Average concentrations of calcium, magnesium, potassium, and silicon in solution (with standard deviation bars) from the column leaching of the Kinleith and Burnham soils. Black symbols indicate soil columns where organic matter was removed to measure weathering release, and white symbols indicate intact soil columns where total leachable ions were measured.

The leaching results of the Kinleith soil were less variable than those of the Burnham soil, as indicated by the typically smaller standard deviations. In addition, the basal concentrations of cations in the Burnham soil were lower in almost all elements (magnesium was the exception to this). Water flow may explain why there was a lower variability in the Kinleith soil and lower cation concentrations with the Burnham soil (in addition to differences in parent materials). The Kinleith soil (Taupo series) was a sandy loam throughout the profile, and the Burnham soil (Lismore series) was a silt loam over a very gravelly, stony, sandy loam. Kinleith had only one parent material, the Taupo ash/pumice, whereas Burnham had loess over gravelly, cobble outwash. Thus, water flow through the Taupo soil would be uniform and extremely consistent throughout the column, resulting in little variation between columns. In addition, contact between the leaching solution and the mineral surfaces would be very consistent. With the Lismore soil, the textural change of a fine texture over a coarse texture undoubtedly resulted in more variable or channelled solution flow through the predominantly coarse-textured profile. This would not only increase variability in the leachate concentrations, but would result in generally lower leachate concentrations. Mineralogical differences appear to have overcome reduced solution:solid contact in the Burnham columns with magnesium. The presence of 18% chlorite in the clay fraction and epidote in the sand and silt of the Lismore soil series explains the higher magnesium release at Burnham compared to the Taupo series.

Included in Fig. 3 are the total leachable calcium, magnesium, potassium, and silicon concentrations from the intact soil columns. Comparing the intact columns with the organic-matter-removed weathering columns, it is obvious that there was no retention of silicon by organisms or organic matter in the untreated soil as the basal silicon concentrations are identical. Ratios of solution silicon to potassium, calcium, and magnesium from the weathering columns of the Burnham soil were approximately 2:1, 2:1, and 0.7:1 respectively. The molar ratios of silicon to potassium and calcium are similar to what would be expected for primary silicate minerals such as feldspar or plagioclase; the low ratio of silicon to magnesium is probably influenced by the abundance of chlorite in this soil. The Kinleith soil had much higher molar ratios of silicon to potassium, calcium, and magnesium (approximately 8, 22, and 12 respectively) than the Burnham soil. These molar ratios are similar to that of the Taupo tephra (20, 56, and 320 respectively — Lowe *et al.* 1999) but are lower, suggesting desorption or weathering of secondary minerals may be contributing cations to the leachate.

Overall, there was generally less total leaching of calcium, magnesium, and potassium from the intact soil columns than from the weathering study columns. Other elements not shown in Fig. 3 also had either a lower basal concentration with the intact soil columns or the same basal leaching as the weathering columns. This indicates that cation immobilisation and adsorption were occurring in both soils.

The total annual weathering determined by both soil columns and calculated using the PROFILE model showed similarities and differences among nutrients, among sites, and between methods used to measure weathering (Table 2). The PROFILE model results showed a range in weathering rates from 10 to 24 kg/ha annually for calcium to less than 3 kg/ha annually for phosphorus. Comparing all nutrients measured using PROFILE, calcium was typically most weatherable, although potassium was similar or higher at some sites; at the Berwick site, potassium weathering was estimated to be 31 kg/ha annually, but was as low as 2.7 kg/ha annually at Tarawera. Weathering of magnesium was next highest, being almost equal to that of calcium at the Burnham site. Phosphorus weathering was low at all sites compared to weathering of other minerals.

Site differences were also noteworthy. A comparison of silicon weathering across all sites should indicate the relative weathering rates at each site as silicon was present in most minerals at each site. Relative weathering rates followed the sequence Berwick > Burnham > Kinleith > Tarawera > Woodhill > Golden Downs. This relative ranking seems reasonable when soil particle surface area and parent materials are considered. Fine-textured loess has a high surface area and a mixed mineralogy, and so loess can be expected to release considerable nutrients through weathering, given adequate leaching. Thus, Berwick had a high weathering rate and Burnham, although low from column leaching, had a reasonably high weathering rate as well due to the presence of loess over the glacial outwash. The sand-dune soil of Woodhill had less surface area, but it still had a mixed assemblage of weatherable minerals for weathering. The soil at Golden Downs was developed from highly-weathered clay-bound greywacke sandstone and siltstone gravels (Pearce *et al.* 1983) which would be expected to have a much lower weathering rate than the other soils studied; although calcium and magnesium release from this soil was lower than the other soils, potassium was still similar.

