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ORIGINAL PAPER

Assesing nutrient sustainability of forest production for different tree species considering Ca, Mg, K, N and P at Björnstorp Estate, Sweden

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Abstract An assessment of nutrient sustainability has been done for stands of European beech, Sycamore maple, European oak, Norway spruce, Larch, Grandis fir and Douglas fir at Björnstorp Estate in southern Sweden. To estimate the nutrient sustainability, mass balance was calculated with respect to Ca, Mg, K, N and P. The release from mineral weathering was calculated using the PROFILE model. The leaching has been estimated from observed soil water concentrations and nutrients removed by harvest from projected production. The results indicate that the planned production is on the limits of sustainability and sometimes in excess of it. The stands will overuse Ca, sometimes also Mg, K and P, if all growth is harvested. Soil acidification is still progessing at Björnstorp Estate, and soil depletion is the result of this. The estimated sustainable yield and the mass balances suggest that the leaching rate is the most uncertain factor for assessing sustainability. Different types of critical loads were investigated, including a new type, based on no excess acidity in the system. The calculations stress the importance of reducing the acid deposition and that nutrient sustainable management must be included in forest management.

Keywords Sustainability · Forest production · Acidification · Nutrients · Norway spruce · European Beech · European larch · Sycamore maple · Grandis fir · Douglas fir · European oak

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Introduction

Background

With regard to forest management, it is important to bring to general attention the necessity for the forest system to be sustainable as a production system of biomass. Sustainable nutrient management is not necessary so long as forest harvests are low compared with the production capacity. At present, whole-tree harvest is already practised in a large part of southern Sweden, and every year large volumes of biomass are removed, which implies that the nutrient resources of the soil are quickly being consumed (Sverdrup and Rosen 1998; Thelin et al. 2002; Akselsson et al. 2005; Sverdrup et al. 2005a, b). The mineral nutrients Ca, Mg, K and P come from soil weathering and from deposition, and the capacity of the weathering rate of soil minerals is limited. Since the beginning of industrialization in the middle of the nineteenth century, industrial activities have resulted in increasing emissions of nitrogen and sulphur, increasing the atmospheric deposition of acidifying substances over Europe. This has caused a significant acidification of the soil in large areas of Europe. Soil acidification interferes with uptake processes, the absorption of base cations in the soil, decomposition of organic matter and the cycling of N. Trees have prehistorically evolved to be adapted to a situation where nitrogen is often limited, so when more N is available through deposition, growth increases and other nutrients may become, in the long term, growth limiting (Warfvinge et al. 1992a, 1996; Sverdrup et al. 1995, 1996; Stjernquist et al. 2002; Makarov and Kiseleva 1995). Acid deposition causes an increase of the soil solution concentration of Al and nutrients such as Ca, Mg, K, leading to increased losses (Alveteg et al. 1996; Akselsson et al. 2005; Sverdrup and Rosen 1998). This implies a temporary increase in available nutrients for the vegetation, which permits high growth rates, sometimes stimulated by extra N inputs. Elevated concentrations of Al disturb root function of trees and impede uptake of essential ions (Sverdrup and Warfvinge 1993a; Stjernquist et al. 2002; Persson and Majdi 1995; Thelin et al. 2002).

The aim of this study was to assess the nutrient sustainability in forest stands of different tree species at Björnstorp Estate with respect to the main bulk mineral nutrients Ca, Mg, K, N, P. In order to do this, mass balances for Ca, Mg, K, N, P and acidity were calculated. We wanted to quantify how much the acidification of the soil interferes with the sustainability at Björnstorp Estate and to explore the magnitude of cost that could be associated with it.

