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Assessing soil calcium depletion following growth and harvesting of Sitka spruce plantation forestry in the acid sensitive Welsh uplands.

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Abstract

A simple mass balance has been used to estimate soil calcium depletion during the growth of a 50 year old Sitka spruce crop on acid, base-poor peaty podzol soils in upland Wales. Growth of the crop will deplete the soil calcium reserve by an amount (205 kgCa ha⁻¹) approximately equivalent to the exchangeable calcium pool to the bottom of the profile and equal to 14% of the total soil calcium reserve to the bottom of the B horizon. Despite these predictions, measurements of exchangeable calcium show no differences beneath mature forest and acid grassland, implying that i) weathering rates in forest soils are greater than long-term estimates and predictions by the PROFILE soil chemistry model ii) the trees can access other sources of calcium or iii) there are significant errors in the mass balance. Following stem-only harvesting, growth of a 50 year old second rotation crop will lead to further depletion of soil calcium, but this amount (79 kgCa ha⁻¹), is less than for a second rotation crop following whole-tree harvesting (197 kgCa ha⁻¹). After the first crop, stem-only harvesting would allow a further 18 rotations before depletion of the total calcium reserve to the bottom of the B horizon. Whole-tree harvesting would allow for seven rotations after the first crop. These calculations assume that all sources of calcium are equally available to the crop. This can only be resolved by dynamic modelling of the calcium cycle at the ecosystem scale based on appropriate field measurements. The potential for significant soil acidification is therefore greater following whole-tree harvesting and, in line with current recommendations (Nisbet *et al.*, 1997), this technique should probably be avoided on acidic, nutrient-poor soils unless remedial measures are included to enhance the soil base cation status.

Introduction

There is widespread concern over the potential for nutrient depletion following repeated tree harvesting and potential problems have been identified from the tropics (eg, Bruijnzeel, 1990) and particularly from the United States (Smith *et al.*, 1986; Johnson and Todd, 1987; Johnson *et al.*, 1988; Hornbeck *et al.*, 1990). The significance of nutrient removal in harvest products varies from nutrient to nutrient and with harvesting regime (Morris and Miller, 1994). In the UK there are unlikely to be any major effects of repeated harvesting on nitrogen status and availability as inputs of nitrogen from the atmosphere more than compensate for losses at harvest (Stevens *et al.*, 1993). In contrast, potential problems have been identified with phosphorus, potassium and/or calcium depletion (Carey, 1980; Anderson, 1985; Stevens *et al.*, 1988; Goulding and Stevens, 1988). For calcium, the overall balance between losses from biomass removal at harvesting and inputs from atmospheric deposition and weathering are likely to prove crucial to the long-term sus-

tainability of second and subsequent conifer crops growing on acid upland soils with a low calcium content. Significant depletion of the soil calcium reserve will also have important implications for soil and stream water acidification (Berden *et al.*, 1987).

One approach to the assessment of long-term nutrient depletion is by complete characterisation of the nutrient cycle through a combination of measurement and dynamic modelling (Morris and Miller, 1994; Currie *et al.*, 1996). In this paper however, a simpler approach has been adopted in which a rotation length calcium budget for Sitka spruce growing in the Welsh uplands has been calculated utilising data from a chronosequence of 20 stands ranging in age between 10 and 55 years (Stevens *et al.*, 1994). The calculations have been supplemented by information on tree biomass calcium content taken from the literature (Miller *et al.*, 1993, Carey and O'Brien, 1979). For ease of calculation with respect to the available data, the rotation length has been set at 50 years.