When the weathering rates determined by column leaching of the Kinleith and Burnham soils were compared with weathering from the PROFILE model, distinct differences were evident not only between methods, but between the methods at each site. In the Kinleith soil, weathering release of magnesium and phosphorus was almost identical between methods, while column leaching resulted in greater calcium, potassium, sodium, and silicon. Weathering of silicon from the soil columns was almost twice that calculated by the PROFILE model. With the Burnham soil, every element was lower in the column leaching than the PROFILE results except sodium, which was almost twice as high. These elemental differences between the methods may be due to several factors. Firstly, soil data used in the PROFILE model may be inaccurate, chemical composition or reactions of the model may

TABLE 2–Annual weathering rates as modelled (using PROFILE ver. 4.2) and measured (by column leaching) (kg/ha) from the upper 1 m of soil at each site.

	Woodhill modelled	Tarawera modelled	Kinleith		Golden Downs modelled	Burnham		Berwick modelled
			modelled	col. leaching		modelled	col. leaching	
Calcium	12	14	15	20	9.6	12	2.6	24
Magnesium	7.2	5.0	4.7	4.0	3.3	10	4.4	6.6
Potassium	9.2	5.4	6.3	12	7.9	15	2.7	31
Phosphorus	1.1	0.5	0.5	0.2	2.5	1.5	0.2	2.2
Sulphur	–	–	–	8.5	–	–	0.6	–
Boron	–	–	–	0.11	–	–	<0.05	–
Sodium	2.0	5.7	3.0	24	1.2	2.6	4.5	6.3
Silicon	50	57	62	110	42	77	5.0	138

not be accurate for these particular soils, or leaching of the columns may not have accurately assessed weathering. This last factor undoubtedly contributed to the lower weathering rate of the Burnham soil with column leaching, as the inability to include the loess of the A horizon and the change in soil texture undoubtedly decreased weathering release of nutrients. Not including the shallow A horizon of the Kinleith soil would have less effect on total weathering of this soil, and column leaching results from this soil should be more accurate; they were also more similar to the PROFILE results. Thus for the Kinleith soil inaccuracies in soil data used in PROFILE are more likely to explain the differences in weathering rates between methods, whereas channelled water flow and lack of the A horizon in the Burnham soil most likely explain the low column weathering rates compared to those of PROFILE.

Weathering of these soils by both methods compares well with other sites of similar parent materials. Reported weathering of cations from glacial outwash annually is in the range 1–62 kg Ca/ha, 1–8.4 kg Mg/ha, and 3–26 kg K/ha (Woodwell & Whittaker 1967; Adams & Boyle 1979; Pastor & Bockheim 1984). Burnham, where the parent materials are loess over glacial outwash, would be expected to have higher weathering than a soil with only glacial outwash because of the large surface area and mixed mineralogy of loess. The PROFILE results were at or somewhat above weathering rates reported from purely glacial outwash soils, but the column leaching results were near the low end of this range. Undoubtedly this was a result of the inability to include in this soil column the fine-textured A horizon where much weathering would be expected. At Kinleith, weathering was from tephra and pumice. Zabowski (1990) reported 9.4 kg Ca/ha, 4.5 kg Mg/ha, and 5.8 kg K/ha annually from tephra over andesite. Again, these results would be expected to be somewhat lower than a soil composed entirely of tephra and pumice with its greater particle surface area and rapid weathering rate of ash. The weathering reported by Zabowski (1990) was somewhat lower than that of the tephra/pumice Kinleith and Tarawera soils for calcium, remarkably similar for magnesium and potassium from PROFILE, and less than the column leaching of potassium at Kinleith. Overall weathering results of the PROFILE model were supported by the column leaching study and by a comparison of weathering with other similar parent materials. PROFILE should provide a good assessment of weathering inputs of calcium, magnesium, potassium, and phosphorus to nutrient cycling if adequate soil physical, chemical, and mineralogical data are available.