Theory

Methods

The method used is to combine integrated soils models with mass balance calculations. Figure 1 shows the workflow adopted in this assessment. The method is a combination of hand calculations, using simple mass balance equations, combined with a biogeochemical model to estimate the weathering input term. In this assessment, the PROFILE model plays a prominent role. The PROFILE model is a biogeochemical model, which specializes in calculating chemical weathering of minerals in the soil, avoiding calibration in operational use (Sverdrup and Warfvinge 1988a, b, c, 1993, 1995; Warfvinge and Sverdrup 1992). The model is an integrated soil chemistry model that calculates steady-state chemistry under input condition. Inside the model the processes have mutual feedbacks on each other. The dynamic version of the model, SAFE, and its successor, ForSAFE-VEG, can be used to assess the evolution of the chemical state of a soil over time (Belyazid et al. 2006). The mass balance model used for the final assessments rests on the continuity principle, a universal principle recognized since antiquity as one of the essential underpinnings of existence and reality.

The mass balances

Mass balance were calculated for all nutrients separately. Taking deposition and weathering as the sources of nutrients, and uptake and leaching as the sinks, the mass balance for each nutrient becomes (Sverdrup and Rosen 1998; Thelin et al. 2002; Holmqvist et al. 2002; Hellsten 2004):

$$\text{diff} = W + D - L - U$$

where U is the uptake, L the leaching, W the release of K, Mg, Ca and P caused by chemical weathering and D the deposition in units of kEq ha^{-1} year^{-1}. Ion exchange and release from decomposition of organic matter were omitted as they are not long-term sustainable sources. The system is sustainable when the long-term stock of nutrients in the soil is not consumed, implying that the average value of the deficit is zero and the chemical status of the soil is kept within limits they can tolerate without showing damage (Sverdrup and Warfvinge 1988a; Warfvinge and Sverdrup 1995; Sverdrup and Rosen 1998; Sverdrup and Svensson 2002, 2004; Mapping Manual 2004).

