FOUR TREE SPECIES AND THE CALCIUM, MAGNESIUM, AND POTASSIUM BUDGETS OF A SWEDISH FOREST SITE

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ABSTRACT

The influence of four tree species on calcium, magnesium, and potassium ecosystem budgets at the Susegården site in south-western Sweden were evaluated. Data on nutrient contents in biomass and soil were obtained from a study in a 32-year-old tree species experiment at Susegården. The species were Norway spruce (*Picea abies* L. Karst.), silver fir (*Abies alba* Mill.), grand fir (*Abies grandis* Lindl.), and Japanese larch (*Larix leptolepis* (Sieb. et Zucc.) Endl.). Deposition levels for the 32 years were calculated from data obtained at nearby monitoring stations, and weathering rates were calculated using the PROFILE model.

For calcium and potassium, lower rates of nutrient uptake by Japanese larch and silver fir than by Norway spruce and grand fir had been followed by increased leaching, thus resulting in export of a major portion of nutrients not taken up. Species-related differences in soil pools of organically bound and exchangeable calcium and potassium could be offset if stems only were harvested or if whole-tree harvest were to be combined with ash recycling. For magnesium, the differences in nutrient uptake among the tree species were relatively small. Still, there had been a higher relative build-up of the soil pool of magnesium in Japanese larch than in the other species, which implies there had been less leaching. For all species, it is likely that the sum of exchangeable and organically bound calcium and potassium in the soil had decreased over the 32-year period.

Keywords: biomass; nutrients; calcium; potassium; magnesium; soil; tree species; uptake; leaching; weathering.

INTRODUCTION

Weathering and deposition and, in some places, lateral fluxes with groundwater are the main inputs of available calcium, magnesium, and potassium to forest ecosystems. These nutrients are exported mainly through biomass harvesting and leaching. If output exceeds input, a decrease in the soil pool will follow, and vice versa. A number of studies have shown that nutrient budgets can be influenced by tree species owing to differences in:

(i) Nutrient uptake per unit of time and/or wood produced (Nihlgård 1972; Alban *et al.* 1978; Perala & Alban 1982; Eriksson & Rosén 1994)

(ii) Deposition filtering abilities (Nordén 1992; Westling *et al.* 1992; Binkley 1995)

(iii) Leaching (Nihlgård 1972; Bergkvist 1987)

(iv) Influence on soil pool sizes (Challinor 1968; Alban *et al.* 1978; Alban 1982; Binkley & Valentine 1991; Eriksson & Rosén 1994).

Fewer studies have been made of tree species effects on weathering and interactions between the inputs and outputs.

More detailed information about the long-term nutrient budgets of different forest management systems is required to improve accuracy in predicting long-term sustainability of the system and in planning resource-efficient nutrient recycling and fertiliser use. We suggest it is not possible to demonstrate the influence of tree species on long-term ecosystem productivity until their effects on nutrient input and output can be related to the total nutrient budget of the system.

This study, which concentrated on calcium, magnesium, and potassium, is based on an earlier comparison of nutrient contents in soil and biomass compartments of four tree species (Eriksson & Rosén 1994). The earlier investigation was conducted at a 32-year-old randomised block experiment at Susegården in south-western Sweden. It showed that Japanese larch and silver fir had less calcium, potassium, and magnesium in their above-ground biomass than Norway spruce and grand fir; Japanese larch had low nutrient concentrations in the biomass, and silver fir had low biomass production at this site. Since differences in soil pools of exchangeable and organically bound calcium, magnesium, and potassium were not throughout inversely related to differences in above-ground biomass pools, it was concluded that one or more of the input/output fluxes other than uptake and change in soil pool (i.e., weathering, deposition, and/or leaching) had also been affected by species. Thus, the species may have differed in their effect on various ecosystem processes for which no measurements were available, e.g., leaching, deposition filtering abilities, and factors that affect weathering rates, such as the water balance and dissolved organic carbon (DOC) concentrations in the soil solution. However, no significant differences in soil pH between species were found in the earlier study.