Nutrient Cycling and Sustainable Harvesting

Results of total and average annual biomass production varied across sites but no site showed extremely poor growth (Table 3). The Berwick and Tarawera sites had the best average annual biomass production, and the lowest growth was at

TABLE 3–Total nutrient pools in first-rotation trees and averaged annual nutrient demand per site. Data on nutrient pools from Dyck *et al.* (1991), Adams *et al.* (in prep.), A.Lowe and A.Thorn (unpubl. data), D.Graham (pers. comm.).

	Biomass (mg/ha)	Ca	Mg	K	P	B	N
		-------	-------	(kg/ha)	-------	-------	-------
Woodhill							
aboveground	404	350	116	343	69	–	284
belowground	92	88	30	66	18	–	24
total	496	438	146	409	87	–	308
annual demand	11.8	10.4	3.5	9.7	2.1	–	7.3
Tarawera							
aboveground	374	344	109	406	57	0.94	355
belowground	89	79	24	60	17	0.15	19
total	463	423	133	466	74	1.09	374
annual demand	17.1	15.7	4.9	17.3	2.7	0.040	13.9
Kinleith							
aboveground	223	207	84	263	37	1	295
belowground	70	62	19	48	13	0.12	15
total	293	269	103	311	50	1.12	310
annual demand	11.3	10.3	4.0	12.0	1.9	0.043	11.9
Golden Downs							
aboveground	500	978	133	434	110	1.2	638
belowground	122	108	32	82	23	0.2	26
total	622	1086	165	516	133	1.4	664
annual demand	14.1	24.7	3.8	11.7	3.0	0.032	15.1
Burnham							
aboveground	170	397	105	350	49	–	457
belowground	47	42	13	32	9	0.08	10
total	217	439	118	382	58	0.08	467
annual demand	8.0	16.3	4.4	14.1	2.1	0.00	17.3
Berwick							
aboveground	302	249	135	541	55	–	509
belowground	131	116	35	88	25	0.22	28
total	433	365	170	629	80	0.22	537
annual demand	16.0	13.5	6.3	23.3	3.0	0.01	19.9

Burnham. There was no obvious correlation between annual nutrient demand and annual biomass production. Phosphorus showed the best agreement with all three of the higher productivity sites having higher phosphorus in annual tree biomass, and all of the lower production sites having lower phosphorus. Calcium, magnesium, potassium, and nitrogen annual nutrient demands did not correlate well with annual biomass production. The trend of increasing biomass production with increasing annual phosphorus demand suggested that available-phosphorus or some other correlate was a growth-limiting factor. However, average annual phosphorus demand calculated by dividing total stand phosphorus by stand age can over-estimate annual phosphorus demand as phosphorus is translocated within pines. The loss of nutrients by litterfall and root turnover was also not considered in this calculation, but it may somewhat balance translocation. Availability of phosphorus is a common factor limiting *P. radiata* growth in New Zealand forests (Will 1985) although it is not expected at all sites (Parfitt *et al*. 1994).

When annual nutrient demands of *P. radiata* are compared with modelled annual weathering rates, phosphorus is the element where weathering is either similar to or below annual nutrient demand at all sites. The annual demand for calcium, magnesium, and potassium is frequently equal to the weathering rate (e.g., magnesium weathering at Kinleith, Tarawera, and Golden Downs); at Golden Downs the calcium weathering rate is less than half the demand rate. Luxury consumption of some nutrients may also be occurring which would result in a higher apparent nutrient demand. These results suggest that if weathering were the only source of nutrients, phosphorus would frequently be limiting to growth, and that base cations could be limiting depending on the soil type, parent materials, and environmental factors that affect weathering rates. Variations in nutrient demand as a forest ages may also result in higher or lower nutrient demand at times relative to the average annual weathering rates given here.