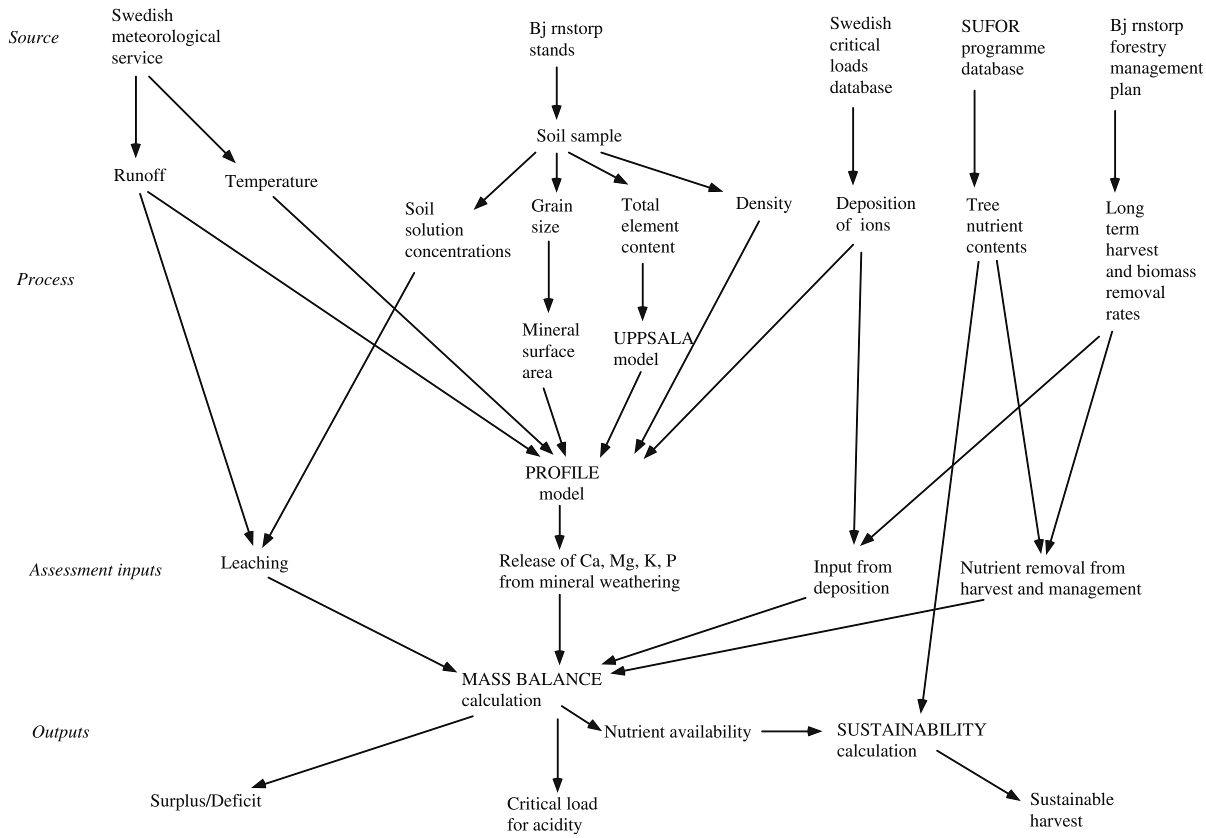

Fig. 1 Flowchart for the processing of data and input information from source to assessment outputs, including the models used internally in the process. The diagram shows the flow of information through a number of transformations and calculation steps to the assessment output

Weathering

By chemical weathering we understand the release of base cations due to chemical dissolution from primary minerals in the soil matrix and the neutralization or production of alkalinity connected to this process. Weathering is an important long-term source of inorganic nutrients for the system and an important factor for determining the chemical status of the soil. To calculate the weathering rate the PROFILE model has been applied (the model is downloadable from the net www2.chemeng.lth.se/models/). The weathering part of the model is the part that has been most thoroughly tested and validated, in tests ranging from laboratory experiments to observations under field conditions on all continents, and it has been shown to predict weathering rates with high accuracy in the range from 0.01kEq ha^{-1} $year^{-1}$ to 25 kEq ha^{-1} $year^{-1}$ (Sverdrup et al. 1992, 1995, 1997; Alveteg et al. 1998; Barkman et al. 1995; Akselsson et al. 2005). The tests have been described, evaluated and discussed since its launching in 1988 (For examples see Warfvinge and Sverdrup 1992; Sverdrup and Warfvinge 1993b, Sverdrup et al. 1992, 1995, 1997; Alveteg et al. 1998; Barkman et al. 1995, 1999; Akselsson et al. 2005; Aherne et al. 1998; Ballesta et al. 1995; Fumuto et al. 2000; Holmqvist et al. 2002; Kurz et al. 1998; Langan et al. 1996; Semenov et al. 2000). Mineralogy is derived with the UPPSALA model and field tested for Sweden and Switzerland (Warfvinge et al. 1992a; Sverdrup et al. 2002; Kurz et al. 1998; Holmqvist et al. 2002). When very accurate input data can be obtained, such as in dedicated research sites, then an accuracy of ±5% can be achieved (Warfvinge and Sverdrup 1992; Sverdrup and Warfvinge

1993b). However, in operational use, input data accuracy is significantly less, limiting the accuracy of the outputs to less than that of the inputs. In practical terms, this implies that we can estimate the weathering rate within ±15–25%, depending much on the quality of the input data (Barkman et al. 1995, 1999). The PROFILE model is set up as a series of mixed compartments, where each compartment represents a soil horizon. The weathering rate in PROFILE is calculated as the dissolution rate of specific minerals, taking into account some geophysical properties of the soil, such as mineral surface available, mineralogy and soil chemical conditions, soil water content and temperature (Sverdrup et al. 2002; Barkman and Sverdrup 1996). The weathering model is based on the transition state theory, working up the weathering rates from molecular level reaction kinetics at the solid–liquid interface (Sverdrup and Warfvinge 1988b, 1988c, 1993b, 1995; Sverdrup 1990; Warfvinge and Sverdrup 1992). Several chemical reactions for each mineral are considered. In each reaction there is one reactant promoting the rate and several components that will retard it. The reactions are considered simultaneously where the mineral surface can react with H ions, water, OH ions, carbon dioxide and dissociated organic acid ligands. The two last reactions can be inhibited by the base cations, and the two first by the base cations and Al. The action of roots and fungi are incorporated through their influence through the carbon dioxide and organic acid reactions. The total release rate by chemical weathering is calculated as the sum of the rates for each reaction in units of kEq ha^{-1} $year^{-1}$.