To our knowledge, there are no tree species experiments several decades old in which all of the variables mentioned above have been measured since the start. Thus, we found it worthwhile to attempt to evaluate how the four species have influenced calcium, magnesium, and potassium input/output budgets at Susegården.

The aims of this study were to:

(1) Evaluate the influences of measured species-related differences in calcium, magnesium, and potassium uptake and soil pools on total calcium, magnesium, and potassium input/output budgets;

(2) Evaluate the potential influences of differences in specific non-measured factors on the calcium, magnesium, and potassium budgets, such as dry deposition, soil moisture, and DOC concentration in the soil water;

(3) Suggest measurements that could be used to decrease the uncertainties in studies with similar approaches in the future.

MATERIAL AND METHODS

The Susegården site

The soil at Susegården, 15 km north of Halmstad in south-western Sweden, is a sandy-silty glacial till. The soil type is a Dystric regosol according to FAO (1988) and a Typic Dystrochrept according to the USDA Soil Survey (1988).

An experiment with nine tree species was established in 1957 with 3- or 4-year-old seedlings, using a randomised block design with three replicates. Nutrient distributions in soil and above-ground biomass in four of the nine tree species were compared in 1989 (Eriksson & Rosén 1994). The species included were Norway spruce, silver fir, grand fir, and Japanese larch. After 32 years of growth at the Susegården site (at tree age 35 or 36), total stemwood production of Norway spruce was 344 m^3/ha, silver fir 174 m^3/ha, grand fir 471 m^3/ha, and Japanese larch 377 m^3/ha.

Nutrient Budgets

The input/output budget equation used for calcium, magnesium, and potassium was as follows:

$$W + D - U - L - CSP = 0 \qquad \text{Eq 1}$$

where W denotes weathering, D deposition, U net biomass uptake, L leaching, and CSP change in the soil pool. The soil pool is here defined as the total pool in the soil except the part which is bound in non-weathered minerals. It is calculated as the estimated sum of the exchangeable pool and the organically bound pool down to a depth of 1 m (*see* below).

Fluxes other than these five were considered negligible at this site. If there are significant lateral nutrient transports with the groundwater, tree growth normally increases downwards along the slope. As this did not occur at this site, lateral flux with groundwater was considered insignificant.

The difference between the annual budgets of any two species ($_{sp}$) must also balance so that

$$(W_{sp1}-W_{sp2}) + (D_{sp1}-D_{sp2}) - (U_{sp1}-U_{sp2}) - (L_{sp1}-L_{sp2}) - (CSP_{sp1}-CSP_{sp2}) = 0$$

or $$\Delta W + \Delta D - \Delta U - \Delta L - \Delta CSP = 0 \qquad \text{Eq 2}$$

Here, Norway spruce was chosen to be the reference tree species, so that ΔCSP_{sp} was defined as

$$\Delta CSP_{sp} = CSP_{sp} - CSP_{\text{Norway spruce}} \text{ (and so on for } \Delta W, \Delta U, \text{ and } \Delta L) \qquad \text{Eq 3}$$

For Norway spruce, annual weathering rates were calculated with a mechanistic weathering model, and average annual deposition levels were obtained from deposition inventory statistics (*see* below). Since leaching (L) and change in the soil pool (CSP) were not measured or estimated for this site, they could not be separated. Therefore, a budget residual (BR) was calculated as

$$BR_{\text{Norway spruce}} = CSP_{\text{Norway spruce}} + L_{\text{Norway spruce}} \qquad \text{Eq 4}$$

However, because annual differences between species in CSP and uptake (U) could be obtained from the field measurements (*see* below), a relative residual (RR), which expresses $\Delta L - \Delta D - \Delta W$, was calculated from Equations 2 and 3 as

$$RR_{sp} = \Delta U_{sp} - \Delta CSP_{sp} \qquad \text{Eq 5}$$

Nutrient Uptake

Average annual net nutrient uptake in the whole tree, including roots, was estimated by multiplying total nutrient contents in the above-ground biomass (Eriksson & Rosén 1994) by 1.2 (derived from Alban *et al.* 1978) and dividing by the number of years since plantation establishment (32 years). The uptake of calcium, magnesium, and potassium is shown in Table 1.