Methods

A simple mass balance approach has been taken in order to assess the effects of forest growth and harvesting on the soil calcium pool. The mass balance has been calculated with respect to inputs and outputs from the soil within the standing forest. In the first rotation, the forest floor is considered as a separate pool distinct from the soil profile in order to evaluate changes in soil calcium status compared to non-forested land. The effects of harvesting and growth of the second rotation crop are considered separately. Thus for the standing forest, the calcium budget for a 50 year rotation can be expressed as a mass balance equation:

$$Ca_{\text{dep}} + Ca_{\text{w}} + Ca_{\text{veg}} - Ca_{\text{bio}} - Ca_{\text{ff}} - Ca_{\text{le}} = P_{\text{Ca}} \quad (1)$$

where:

Ca_{dep} = wet + dry calcium deposition to the forest over 50 years

Ca_{w} = accumulated weathering input of calcium

Ca_{veg} = release of calcium from pre-existing ground vegetation

Ca_{bio} = calcium accumulated in tree biomass at 50 years of age

Ca_{ff} = calcium accumulated in forest floor after 50 years

Ca_{le} = total calcium leaching losses from below the rooting zone

P_{Ca} = change in soil calcium pool over 50 years

Units = kg ha^{-1}

ATMOSPHERIC DEPOSITION

The chronosequence of Sitka spruce stands were located as five groups of four sites in each of Beddgelert, Dyfnant, Dyfi, Hafren and Twyi forest areas in north and mid-Wales. Within each group, precipitation chemistry was sampled at a site on adjacent open moorland using a continuously open collector which was emptied monthly. Each of the forest sites was instrumented with throughfall collectors which were also emptied monthly (Stevens *et al.*, 1994). Calcium deposition to the moorland sites was calculated as the annual sum of the product of monthly bulk precipitation chemistry and monthly rainfall. Total calcium deposition to the spruce canopy of each forest stand was estimated using the simple ratio technique proposed by Sverdrup *et al.*, (1990), in which it is assumed that sodium is unaffected by canopy leaching and ion exchange processes, so that a scaling factor for dry deposition can be calculated as the ratio of sodium inputs in throughfall to those in wet deposition. Total deposition of calcium to each spruce stand was estimated by multiplying the wet deposited calcium by the sodium scaling factor (Reynolds, 1996). There is a significant non-seasalt component to calcium deposition in Wales (Donald and Stoner, 1989) so that it is possible that calcium inputs are underestimated by a scaling technique which relies on an ion derived almost entirely from seasalts. The extent of this underes-

timation is unknown. An alternative estimate of deposition is provided by calcium in throughfall, however this contains an unknown canopy leaching component of calcium cycled through the tree and will thus overestimate deposition inputs. A recent study of 12-year-old Sitka spruce in which atmospheric inputs of calcium were modelled independently indicate that about thirty percent of the calcium in throughfall is derived from canopy leaching (Reynolds *et al.* in press).

Analysis of variance of the calcium deposition data showed that there were no statistically significant effects of either age or site location. Therefore the arithmetic mean deposition to the 20 stands was considered to be the best estimate of annual deposition to the trees between 10 and 50 years of age (Table 1). Annual deposition from years one to nine was estimated by ramping the average annual deposition to the five moorland sites (Table 1) up to the average forest figure to account for the effect of the increasing forest canopy.

Table 1. Mean (and standard deviation) of calcium deposition and leaching losses for moorland and forest sites in upland Wales.

	Atmospheric deposition $\text{kg ha}^{-1} \text{yr}^{-1}$	Leaching loss $\text{kg ha}^{-1} \text{yr}^{-1}$
Moorland	3.97 (0.55)	4.95 (1.66)
Forest	6.35 (1.64)	4.60 (2.84)