Leaching

Leaching of chemical components from the soil profile occurs as a consequence of water flowing through the soil profile. The leaching is dependent on water movement and the solution concentration. Leaching was calculated using:

$$L = Q * [C_i]$$

L is leaching in units of kEq ha^{-1} $year^{-1}$, Q is the runoff in units of m^3 m^{-2} $year^{-1}$ and $[C_i]$ is the annual average soil solution concentration in kEq m^{-3}. The minimum leaching is estimated from the assumptions that: (a) the trees have no uptake in winter, during a fraction of the year, and (b) the trees take up to full root efficiency E during the growth season. We get (Sverdrup et al. 2002; Thelin et al. 2002):

$$L_{\min} = ((1 - v)*(1 - E) + v)*(W + D)$$

where W is weathering rate release of the nutrient, v the fraction of the year with no uptake, E is the root efficiency of taking up available nutrients and D is the deposition input. This formula represents our best case when calculating the mass balance; the trees take up everything physically possible. Smaller leaching than this suggests that some internal process other than tree uptake is consuming the nutrient.

Deposition

Atmospheric deposition of substances includes SO_4, NO_3, Cl, NH_4, Cl, P, Mg, K, Na and Ca. Wet and dry deposition was considered when the deposition was estimated. We assumed higher dry deposition rates for conifers than for the deciduous trees (Thelin et al. 2002; Bergkvist and Folkesson 1995). The deposition was taken from the national critical loads assessment database (Mapping Manual 2004).

Uptake

Net uptake represents the removal of nutrients from the system while the difference between total and net uptake is circulated internally on a long-term basis. Uptake of nutrients by roots from soil solution is usually the most important mechanism for plant nutrition, but it can also occur through leaves. The quantity of nutrients taken up annually by plants is influenced by the availability of nutrients to the plants and the plants' nutrient requirements, which, in turn, depend upon the species and their physiological maturity. It is high in younger stands and decrease as the stand becomes more dependent on internal retranslocation of nutrients (Kimmins 1997; Stjernquist et al. 2002). In this study, the uptake to the biomass of each base cation has been estimated without any consideration for nutrient availability or soil chemistry feedback on plants. It is based on the relation between nutrient uptake U and growth, as follows (Mapping Manual 2004; Thelin et al. 2002; Hellsten 2004):

$$U = G * \rho * x$$

G is the net long-term growth rate that is to be harvested (m^3 ha^{-1} $year^{-1}$), ρ is the specific density of the harvested biomass in units of kg m^{-3} and x is the fraction of each cation in the harvested biomass per dry weight. Growth of plants is assumed to be directly proportional to nutrient uptake (Thelin et al. 2002; Holmqvist et al. 2002).

$$G = U/(\rho * x)$$

U is proportional to nutrient available on the root surface, depending on nutrient concentrations and any eventual competitors for root adsorption, such as Al of H (Sverdrup and Warfvinge 1993a). For a certain amount of N taken up by trees, a proportional amount of Ca, Mg, K and P must be taken up to create stemwood, bark or leaf. If not, only a certain amount of biomass will be created proportional to the nutrient least available, and the excess N will be excreted or it will be used for N-richer non-wood substances. If one of the essential elements for wood production decreases to a level where it becomes growth limiting, the stemwood production will also decrease (Sverdrup and Rosen 1996; Kimmins 1997).