TABLE 1–Budget calculations for calcium, magnesium, and potassium: Net nutrient uptake (U) by Norway spruce, silver fir, grand fir, and Japanese larch. Deposition (D), weathering (W), and budget residuals (BR) for Norway spruce (Eq 1). ΔU, ΔCSP, ΔL, ΔD, ΔW are differences from Norway spruce in U, CSP, L, D, and W, respectively. BR is the sum of change in soil pool (CSP) and leaching (L). Relative residuals (RR) is the difference in leaching minus the differences in deposition and weathering (ΔL–ΔD–ΔW) (Eq 2 and 3). Different letters show significant differences (p<0.05).

	U	$D_{N. spruce}$	$W_{N. spruce}$	BR (CSP+L)	ΔU	ΔCSP	RR (ΔL–ΔD–ΔW)
	kg/ha/year						
Calcium							
Norway spruce	13.8	5.2	3.9	–4.7	0* a	0* a	0* a
Silver fir	9.3				–4.5 b	–0.4 a	4.9 b
Grand fir	13.1				–0.7 ab	0.6 a	0.1 a
Japanese larch	4.2				–9.6 c	1.8 a	7.8 b
Magnesium							
Norway spruce	2.5	3.9	1.6	3.0	0 ab	0 a	0 a
Silver fir	1.7				–0.8 c	0.3 a	0.5 a
Grand fir	2.8				0.3 a	0.1 a	–0.4 ab
Japanese larch	1.9				–0.6 bc	1.8 b	–1.2 b
Potassium							
Norway spruce	8.1	3.1	2.4	–2.6	0 a	0 a	0 a
Silver fir	5.6				–2.5 b	0.1 a	2.4 b
Grand fir	9.0				0.9 a	-0.4 a	–0.5 a
Japanese larch	6.7				–1.4 ab	0.6 a	0.8 ab

*Zero by definition (cf. Eq 3)

Soil Pool

The soil pool here refers to the sum of the exchangeable pool and the non-mineralised pool in dead organic matter. The mor humus layers (O) were between 3 and 7 cm thick (Eriksson & Rosén 1994). The transition layers (A_1) between the organic and mineral soil layers were between 1 and 2 cm thick. Based on the soil data of Eriksson & Rosén (1994), the total soil pool (Table 2) was calculated as

Soil pool = (total pool in O) + 2* (exchangeable pool in A_1)
+ exchangeable pool in the mineral soil at 0–95 cm)

It was difficult to estimate the non-mineralised organically bound pool in the transition layer (A_1) between the organic and the mineral soil horizons. A chemical analysis of total cation contents in this layer would also extract cations from non-weathered minerals. The reason for estimating the soil pool of exchangeable and organically bound calcium,

TABLE 2–Soil pools (sums of exchangeable and non-mineralised organic pools) of calcium, magnesium, and potassium (n=3) in the O layer, A_1 layer, and mineral soil 0–95 cm of the Norway spruce, silver fir, grand fir, and Japanese larch plots.

		Calcium	Magnesium	Potassium
		kg/ha		
Norway spruce	O layer	191	62	52
	A_1 layer	61	19	29
	Mineral 0–95	38	22	87
	Total soil pool	**290**	**103**	**169**
Silver fir	O layer	202	77	64
	A_1 layer	44	17	33
	Mineral 0–95	33	20	75
	Total soil pool	**278**	**114**	**172**
Grand fir	O layer	210	65	49
	A_1 layer	57	18	19
	Mineral 0-95	42	22	88
	Total soil pool	**309**	**106**	**156**
Japanese larch	O layer	273	125	87
	A_1 layer	34	15	24
	Mineral 0-95	40	21	76
	Total soil pool	**346**	**161**	**187**