However, mineralisation of nutrients stored in soil organic matter is an additional source of nutrients that can supplement weathering. The pool of nutrients stored in the O horizon is listed in Table 4, along with estimated nutrient release rates calculated using the Burnham O horizon leaching rate (Table 5). Nutrient release rates from the O horizons at Woodhill, Tarawera, Golden Downs, and Berwick were not available, and the nutrient pools in the O horizon of Kinleith were notably lower in calcium, magnesium, and potassium than those of any other site; therefore Burnham leaching rates were used to estimate nutrient release from the O horizons at Woodhill, Tarawera, Golden Downs, and Berwick, using each site's O horizon nutrient pool. A substantial amount of nutrients will be available from mineralisation of the O horizon, on some sites more than that calculated to be available from weathering (Parfitt *et al*. 1994; Zabowski *et al*. 1996). While nutrients mineralised from the litter can be taken up by the trees and recycled as litterfall, the nutrients remaining in the tree would need to be replaced by weathering if the O horizon is to remain in steady state.

Organic matter within the mineral soil can also release nutrients by mineralisation or absorb nutrients, and soil organisms can immobilise them. Equation (1) can be used to compare the leachable nutrients from the mineral soil (Table 5) with weathering rates (Table 2) to determine if the mineral soil is mineralising nutrients or

TABLE 4–Total nutrient pool in O horizon of all sites and estimated annual nutrient release rate from leaching of the O horizon. Data on O horizon pools from Dyck *et al.* (1991), A.Lowe and A.Thorn (unpubl. data), D.Graham (pers. comm.), and Adams *et al.* (unpubl. data). Nitrogen O horizon pool is included for comparison.

	Woodhill*	Tarawera*	Kinleith	Golden Downs*	Burnham	Berwick*
Pool (kg/ha)						
Calcium	270	195	98	285	209	207
Magnesium	148	107	15	25	67	58
Potassium	76	60	42	31	108	64
Phosphorus	--	22	23	18	26	23
Boron	--	0.3	0.22	0.25	--	--
Nitrogen	464	360	436	162	534	332
O horizon leachable (kg/ha annually)						
Calcium	26	19	11	27	20	20
Magnesium	26	19	6.4	4	12	10
Potassium	18	14	38	7	26	15
Phosphorus	--	0.6	1.3	0.5	0.7	.6
Boron	--	--	0.5	--	0.2	--

* Calculated using *in situ* mass of O horizon with the leaching rate of the Burnham site O horizon

TABLE 5–Leachable nutrients from top 1 m of mineral soil at Kinleith and Burnham.

	Mineral soil leaching (kg/ha annually)	
	Kinleith	Burnham
Calcium	6.5	0.5
Magnesium	1.3	0.8
Potassium	11	1.7
Phosphorus	0.1	0.2
Boron	0.1	<0.1

immobilising them (at 15°C soil temperature), assuming no change in exchangeable nutrients. Thus, both the Kinleith and Burnham soils were immobilising calcium, magnesium, and potassium, and Kinleith was immobilising phosphorus as leachable nutrients are less than weathering (at Burnham leachable phosphorus equals weathering phosphorus). This suggests that cation and phosphorus availability from mineralisation of organic matter *within* mineral soil below the A horizon is nominal compared to immobilisation and adsorption (and secondary mineral formation), and that weathering and mineralisation of the O horizon organic matter should be considered the major sources of calcium, magnesium, potassium, and phosphorus.

If disturbance to soil is minimal during timber harvesting, the major loss of nutrients is by off-site removal of nutrients stored in trees. Whole-tree harvesting (WTH) will remove bole, foliar, and branch nutrients (essentially all above-ground forest nutrients) and result in the greatest losses of nutrients from a site. Total harvesting exports for whole-tree harvesting and total weathering of calcium, magnesium, potassium, and phosphorus for a rotation of 27 years are given in Fig. 4. Error bars were set at 20% to include the uncertainty of PROFILE. At all sites except Berwick, whole-tree harvesting would result in removal of phosphorus exceeding