Effects of acidification

In the soil, acidity is partly neutralized by alkalinity originating from weathering of soil minerals. However, in southern Sweden with its high deposition of air pollutants, the weathering capacity of the soil minerals is not high enough to compensate for the acid input (Mapping Manual 2004; Kurz et al. 1998; Martinsson et al. 2005; Karltun 1994). The residual acidity will compete at adsorption sites in the root membrane and cytoplasm with Ca, Mg and K; thereby, the concentration of Ca, Mg and K in the soil solution increases and the leaching of these ions increases. The function was derived from a causal mechanism (Sverdrup and Warfvinge 1993a). The equation is similar to a Michaelis–Menten type of equation with Al^{3+} and H^{+} in the saturation constant. In PROFILE, the soil acidity response is applied as:

$$U = U_0 * [BC^{2+}]^m / ([BC^{2+}]^m + k([Al^{3+}]^n + m * [H^+]))$$

U_0 is the uptake under ideal conditions and U the real uptake; m=n=1 for conifers, m=3, n=2 for deciduous trees. There is a limited capacity in the soil for neutralizing the input of acidic ions. If it is insufficient, the acidity in the soil solution increases (Sverdrup and Warfrvinge 1988a, b, 1993a, b, 1995). Positive ions in the soil, such as hydrogen ions, base cations and Al ions, are either dissolved in the soil solution or attached to the soil exchange matrix. The maximum size of this storage is equivalent to the cation exchange capacity (Kimmins 1997). The depletion of the exchange phase leads to a high soil solution concentration and, subsequently, a high leaching of the base cations. This results in long-term depletion of cation nutrients in the soil and, in later stages, damages to tree species. Trees require relatively fixed ratios of available N to base cations in order to produce needles, stems and roots. Therefore, when the trees have more nitrogen than needed due to acid deposition, but less than needed of Mg or K, damage such as defoliation, discoloration and decreased growth may happen. Decreased contents of Mg and K have been detected in spruce needles (Barkman and Sverdrup 1996; Jönsson et al. 2003; Schlyter and Anderson 1992). At present, the soils in southern Sweden accumulate large amounts of nitrogen, more than is needed for sustainable growth. From 1850 to 2000 the soil store of nitrogen has more than doubled, from 1 to 2 ton ha^{-1} to more than 5 ton ha^{-1} (Thelin et al. 1998). Anthropogenic nutrient sources such as deposition and fertilization or sinks as enhanced forest growth and harvest have changed the nitrogen-to base-cation balance. Together with a non-optimized relation between harvesting, supply from weathering and sustainability capacity for harvest indicate that the forest ecosystem is being threatened.

Critical loads of acidity

In order to establish a principle that would ensure levels of pollution that would yield a sustainable environment, the concept of critical load was developed. The United Nations Economic Commission for Europe (UN/ECE) Convention on Large Transboundary Air Pollution (CLRTAP) adopted the concept of critical load in 1988, providing the basis of future developments of international agreements on reductions of the emission of air pollutants (Barkman et al. 1995; Sverdrup et al. 1990; Sverdrup and Warfvinge 1988b, c, 1993b; Warfvinge and Sverdrup 1992, 1995, Mapping Manual 2004). In Sweden, the following definition was adopted: The *Critical load* of acidity is the deposition of acidifying compounds that will not cause chemical changes leading to long-term harmful effects on ecosystem structure and function. Critical loads of acidity have been calculated in this study, as well as the excess acidity for each tree stand. Traditionally, critical loads depend on tree vitality, based on a BC/Al limit set for the root vitality of a specific tree species (Sverdrup and Warfvinge 1993a, Mapping Manual 2004). In this study a new approach has been proposed, based on the protection of the ecosystem from excess leaching of ions. Thereby, the excess of acidity is calculated, and, from this value, the critical load is estimated. The excess of acidity has been calculated with the following equation:

$$\mathrm{EA} = D_{\mathrm{Acid}} + \mathrm{Bio}_{\mathrm{Acid}} - W_{\mathrm{tot}}$$

where D_{Acid} is the deposition of acidity, Bio_{Acid} is the acidity generated from the biology activity and W_{tot} is the total weathering, including Na, equivalent to the neutralization rate. The deposition of acidity is expressed as (Mapping Manual 2004):