magnesium, and potassium in the A_1 layer by multiplying the exchangeable pool by two, was that in the pure organic O layer, the exchangeable contents were about half of the total contents (Eriksson & Rosén 1994). Since organic matter probably provides over 90% of the exchangeable sites in the A_1 layer, the relationship 1:1 (organically bound to exchangeable) was assumed to be similar for the O and A_1 layers. The organically bound pools at lower depths were considered negligible. The soil pools of the O, A_1, and mineral soil (0–95 cm) layers are summarised in Table 2. The annual average of the difference from Norway spruce in soil pool (CSP) for the other species was calculated as

$$\Delta CSP_{sp} = (\text{soil pool}_{sp} - \text{soil pool}_{\text{Norway spruce}})/32 \qquad \text{Eq 6}$$

Deposition

Average values of present-day wet and dry deposition for Norway spruce for the years 1985–90 were taken from the grid database of deposition in the Nordic countries, which is based on interpolation between monitoring sites (Lövblad *et al.* 1991, 1992). Five monitoring sites are situated within 40 km of Susegården. From present-day data, the average deposition rate for the period 1957–89 (Table 3) was calculated using historical emission data (Mylona 1993). In the calculations, the positive relationship between filtering ability and the growing stand canopy volume was taken into account. A lower deposition rate, determined as above for pine and deciduous stands (Table 3), was used to evaluate the influence of deposition rate on nutrient budgets.

Weathering

The PROFILE model is a mechanistic geochemical model that calculates steady-state chemistry of soils, groundwater, and surface waters (Warfvinge & Sverdrup 1992). It has been used to calculate weathering rates and critical loads of acidity for soil in large areas of

TABLE 3–Calculated deposition rate at the Susegården site.

		Norway spruce (basic case)	Pine/deciduous (low)
		kmol$_c$/ha/year	
Cations	Ca^{2+}	0.26	0.20
	Mg^{2+}	0.32	0.24
	K^+	0.08	0.06
	Na^+	1.0	0.74
	H^+	0.6	0.6
	NH_4^+	0.6	0.5
Anions	SO_4^{2-}	1.27	1.09
	NO_3^-	0.6	0.5
	Cl^-	1.0	0.74

Europe (Warfvinge & Sverdrup 1992; Sverdrup & Warfvinge 1993). For this purpose, the soil profile is divided into compartments which correspond to the natural stratification, and each compartment is assumed to have homogeneous properties. Weathering is here defined as the release of alkalinity and base cations.

Several chemical reactions contribute to the base cation release rate. The total rate is calculated as the sum of the net rates of all these mineral-dissolving reactions. In the model, the weathering rate is increased by high H^+ concentration, high soil moisture content, high carbon dioxide pressure, and the presence of organic acids. Weathering rates are decreased by high concentrations of reaction products in the soil solution, such as inorganic aluminium and base cations. The surface activity is calculated as dependent on the mineral surface area, temperature, and soil moisture saturation. Soil moisture saturation is important for the reaction rate as reactions will take place only on wetted surfaces. The degree of surface wetting, and thus of surface activity, is calculated from soil bulk density, solid particle density, and volumetric water content.

Weathering rates calculated using the PROFILE model have been compared with weathering rates determined by other methods at 15 sites in Scandinavia, Central Europe, and North America (Sverdrup & Warfvinge 1993). This study showed that the model was capable of estimating weathering rates within ±20% of the values estimated by other methods.

One composite sample of mineral soil from a depth of 20–40 cm (particle sizes <2 mm) from the plots sampled at Susegården was washed on cemented iron and ground. The relative mineral composition was determined using X-ray diffraction analysis and a model for transformation to weight estimates (Melkerud 1983) (Table 4). Since the soil was a well-mixed glacial till, the mineral composition was assumed to be homogeneous throughout the soil profile. Other input data required by the model were taken partly from site measurements and partly from databases for similar sites (Tables 3, 5, and 6). Nutrient uptake data obtained for Norway spruce were used (Table 1).