WEATHERING

It was assumed that the forest calcium cycle would be calculated for trees growing on stagnopodzol soils developed from Lower Palaeozoic greywackes. The input of calcium from weathering was estimated for the soil profile using data from Plynlimon and Beddgelert giving the rate of calcium depletion over the last 10,000 years, relative to the stable mineral components zirconium and rutile (Langan *et al.*, 1995). The figure ($0.2 \text{ kg ha}^{-1} \text{yr}^{-1}$; Table 2) is very close to the average weathering rate predicted by the PROFILE model (Sverdrup and Warfvinge, 1993) but is much smaller than values calculated from catchment mass balance ($16.4 \text{ kg ha}^{-1} \text{yr}^{-1}$) and from applications of the MAGIC model to Welsh upland catchments ($13.7 \text{ kg ha}^{-1} \text{yr}^{-1}$). The discrepancy between soil and catchment based estimates is indicative of contributions beneath the soil profile from deeper weathering sources within the drift and bedrock which may, in some cases, be influenced by the presence of rapidly weathering carbonate minerals. This source of weathering has been confirmed by the presence of highly alkaline, base cation enriched groundwater in many upland Welsh catchments underlain by Lower Palaeozoic shales and mudstones (Neal *et al.*, 1997).

Table 2. Summary of calcium weathering rates for Lower Palaeozoic mudstones and shales in upland Wales.

Method	Weathering rate kg ha ⁻¹ yr ⁻¹	Reference
Soil profile element depletion (2 sites)	0.20	Hornung <i>et al.</i> , 1987; ITE unpublished data
PROFILE model (3 sites)	0.21	Reynolds <i>et al.</i> , 1995; Reynolds <i>et al.</i> , in press
Catchment mass balance (4 sites)	16.37	Reynolds <i>et al.</i> , 1987; Reynolds <i>et al.</i> 1997
MAGIC model (3 sites + 1984 Welsh regional acid waters survey)	13.67	Whitehead <i>et al.</i> , 1988a Whitehead <i>et al.</i> , 1988b Jenkins and Wright 1992 Jenkins <i>et al.</i> , 1990

PRE-EXISTING VEGETATION

The pre-existing moorland vegetation is gradually shaded out as the forest closes canopy and it therefore provides a potential source of calcium to the first forest rotation. The quantity of calcium present in the moorland vegetation was estimated using biomass data from open moorland adjacent to Aber forest in north Wales (Emmett *et al.*, 1997) combined with measurements of calcium content taken from a site with similar vegetation at Llanbrynmair in mid-Wales (Reynolds *et al.* in press). For the purposes of the budget calculation, it was assumed that all the vegetation will have decomposed during the 50 years releasing all the calcium.

BIOMASS ACCUMULATION

Calcium data for the above-ground components of fifty year old Sitka spruce have been published by Miller *et al.*, (1993) for Scotland and by Stevens *et al.*, (1988) for Wales and these results have been used in this budget. Total above ground biomass calcium content measured in the two studies was very similar at 281 and 279 kg Ca ha⁻¹ respectively so an average value of 280 kgCa ha⁻¹ has been used for this budget. From the two studies, an average of 58% of the above ground biomass calcium is held in the stem (wood + bark) and 42% in needles and twigs (Table 3).

Few data are available describing nutrient pools in below ground biomass of Sitka spruce. From data published by Carey and O'Brien, (1979) for 33 year old, unthinned Sitka spruce, coarse woody roots account for 15% and fine roots about 1% of the total tree biomass on a dry weight basis. The contribution of roots to total biomass probably changes as the stand develops but, as no information is available about this effect it was assumed that the proportions remained constant with age. Assuming that the above ground biomass of 50 year old Sitka spruce is 300 tonne ha⁻¹ (Miller *et al.*, 1993), then total tree biomass can be estimated as 357 tonne ha⁻¹ of which 53.5 and 3.5 tonne ha⁻¹

will be associated with coarse and fine roots respectively. In the absence of any specific calcium data for these components, it was assumed that the calcium concentration in woody roots was the same as that published for stem wood by Miller *et al.*, (1993), whilst the calcium content of fine roots was assumed to be similar to that of needles. From this, 24 kg Ca ha⁻¹ is estimated to be held in coarse woody roots and 11 kg Ca ha⁻¹ in fine roots (Table 3).