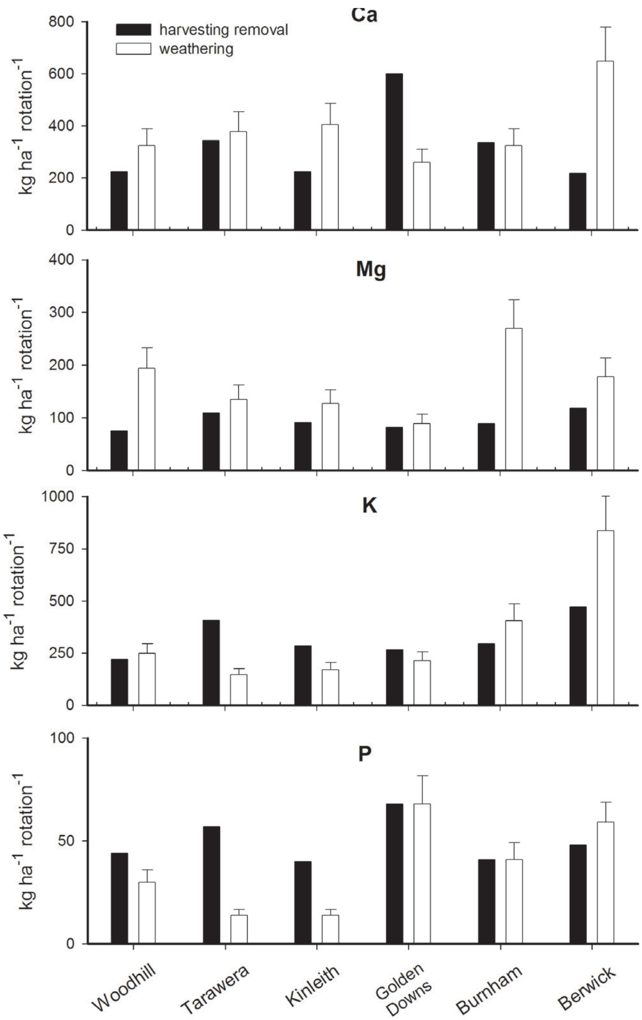

FIG. 4–Whole-tree harvesting removals and weathering replenishment of calcium, magnesium, potassium, and phosphorus in a 27-year-old *Pinus radiata* stand for six sites in New Zealand. Error bars indicate a 20% uncertainty in calculation of weathering rates.

replacement of available-phosphorus by weathering (not including any atmospheric deposition of nutrients). With calcium, magnesium, and potassium, many sites other than Berwick could have inadequate weathering of cations to replace those lost by harvesting. Results here suggest that increasing amounts of phosphorus fertiliser may be required in future, and that some stands that may not have required calcium, magnesium, potassium, or boron during current or past rotations will require them in the future. Protecting the O horizon may become crucial to helping supply "recycled" nutrients to help offset harvesting removals.

Loss of the O horizon during harvesting activities or subsequent erosion would have a major impact on subsequent nutrient supply. Skinner *et al.* (1989) found *P. radiata* volume to be reduced by 30% with loss of the O horizon in the first 10 years of growth. A loss of organic acids leaching from the O horizon could reduce weathering rates (Zabowski *et al.* 1996). Changes in organic acids released from the O horizon throughout a rotation or changes in the O horizon from disturbance could also alter weathering rates by affecting the quantity of protons released that can weather minerals.

One method to ensure adequate nutrient supply over multiple rotations is the application of fertiliser. Large-scale fertiliser application may not always be an option for all forests; weathering release of nutrients will remain a critical factor for sustainable forest management and may limit production, management methods, and rotation lengths depending on the soil type. Protection for the O horizon (or litter layer) and knowledge of the nutrient supply rate from weathering and mineralisation of the O horizon will help determine sustainable timber production for a site.

CONCLUSIONS

One of the most difficult processes to quantify in nutrient cycling is weathering. Determination of *in situ* weathering for long-term forest productivity is difficult due to the complexity of nutrient cycling. Using six New Zealand forest soils, weathering rates were determined using the PROFILE model, and column leaching was used for two of the sites. Column leaching estimates of weathering worked well if used with a soil that has a consistent texture throughout the soil profile, as occurred at the Kinleith. Overall, column leaching estimates of weathering rates were comparable to those of PROFILE. PROFILE weathering rates appeared reasonable for all sites, confirming its usefulness for predicting nutrient supply by weathering over multiple rotations if sufficient soil and site data are available. Annual weathering rates were 3–24 kg Ca/ha, 3–10 kg Mg/ha, 3–31 kg K/ha, and 0.2–2.5 kg P/ha. Weathering rates calculated using PROFILE and leaching of nutrients from the O horizon suggest that both weathering and O horizon decomposition are critical to sustainable forest production over multiple rotations. A comparison of nutrient removals with whole-tree harvesting and those with weathering suggests some nutrients may be depleted at current rotation lengths without fertiliser additions but O horizon mineralisation can offset this difference.