Factor Evaluation

To assess how known differences between species in nutrient uptake as well as potential differences in dry deposition, soil moisture, and DOC concentration influence weathering

TABLE 4–Mineral composition of the fine earth (<2 mm) at Susegården (20–40 cm depth).

	Percentage of total
K-feldspar	14
Plagioclase	27
Hornblende	7
Pyroxene	0.05
Chlorite	0.5

TABLE 5–General input data for the Susegården site. Precipitation and mean temperature (Anonymous 1993). Throughfall and runoff estimated.

Parameter	
Precipitation (m/year)	1.04
Throughfall (m/year)	0.80
Runoff (m/year)	0.45
Mean temperature (°C)	6.4

TABLE 6–Soil layer specific input for the Susegården site. Layer No.0 represents the humus layer, and 1, 2, and 3 are mineral soil layers at soil depth of 5–20 cm, 20–50 cm, and 50–100 cm respectively.

Parameter	Soil layer			
	0	1	2	3
Layer thickness* (m)	0.05	0.15	0.3	0.5
Soil bulk density* (kg/m^3)	900	1438	1600	1600
Specific surface area* (m^2/m^3 × 10^{-6})	0.8	1.60	1.39	1.39
Soil volumetric water content				
basic case(m^3/m^3)	0.20	0.20	0.20	0.20
+10%(m^3/m^3)	0.22	0.22	0.22	0.22
CO_2 pressure (times ambient)	5	3	3	2
Log gibbsite equilibr. const.	6.5	7.5	8.5	9.5
Inflow (% of throughfall)	100	65	61	58
Percolation (% of throughfall)	65	61	58	56
Ca, Mg, K, and N uptake (% of total)	50	30	15	5
Dissolved organic carbon				
basic case [mg/ℓ]	20	10	5	5
high [mg/ℓ]	80	40	20	20

* From field measurements at Susegården (Eriksson & Rosén 1994).

rates and budget residuals (BR), four PROFILE calculations were made that differed from the basic calculation for Norway spruce, each in one aspect:

(i) With Japanese larch uptake instead of Norway spruce uptake

(ii) With a lower deposition level (Table 3)

(iii) With a 10% higher soil moisture value (Table 6)

(iv) With a four times higher DOC concentration in the soil solution (Table 6).

Statistical Analysis

Analysis of variance (ANOVA) for a randomised block design and comparisons between means for U, CSP, and relative residuals (cf. Eq 2) were made according to the basic model described by Mead & Curnow (1983).

RESULTS AND DISCUSSION

Effects on Budgets

According to the calculated weathering rates and deposition, average input of calcium and potassium has been lower than average net uptake by Norway spruce trees over the 32 years since planting (Table 1). Since the leaching part of the budget residuals (BR) cannot be negative, this implies that soil pools of calcium and potassium under Norway spruce have decreased by at least 4.7 and 2.6 kg/ha/year, respectively. Since soil pools of the other species differed from Norway spruce with smaller amounts (cf. ΔCSP, Table 1), it is likely that soil pools of calcium and potassium have decreased for all species over the 32 years.

Silver fir and Japanese larch have fairly high relative residuals ($RR = \Delta L - \Delta D - \Delta W$) for calcium and potassium compared with Norway spruce (Table 1). Since differences between species in the sum of deposition (ΔD) and weathering (ΔW) probably have been small in relation to these values (cf. below), it is likely that calcium and potassium leaching has been higher for silver fir and Japanese larch than for Norway spruce. For grand fir, average leaching has probably been similar to the level for Norway spruce.