$$D_{\mathrm{Acid}} = \mathrm{S} + \mathrm{N} + \mathrm{Cl} - \mathrm{BC}$$

where *S* is the sulphur deposition, *N* the nitrogen deposition, *Cl* the chloride deposition and *BC* the base cation deposition, and assuming that no ammonium is leaching. Any ammonium leached must be subtracted from D_{Acid}. The acidity generated by growth of trees and their subsequent removal through harvest, $\mathrm{Bio}_{\mathrm{Acid}}$, can be shown to be equal to (Sverdrup et al. 1990; Mapping Manual 2004):

$$\mathrm{Bio}_{\mathrm{Acid}} = (U_{\mathrm{BC}} - U_{\mathrm{N}})_{\mathrm{net}}$$

where U_{BC} is the net base cation uptake and U_N the nitrogen net uptake. This is in terms of net uptake to the parts harvested. If the excess of acidity (EA) is higher than zero, it will mean that the soil is acidified. The estimation of the critical loads of acidity is made by setting EA to zero. It is defined using the equation of the excess of acidity as follows (Mapping Manual 2004):

$$\mathrm{CL} = W_{\mathrm{tot}} - U_{\mathrm{BC}} + U_{\mathrm{N}}$$

CL is the deposition that is balanced by the weathering rate minus the biologically produced net acidity. The value of the exceeding of the critical load is given by (Mapping Manual 2004):

$$\mathrm{EX} = \mathrm{CL} - D_{\mathrm{acid}}$$

where D_{acid} must be expressed as in the equation given above.

Sustainable yield

The sustainable yield is defined as the maximum yield that can be obtained on the basis of the nutrients available in the system. In estimating this, sustainability is measured as long-term sustainable yield, *Y*, expressed as $m^3\ ha^{-1}\ year^{-1}$, and the equation employed is (Warfvinge et al. 1992a; Thelin et al. 2002):

$$Y = U_{\mathrm{BCi}} * \mathrm{ME}_i / \rho_i * x_i$$

where U_{BCi} is the critical uptake of element *i* = Ca, Mg or K; ME_i is the equivalent weight of element *i*; ρ is the specific density of the harvested biomass; and x_i is the concentration of the element *i* in the harvested biomass. The critical uptake is limited by the nutrients available (Warfvinge et al. 1992a; Warfvinge and Sverdrup 1995):

$$U_{\mathrm{crit}} = W + D - L$$

where *W* is the weathering release of element *i*, *D* is the atmospheric deposition of element *i* and *L* is the rate of leaching from the system.

Data

Study site

The sites are located at Björnstorp Estate, 13 km due east of the city of Lund, in the Province of Skåne in southwestern Sweden. The latitude is 55° 37′ and the longitude 13° 30′, and the Estate is approximately 90 m above sea level. The total area of the study site is 1,250 ha and is part of a bigger forest area of approximately 5,000 ha. Forestry of different vegetal species is carried out here. The location has been used for forestry since 1880–1900 and before that it was used as pasture. Nothing has been added to the forested soils since that period. Usually, branches are left on the ground in thinning operations (during the rotation period), and, in clear-cutting, occasionally, the branches are taken out in beech, but not in the other types of stands. The soil sampling at Björnstorp Estate was performed in September 2004, when the canopy was still green. For this study stands with different tree species were selected. The point where the soils were sampled was selected with respect to tree roots, stoniness, vegetation and topography. Three horizons were sampled in each soil pit; in total, 21 samples were collected. The soil pits were approximately 0.5–0.6 m deep, and samples were taken at 0–0.1 m, 0.2–0.3 m and 0.45–0.55 m depth. The location of the stands is shown in Fig. 2 and Table 1, indicating the tree species at each site.