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REFERENCES

ADAMS, M.B.; CLINTON, P.W.; KIMBERLY, M.O.; LOWE, A.T.: Site fertility sustains nutrition and productivity of radiata pine following harvesting (in prep.)

ADAMS, P.W.; BOYLE, J.R. 1979: Cation release from Michigan Spodosols leached with aspen leaf extracts. *Soil Science Society of America Journal 43*: 593–596.

APRIL, R.; NEWTON, R. 1992: Mineralogy and mineral weathering. Pp. 378–425 *in* Johnson, D.W.; Lindberg, S.E. (Ed.) "Atmospheric Deposition and Nutrient Cycling in Forest Ecosystems". Springer-Verlag, New York.

CROMACK, K.Jr; SOLLINS, P.; GRAUSTEIN, W.C.; SPEIDEL, K.; TODD, A.W.; SPYCHER, G.; LI, C.Y.; TODD, R.L. 1979: Calcium oxalate accumulation and soil weathering in mats of the hypogeous fungus *Hysterangium crassium*. *Soil Biology & Biochemistry 11*: 463–468.

DYCK, W.J.; HODGKISS, P.D.; OLIVER, G.R.; MEES, C.A. 1991: Harvesting sand-dune forests: impacts on second-rotation productivity. Pp. 163–176 *in* Dyck, W.J.; Mees, C.A. (Ed.) "Long-term Field Trials to Assess Environmental Impacts of Harvesting", Proceedings, IEA/BE T6/A6 Workshop, Florida, USA, February 1990. IEA/BE T6/A6 Report No. 5. *Forest Research Institute, Rotorua, New Zealand, FRI Bulletin No. 161*.

JACKSON, D.S.; CHITTENDEN, J. 1981: Estimation of dry matter in *Pinus radiata* root systems 1. Individual trees. *New Zealand Journal of Forestry Science 11(2)*: 164–182.

JÖNSSON, C.; WARFVINGE, P.; SVERDRUP, H. 1995: Uncertainty in prediction of weathering rate and environmental stress factors with the PROFILE model. *Water Air Soil Pollution 81(1/2)*: 1–23.

JONES, D.L. 1998: Organic acids in the rhizosphere—a critical review. *Plant and Soil 205*: 25–44.

LOWE, D.J.; NEWNHAM, R.M.; WARD, C.M. 1999: Stratigraphy and chronology of a 15 ka sequence of multi-sourced silicic tephras in a montane peat bog, eastern North Island, New Zealand. *New Zealand Journal of Geology & Geophysics 42*: 565–579.

NEWNHAM, R.M.; LOWE, D.J.; MATTHEWS, B.W. 1998: A late-Holocene and prehistoric record of environmental change from Lake Waikaremoana, New Zealand. *The Holocene 8(4)*: 443–454.

NEW ZEALAND MINISTRY OF FORESTRY 2001: "New Zealand Forestry Statistics 2000". Ministry of Forestry, Wellington, New Zealand.

NEW ZEALAND SOIL BUREAU 1954: General survey of the soils of North Island, New Zealand. *New Zealand Department of Scientific and Industrial Research, Soil Bureau Bulletin 5*.

———1968a: Soils of New Zealand, Part 3. *New Zealand Department of Scientific and Industrial Research, Soil Bureau Bulletin 26(3)*.

———1968b: General survey of the soils of South Island, New Zealand. *New Zealand Department of Scientific and Industrial Research, Soil Bureau Bulletin 27*.

NICHOL, S.E.; HARVEY, M.J.; BOYD, I.S. 1997: Ten years of rainfall chemistry in New Zealand. *Clean Air 31(1)*: 30–37.

PARFITT, R.L.; TATE, K.R.; YATES, G.W. 1994: Phosphorus cycling in a sandy podsol under *Pinus radiata*. *New Zealand Journal of Forestry Science 24(2/3)*: 253–267.