FOREST FLOOR

As the 50 year old forest stands in the chronosequence were all first rotation, the calcium accumulated in the forest floor over the rotation was measured directly by sampling L and F horizon material at each 50 year old site (Emmett *et al.*, 1993). This removed the need to calculate the accumulated calcium as the difference between calcium returned in litter and that mineralised from the forest floor. The forest floor calcium at 50 years represents the net change to this store over the period of forest development and assumes that any calcium mineralised from litter during forest growth is accounted for either by biomass uptake or in leaching losses.

Table 3. Calcium held in the various biomass components of 50 year old Sitka spruce. Values calculated from data published by Carey and O'Brien (1979); Stevens *et al.* (1988) and Miller *et al.* (1993).

Biomass component	Calcium pool (kg Ca ha ⁻¹)
Stem (wood + bark)	162
Needles & twigs	118
Total above ground	280
Coarse roots	24
Fine roots	11
Total below ground	35
Total tree	315

Table 4. Calcium reserves in peaty podzol soils planted with Sitka spruce in north and mid-Wales.

Site	Forest age (yr)	Profile depth (m)	Depth to base of B horizon (m)	Total Ca to bottom of profile (kg ha ⁻¹)	Total Ca to base of B horizon (kg ha ⁻¹)	Exchangeable Ca to bottom of profile (kg ha ⁻¹)	Exchangeable Ca to base of B horizon (kg ha ⁻¹)
Plynlimon	40	0.77	0.37	3660	1591	270	173
Beddgelert	55	0.75	0.46	2299	1389	141	112
Llanbrynmair	12	na	0.65	na	1141	na	na
Llyn Brianne	30	0.81	0.55	2519	1557	278	197
Mean (std dev)		0.78 (0.02)	0.51 (0.10)	2826 (597)	1420 (178)	230 (63)	161 (36)

na: no data available

LEACHING LOSSES

Leaching losses from the forest and moorland sites were calculated as the product of the modelled annual flux of percolating water (Emmett *et al.*, 1993) and the annual volume-weighted average of monthly B horizon soil water calcium concentrations sampled using suction lysimeters (Stevens *et al.*, 1994). Suction lysimeters sample soil solution from the bulk of the soil matrix and this may not be of the same chemical composition as water moving rapidly through macropores in response to storm events. Further, the lysimeters give a time-integrated sample over the measurement period. It is uncertain, therefore, the extent to which the suction lysimeter samples represent the chemistry of water freely percolating through the soil. However, for much of the year the forest soils are very wet and there is likely to be good connectivity between the sampled and percolating water.

The flux of percolating water for each forest site was calculated from an evaporation model published by Calder, (1990) in which total evaporation was predicted from the sum of interception loss plus transpiration. The transpiration term was calculated from daily Penman evapotranspiration estimates based on climatological data collected in each forest area (Emmett *et al.*, 1993), multiplied by the transpiration fraction β (Calder, 1990) and the fraction of time for which the canopy was dry (Calder and Newson, 1979). Interception loss was calculated as the difference between rainfall and throughfall measured at each site.

Analysis of variance performed on leaching data from the forest sites showed no statistically significant effects of either forest age or site location. Therefore the arithmetic mean leaching loss for the 20 forest stands was considered to be the best estimate of annual leaching losses from stands between 10 and 50 years of age (Table 1). Annual leaching losses from the stands between one and nine years old was estimated by ramping the average annual leaching loss from the five moorland sites (Table 1) down to the average forest figure.