Soil parameters

The properties analysed in the different samples were soil water constituents and pH, total element content, carbon content, nitrogen content, and the adsorbed ions expressed as $BaCl_2$ extractable. Every sample was sieved with a 2 mm sieve. We extracted the exchangeable cations by mixing a 20 g mineral soil sample in a 200 ml bottle with 100 ml of 0.1 M $BaCl_2$ for 2 h. The extract was filtered and analysed on ICP-AES for Mg, Ca, K, Na and Al. For Cl^-, NO_3^- and SO_4^{2-} were analysed by ion chromatography; and NH_4^+ was analysed by FIA. To determine the elemental composition of the minerals in the bottom layer, we used digestion with $Li_2B_4O_7$. The soil sample was pre-heated to 550°C for 2 h, 0.1 g of the ash being mixed then with 0.5 g of $Li_2B_4O_7$. The mixture was heated to 1,000 °C for 15 min and fused to a homogeneous melt. The melt was dissolved in heated concentrated HNO_3. Finally, the amount dissolved in the $Li_2B_4O_7$ melt was analysed on ICP-AES for Al, Ca, K, Mg, Na, P and Si. We selected the different stands taking into account comparability of the stands and the age of each stand. Soil solution pH and solid phase chemistry is shown in Table 2. The cation exchangeable capacity (CEC) and the base saturation (BS) decrease from upper layers to deeper. The base saturation values are very low in all layers, suggesting a history of depletion in the past. The C:N ratio shows low values and suggests a high input of N for a long period of time.

Deposition and climate data

Data on deposition in spruce, beech, and oak were taken from Hallgren-Larsson (2001). Averages for the years 1996–1999 from one Norway spruce stand, one beech stand, and one oak stand were used. For Ca, K, Mg, and Na total deposition estimates, for Cl and SO_4–throughfall measurements, and for NO_3 and NH_4, open field measurements, multiplied by 1.4 for Douglas fir, Grandis fir and Norway spruce, 1.2 for European beech, Sycamore maple, larch and European oak, were used. The mean temperature was set at 7°C, and the precipitation rate at 0.85 m $year^{-1}$. The runoff rate was set to 0.35 m $year^{-1}$. The composition of the atmospheric deposition is depicted in Table 3.

Weathering rates

Weathering rate was calculated using PROFILE, and input data are required for each stand. The soil mineralogy was obtained from the measurement of the total element content of the soil and with the help of the UPPSALA model. The UPPSALA model is a normative back-calculation model for reconstructing the mineralogy from the total analysis in order to provide input to models such as PROFILE from simple survey data (Warfvinge and Sverdrup 1995; Holmqvist et al. 2002; Thelin et al. 2002; Sverdrup et al. 2005a, b).

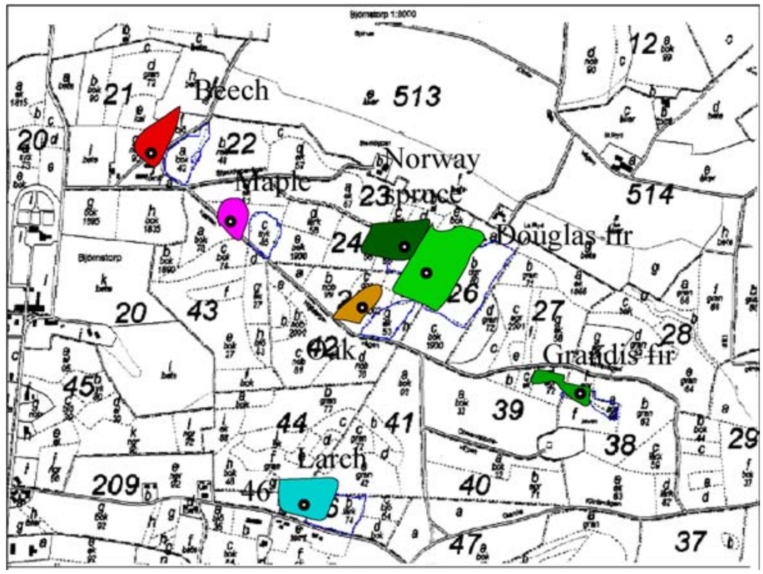

Fig. 2 Map showing the area used for forestry activities at Björnstorp Estate. The stands that are shaded are the ones that have been used on this study