PASTOR, J.; BOCKHEIM, J.G. 1984: Distribution and cycling of nutrients in an aspen-mixed-hardwood-spodosol ecosystem in northern Wisconsin. *Ecology 65*: 339–353.

PAYN, T.W.; SKINNER, M.F.; CLINTON, P.W. 1998: Future nutrient requirements of New Zealand plantation forests. Pp. 97–110 *in* Currie, L.D.; Loganathan., P. (Ed.) "Long-term Nutrient Needs for New Zealand's Primary Industries: Global Supply, Production Requirements and Environmental Constraints". *Fertilizer and Lime Research Centre, Massey University, Palmerston North, Occasional Report No. 11*.

PAYN, T.W.; SKINNER, M.F.; HILL, R.B.; THORN, A.J.; SCOTT, J.; DOWNS, S.; CHAPMAN, H. 2000: Scaling up or scaling down: the use of foliage and soil information for optimising the phosphate nutrition of radiata pine. *Forest Ecology & Management 138(1–3)*: 79–89.

PEARCE, A.J.; PHILLIPS, C.J.; CAMPBELL, I.B. 1983: Regolith profiles on slopes underlain by Moutere Gravel formation, Big Bush State Forest: hydrologic and geomorphic implications. *New Zealand Journal of Geology & Geophysics 26*: 57–70.

SKINNER, M.F.; MURPHY, G.; ROBERSTON, E.D.; FIRTH, J.G. 1989: Deleterious effects of soil disturbance on soil properties and the subsequent early growth of second-rotation radiata pine. Pp. 210–211 *in* Dyck, W.J.; Mees, C.A. (Ed.) "Research Strategies for Long-term Site Productivity", Proceedings, IEA/BE A3 Workshop, Seattle, WA, August 1989. IEA/BE A3 Report No. 8. *Forest Research Institute, Rotorua, New Zealand, FRI Bulletin No. 152*.

STOKES, S.; LOWE, D.J.; FROGGATT, P.C. 1992: Discriminant function analysis and correlation of late quaternary rhyolitic tephra deposits from Taupo and Okataina volcanoes, New Zealand, using glass shard major element composition.

SVERDRUP, H.; ROSEN, K. 1998: Long-term base cation balances for Swedish forest and the concept of sustainability. *Forest Ecology & Management 110*: 221–236.

SVERDRUP, H.; WARFVINGE, P. 1988a: Chemical weathering of minerals in the Gårdsjön catchment in relation to a model based on laboratory rate coefficients. Pp. 131–150 in Nilsson, J. (Ed.) "Critical Loads for Sulphur and Nitrogen". Nordic Council of Ministers and The United Nations Economic Commission for Europe (ECE). *Miljörapport 1988: 15*.

——1988b: Weathering of primary silicate minerals in the natural soils environment in relation to a chemical weathering model. *Water Air Soil Pollution 38*: 387–408.

WARFVINGE, P.; SVERDRUP, H. 1992: Calculating critical loads of acid deposition with PROFILE — a steady state soil chemistry model. *Water Air Soil Pollution 63*: 119–143.

WILL, G. 1985: Nutrient deficiencies and fertiliser use in New Zealand exotic forests. *New Zealand Forest Research Institute, Rotorua, FRI Bulletin No. 97*.

WOODWELL, G.M.; WHITTAKER, R.H. 1967: Primary production and the cation budget of the Brookhaven Forest. *In* "Primary Productivity and Mineral Cycling in Natural Ecosystems", Symposium Proceedings, American Association for the Advancement of Science, New York.

ZABOWSKI, D. 1990: Role of weathering in long-term site productivity. Pp. 55–71 *in* Dyck, W.J.; Mees, C.A. (Ed.) "Impact of Intensive Harvesting on Forest Site Productivity", Proceedings, IEA/BE A3 Workshop, South Island, New Zealand, March 1989. IEA/BE/A6 Report No. 2. *Forest Research Institute, Rotorua, New Zealand, FRI Bulletin No. 159*.

ZABOWSKI, D.; SKINNER, M.F.; RYGIEWICZ, P.T. 1996: Site disturbance effects on a clay soil under radiata pine 1. Soil solutions and clay mineral stability. *Plant and Soil 186*: 343–351.