For magnesium, input from weathering and deposition most likely exceeded uptake for all species (Table 1). Since the relative residual was low for Japanese larch, leaching for this species seems to have been low compared with that for the other species. The divergence between annual soil pool changes of Japanese larch and Norway spruce ($\Delta CSP_{Japanese\ larch}$) had been larger than the difference in net uptake by the trees ($\Delta U_{Japanese\ larch}$). The humus layer of Japanese larch contained 86 t organic matter/ha, which was significantly higher than the 70–74 t/ha of the other species (Eriksson & Rosén 1994). Compared with calcium and potassium, a higher proportion of the magnesium input is contributed by deposition, which is added from above, and a lower proportion from weathering (Table 1), added throughout the mineral soil profile. This fact, in combination with the thicker humus layer of Japanese larch, may explain less loss by leaching and thus the "build-up" of the magnesium soil pool for Japanese larch in relation to the other species.

These stands were in an aggrading growth phase during the 32-year period. In coming decades, annual net nutrient uptake will be lower. Furthermore, not all of the nutrients in the biomass will be harvested. About 40% of the calcium, magnesium, and potassium is found in the stems. Another 25–40% would be extracted with whole-tree harvesting.

Consequently, species-related differences in soil pools of calcium and potassium could be offset by leaving branches and tops on site at harvest, or by recycling ash from forest fuels. (In Sweden, when branches and tops are harvested they are used for direct energy production. Bark and parts of the stemwood are also used as fuels.) However, differences in soil pools of magnesium have little to do with differences in nutrient uptake and are therefore more difficult to offset by nutrient recycling measures. On the other hand, magnesium budgets seem less unbalanced than calcium and potassium budgets.

The level of base saturation of the mineral soil was very low (Eriksson & Rosén 1994), and acid deposition has been high (Table 3). It is possible that soils under the two species with high calcium and potassium uptake, Norway spruce and grand fir, have not been able to buffer the acid deposition by cation exchange to the same degree as soils under silver fir and Japanese larch during this period (i.e., leaching water has been more acidic under Norway spruce and grand fir). Perhaps, at a site with less acid deposition, the cation-depletion effect of leaching would have been smaller and the differences in soil pools would have been larger between species with low and high nutrient uptakes. In a tree species comparison in Minnesota (Alban *et al.* 1978), there was a more pronounced inverse relationship between nutrient pools in biomass and soil than at Susegården.

Effects on the long-term cation budgets also depend on conditions that occur after clearfelling. For example, differences in nitrogen status of the soil, pH, or mineralisation rates might cause different rates of nitrification and thus nitrate leaching, which can have a strong influence on cation leaching rates (Homann *et al.* 1992).

Factor Evaluation

According to the PROFILE model, the weathering rates in this soil are only slightly influenced by nutrient uptake rates (compare Norway spruce with Japanese larch uptake in Table 7) and dry deposition rates (compare Norway spruce with Low deposition in Table 7). Thus, for these examples the differences in uptake rates and dry deposition correspond almost directly to differences in budget residuals (BR).

TABLE 7–Net nutrient uptake (U), deposition (D), PROFILE calculated weathering (W), and budget residuals (BR) of calcium, magnesium, and potassium for four forest systems that differ from the basic calculations for Norway spruce in one aspect each: "Japanese larch uptake" with net nutrient uptake for Japanese larch instead of for Norway spruce; "Low deposition" with the lower deposition calculated for pine and deciduous stands instead of the higher (Table 5); "+10% moisture" with 10% higher average soil moisture levels; and "High DOC" with, on average, four times as high DOC in the soil solution. BR is the sum of change in soil pool (CSP) and leaching (L).

		U	D	W	BR (CSP+L)
		kg/ha/year			
Calcium	Norway spruce	13.8	5.2	3.9	–4.7
	Japanese larch uptake	4.2	5.2	3.8	4.8
	Low deposition	13.8	4.0	4.0	–5.8
	+10% moisture	13.8	5.2	4.3	–4.3
	High DOC	13.8	5.2	4.2	–4.4
Magnesium	Norway spruce	2.5	3.9	1.6	3.0
	Japanese larch uptake	1.9	3.9	1.6	3.6
	Low deposition	2.5	3.1	1.7	2.3
	+10% moisture	2.5	3.9	1.8	3.2
	High DOC	2.5	3.9	1.8	3.3
Potassium	Norway spruce	8.1	3.1	2.4	–2.6
	Japanese larch uptake	6.7	3.1	2.3	–1.3
	Low deposition	8.1	2.5	2.5	–3.1
	+10% moisture	8.1	3.1	2.6	–2.3
	High DOC	8.1	3.1	2.4	-2.6