SOIL CALCIUM RESERVES

The total reserves of calcium and the amount held in exchangeable form have been calculated for acid peaty podzol soils beneath Sitka spruce of different ages at sites in north and mid-Wales (Table 4). This soil is developed from base-poor Lower Palaeozoic mudstones and shales and is a common forest soil type throughout the uplands of Wales. The soil exchangeable calcium reserves for Plynlimon (Table 4) were calculated using chemical data from Reynolds *et al.*, (1988) whilst estimates of total soil calcium used unpublished total silicate analyses from the British Geological Survey. For Beddgelert, soil exchangeable and total calcium analyses were from unpublished ITE and INRA (Nancy) sources respectively. Bulk densities and soil depths were measured at the sites using standard techniques (Hodgson, 1976). Soil chemistry, horizon depth and bulk density data for Llanbrynmair and Llyn Brianne were taken from Reynolds *et al.*, (in press) and Soulsby, (1991) respectively. Total calcium chemistry for each horizon at Llyn Brianne came from Kennedy, (1997)

Results and discussion

The calcium balance sheet with respect to the soil for a 50 year old standing crop of Sitka spruce is shown in Table 5. The balance shows that to grow the forest stand and develop the forest floor required depletion of the soil calcium pool by 205 kg Ca ha⁻¹. This is of the same order of magnitude as the exchangeable calcium pool to the base of the C horizon of the stagnopodzol soil to a depth of about 80 cm (Table 4) and is equivalent to 7% of the total calcium pool to this depth. However, from detailed soil profile descriptions at Plynlimon, Beddgelert Forest and Llyn Brianne, Sitka spruce roots rarely penetrate below the bottom of the B horizon at a depth of about 50 cm (Reynolds *et al.*, 1988, Soulsby, 1991). To this depth, the exchangeable calcium pool is 161 kg Ca ha⁻¹, or 11% of the total calcium (1420 kg Ca ha⁻¹). If the calcium accounted for by soil

depletion is derived from the exchangeable cation pool and mineral weathering rates are assumed to be constant at the low value of c. $0.2 \text{ kg Ca ha}^{-1} \text{ yr}^{-1}$, then a large decline in exchangeable calcium should occur during forest development. However data from Plynlimon indicate that this is not the case, as the exchangeable calcium reserve in the forest soils (173 kgCa ha^{-1}) is only slightly smaller than that measured to the same depth in stagnopodzol soils under unimproved grassland ($193 \text{ kg Ca ha}^{-1}$). A similar result was obtained at Beddgelert forest in North Wales, where ITE unpublished data show no differences in exchangeable calcium between stagnopodzols beneath a fifty year old first rotation spruce stand and those under adjacent semi-natural acid grassland. One explanation for this is that the presence of the forest has increased mineral weathering rates above long-term values and those predicted by modelling of soil chemistry, thereby allowing the exchange complex to be maintained whilst calcium is taken up in to biomass. In a review of changes in soil chemistry beneath Swedish forests, Binkley and Hogberg, (1997) come to a similar conclusion. There are a number of mechanisms by which this could occur including i) the effects of pre-planting cultivation and drainage in breaking up the soil and increasing access for water, ii) changes in the nature and acidity of accumulated organic matter, iii) increases in soil pCO_2 accompanying the enhanced rates of organic matter mineralisation in forest compared to moorland soils (Emmett *et al.*, 1997) and iv) increased exploration of the soil by tree roots compared to moorland vegetation. A further possibility is that under dry conditions, trees may cause upward movement of shallow 'groundwater' which is known to be enriched in calcium (Neal *et al.*, 1998) and there may be lateral movement of such water into down slope sites.

An important caveat attached to the interpretation of mass balance calculations is the size of the possible errors associated with each of the terms. Atmospheric deposition and leaching comprise two of the largest terms in the equation and both are associated with major uncertainties. Averaged over 50 years, the imbalance in calcium amounts to approximately $4 \text{ kg ha}^{-1} \text{ yr}^{-1}$ which is of the same order as the annual deposition and leaching rates. An estimate of the variation in these is given in Table 1. The effect of this variation on the calcium budget can be illustrated by recalculating the mass balance using 'best' and 'worst case' scenarios of the atmospheric deposition plus/minus one standard deviation combined with the leaching loss minus/plus one standard deviation. This gives $\Delta\text{P}_{\text{Ca}}$ values of +5 and $-414 \text{ kgCa ha}^{-1}$ respectively. Thus, with the largest atmospheric inputs and lowest leaching losses, the calcium budget is approximately in balance.