The silver fir stands grew slowly and have therefore been lower in height than surrounding stands during the entire period. The Japanese larch stands have had an average rate of growth similar to that of Norway spruce and grand fir, but since the Japanese larch stands were thinned more often and more severely, they have been periodically less dense than stands of the other three species. Only Japanese larch had a well-developed field understorey and, moreover, Japanese larch is a deciduous species that lacks a green crown during wintertime. Therefore, it is likely that if dry deposition differed significantly between species, silver fir and/or Japanese larch would have been the species that intercepted the least dry deposition. Because of lower interception and transpiration, soils in silver fir and/or Japanese larch plots may have had higher moisture levels and thus higher weathering rates. The weathering rate is assumed to be proportional to soil moisture saturation in the PROFILE model (compare Norway spruce with 10% higher soil moisture in Table 7). Consequently, for this site it seems probable that a lower cation input from dry deposition for one species relative to another could be partly offset by higher weathering rates. Considering the medium-coarse soil texture and the relatively high precipitation at the Susegården site, it is highly unlikely that differences in average soil moisture levels between species have exceeded 20% in the mineral soil.

We were unable to find information about species-related differences in soil solution DOC concentrations or types of organic acids produced. Since the amount of humus under the various species differed (Eriksson & Rosén 1994), DOC concentrations and types of organic acids in the soil water may have differed as well. In a laboratory experiment, it was shown that silicate weathering rates in natural silt were about 2.5 times higher in a soil water with natural organic acids than in distilled water at the same pH (Lundström & Öhman 1990). However, there were only slight differences in silicate weathering between mor extract, natural streamwater, and peat extract with DOC concentrations of 200, 29, and 36 mg/ℓ, respectively. These results do not support the hypothesis that amounts and types of organic acids strongly determine weathering rates in forest ecosystems.

CONCLUSIONS

For the Susegården site, the analysis indicated that species-related differences were larger for nutrient uptake and/or leaching of calcium, magnesium, and potassium than for weathering. Species-related differences in soil pools of calcium and potassium could be offset by leaving branches and tops on site or by recycling wood ash from residue fuels, although these measures would not offset differences in soil magnesium pools. However, input-output budgets of magnesium seemed to balance better than those of calcium and potassium at this site.

We believe the limitations of this study underline the need for more complete base cation budget studies when comparing long-term effects of different forest management systems. To obtain a complete budget comparison in a normal plot experiment, it is preferable that all factors of the base cation budget should be studied. Biomass and soil pool changes as well as wet and dry deposition can be determined directly by regular sampling and analysis. For practical reasons, leaching cannot be measured continuously in a plot experiment with trees. A comparison between treatments can be obtained by using the sub-pressure lysimeter method. Total leaching losses can be estimated if determinations of average ion concentrations are combined with runoff calculations using a hydrological model. For this purpose, there is an advantage in determining water-balance-related parameters through field measurements (e.g., precipitation, throughfall, soil moisture variations). If reliable determinations of nutrient uptake, soil pool changes, total deposition, and leaching can be obtained, weathering rates and rate differences can be estimated from budget calculations. Still, it would be better if an independent estimate of actual weathering rates could be obtained from an analytical model, such as PROFILE, since comparisons could then be made between field determinations/ estimations and budget calculations of all factors. When weathering rates are calculated with a model, field measurements of important parameters that might differ between treatments are preferable. Again, measurements of water-balance-related parameters should be given high priority. Factors such as carbon dioxide pressure and amounts and types of organic and other acids prevailing in the soil solution and soil temperature could also be important.

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