FOREST HARVESTING AND THE SECOND ROTATION CROP

Stem-only harvesting is the most commonly practised technique in UK upland forests in which branches,

needles and roots are left on site whilst only the stem (wood + bark) are removed. Whole tree harvesting, in which all the above ground material is removed from the site, is much less common although it has been used in some Welsh forest districts. Replanting with Sitka spruce seedlings normally follows within two years of whichever harvesting method is used.

The removal of calcium in harvest products has been discussed in previous UK studies (Stevens *et al.*, 1988; Miller *et al.*, 1993), however these have tended to focus on *site* nutrient depletion and have not fully considered the effects on the soil. Depending on the technique used, several potential sources of calcium remain on site which can offset the drain on the soil reserve caused by growth of the second rotation crop. Following stem-only and whole-tree harvesting, calcium accumulated in the forest floor (44 kgCa ha^{-1} ; Table 5) and in the below ground biomass (35 kgCa ha^{-1} ; Table 3) is potentially available to the next crop and amounts to 79 kg Ca ha^{-1} . If stem-only harvesting is used, this can be supplemented by a further $118 \text{ kg Ca ha}^{-1}$ from the twigs and needles left on site (Table 3). Assuming that 1) there are no accelerated leaching losses of calcium at harvesting, 2) that the nutrient dynamics of the second crop are the same as those of the first with respect to atmospheric deposition, weathering rates, leaching losses, biomass and forest floor accumulation and 3) that all the calcium accumulated in forest floor, forest debris and below ground biomass is available to the next rotation, then the net change in the soil calcium pool after 50 years of second rotation forest following stem-only harvesting would be -79 kgCa ha^{-1} . In the absence of felling debris, the net change in the soil pool after 50 years of forest growth following whole-tree harvesting would be $-197 \text{ kgCa ha}^{-1}$.

These predictions of soil calcium depletion rest crucially upon the stated assumptions. Data from experimental studies at Beddgelert forest (Stevens *et al.*, 1995) provide some insight into the short-term effects of harvesting on

Table 5. Soil calcium balance sheet for a first rotation, 50 year old standing crop of Sitka spruce growing on peaty podzol soils in the Welsh uplands.

Inputs	Flux (kg Ca ha^{-1})
Atmospheric deposition	300
Soil mineral weathering	10
Release from pre-existing ground flora	71
Total input to soil	381
Outputs	
Leaching losses	227
Tree biomass	315
Forest floor accumulation	44
Total output from soil	586
Balance $\Delta\text{P}_{\text{Ca}}$	-205

Table 6. Calcium fluxes to and from the soil over a period of 4 years following harvesting of Sitka spruce at Beddgelert forest (summarised from Stevens *et al.* 1995).

	Stem-only harvesting kgCa ha ⁻¹	Whole tree harvesting kgCa ha ⁻¹
External inputs to soil		
Rainfall	29	29
Leached from brash	40	0
Total inputs	69	29
Outputs from soil		
Re-vegetation	9	14
Leaching losses	79	32
Total losses	88	46
Inputs-Outputs	-19	-17

the soil calcium economy. Calcium leaching from the felling debris at Beddgelert four years after harvesting (Table 6) was equivalent to 31% of the total amount present in brash (128 kgCa ha⁻¹; Stevens *et al.*, 1995) and it appears that the majority of this calcium was lost from the site. A further 10 kgCa ha⁻¹ was lost from the soil to the bottom of the surface organic layer (Oh horizon), presumably from mineralisation of fine roots and / or forest floor material. The re-establishing vegetation retained 9 kgCa ha⁻¹ and this would potentially be available to the next crop. In contrast, calcium leaching losses following whole-tree harvesting were only marginally greater than rainfall inputs with only 3 kgCa ha⁻¹ being mobilised and lost from the soil organic and litter layers. Re-establishing vegetation retained 14 kgCa ha⁻¹. Thus whilst approximately the same amounts of calcium were mobilised from the soil under the two harvesting treatments, approximately 50% of this calcium was lost from the stem-only harvested site because there was less retention in the re-establishing vegetation. However, at the end of four years, the pool of calcium held in felling debris and re-established vegetation amounted to 97 kgCa ha⁻¹ in the stem-only harvest site, compared to 14 kgCa ha⁻¹ in the whole-tree harvest site where there was no felling debris present.

EFFECTS OF FOREST FERTILISATION

On most upland soils in Wales, crops would generally respond to phosphate fertiliser applied at or around year eight (Taylor, 1991) and rock phosphate is now the main type of fertiliser used. Although the chemical composition is variable, rock phosphate (Gafsa phosphate) typically contains 37% calcium by weight (Edwards, personal communication, 1998). The recommended application rate to supply 60 kg ha⁻¹ of phosphorus is 450 kg ha⁻¹ of rock

phosphate which would add 166 kgCa ha⁻¹ to the forest. Thus, as noted by Nisbet *et al.*, (1997), rock phosphate provides a relatively large potential source of calcium to the soil, equivalent to about 80% of the depleted calcium in the first rotation, assuming that the fertiliser calcium is completely available. For the second rotation following stem-only harvesting, calcium from rock phosphate would be more than adequate to offset the drain on soil reserves, whilst it would offset about 84% of the depleted calcium following whole-tree harvesting. Whilst the soil calcium mass balance would appear to be satisfied by calcium phosphate additions, the key issue is the extent to which this potential calcium source is actually available to either the growing crop and/or the soil exchange complex. This remains an area of uncertainty which needs to be resolved. It is interesting to note, that Forestry Commission records show that no rock phosphate was applied to the parts of Beddgelert forest sampled for soil exchangeable calcium content. In this case, the lack of evidence for depletion in soil exchangeable calcium, inferred from a comparison with adjacent grassland soils, cannot be attributed to calcium from rock phosphate.

Conclusions

The simple rotation-length mass balance approach indicates that development of a 50 year old stand of Sitka spruce on acid upland soils in Wales will deplete the soil calcium reserve by an amount approximately equivalent to the exchangeable calcium pool. This amounts to 14% of the total soil calcium reserve to the bottom of the main rooting zone (base of B horizon). Despite these predictions, measurements of exchangeable calcium show no differences beneath mature forest and acid grassland, implying that i) weathering rates in forest soils are greater than long-term estimates or model predictions ii) the trees can access other sources of calcium, iii) there are significant errors in the mass balance, or iv) that rock phosphate may have been added to the stands and is providing a significant calcium input to the forest. A central uncertainty to the mass balance approach is that it assumes that all sources of calcium are equally available to the crop. This can only be resolved by dynamic modelling of the calcium cycle at the ecosystem scale based on appropriate field measurements.

Forest harvesting techniques have a major influence on the soil calcium balance for the second rotation crop. Assuming that the calcium in the organic remains (roots, forest floor, needles and branches) of the first rotation is fully available to the second crop, depletion of soil calcium by growth of the second crop is much smaller following stem-only harvesting compared to either whole-tree harvesting or the development of the first crop. After the first crop (felled at 50 years), stem-only harvesting would allow a further 18 rotations before depletion of the total calcium reserve to the bottom of the B horizon. Whole-tree

harvesting would allow for seven rotations after the first crop. The potential for significant soil acidification, defined as a depletion of the base cation store, is therefore much greater following whole-tree harvesting. In line with current recommendations (Nisbet *et al.*, 1997), this technique should probably be avoided on acidic, nutrient-poor soils unless remedial measures are included to enhance the soil base cation status, for example, by addition of rock phosphate fertiliser.

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