Table 1 Age and location on the map of each stand

Parameter	Beech	Maple	Larch	Oak	Norway spruce	Grandis fir	Douglas fir
Stand	22a	24c	46b	25g	24h	38a	26b
Age (years)	42	19	32	51	32	38	24
Planting year	1962	1985	1972	1953	1972	1966	1980
Rotation (years)	100	80	70	120	60	50	70

The method finds a soil mineralogy that is consistent with the observed total analysis by simple mass balance, assuming standard stoichiometries for the soil minerals. The minerals are grouped into assemblies of minerals with similar composition and dissolution rate. Soil samples from the bottom layer were selected to measure the total analysis of the soil. The total analysis comprised Al, Ca, K, Mg, Na, P and Si. Input data to the UPPSALA model for converting total analysis to mineralogy are Al_2O_3, CaO, K_2O, MgO, Na_2O, P_2O_5 and SiO_2 as percent weight. The percent weight content of the individual minerals is shown in Table 4. The calculation is checked by determination of the total mineral amount, and only such sites that have total mineral content within the range 95–105% are accepted. When no more adequate ions are available for the formation of a mineral, then the content of that mineral is set to zero. The total analysis was carried out on the samples from the C-layer. For the other layers all the minerals maintained the same values except vermiculite and hornblende. Percentage of maximum mineral contents in each soil layer for vermiculite, which forms predominantly from weathering products in the B-layer, and for hornblende, which is partly the source, were most consumed in the top of the profile. Vermiculite was set at 0, 50%, 100% and 50% in the first to fourth layer, and for hornblende the content was reduced by 50% in the first layer.

The texture is related to the exposed mineral surface area, which is an important parameter when one is calculating the weathering rate. In this study no texture analysis was done. The texture from a site, Ullstorp, some kilometres to the north was used, with the removal of the part of the surface contributed by the clay fraction. This was used, and the surface area contributed from clay at Björnstorp Estate was added, using the estimated amount of clay mineral from the Björnstorp Estate soil samples. This is shown in Table 5. To calculate the available surface area the following equation was used:

Table 2 Soil parameters in the different tree stands and the different layers. Al, Ca, Mg, K and CEC (μEq g^{-1} of dry soil). *C* carbon (mg g^{-1}). pH is of water suspension

Layer	pH	Al	Ca	Mg	K	CEC	BS	C:N	C
Beech									
A/E		89	14.30	4.49	2.12	111.07	19.16	17	64.13
B	4.76	64	0.78	0.23	0.52	65.73	2.49	15	14.31
C		50	0.91	0.29	0.23	51.62	3.00	13.6	7.47
Maple									
A/E		110	14.20	3.59	0.65	129.37	14.42	13	55.82
B	5.29	72	1.82	0.38	0.13	74.64	3.42	13	23.98
C		287	0.58	0.15	0.11	287.98	0.33	12	5.82
Larch									
A/E		199	19.98	6.38	0.42	227.48	12.01	19	98.37
B	5.29	114	1.12	0.34	0.21	115.92	1.60	19	21.75
C		143	1.99	0.78	0.32	146.46	2.28	17	17.05
Oak									
A/E		100	7.98	4.04	0.71	116.44	11.28	16	110.60
B	5.90	141	1.37	0.41	0.14	143.37	1.46	16	29.32
C		41	0.53	0.15	0.07	42.00	2.24	14	14.41
Spruce									
A/E		166	5.84	1.51	0.17	174.54	4.44	15.5	63.21
B	6.21	80	0.23	0.14	0.05	80.60	0.63	14	14.58
C		33	0.25	0.07	0.06	33.56	1.55	13	5.05
G. fir									
A/E		124	12.60	2.15	0.12	140.3	10.83	17	101.30
B	5.02	98	0.75	0.24	0.04	99.22	1.13	15.6	20.71
C		46	0.40	0.10	0.06	46.74	1.48	14	8.55
D. fir									
A/E		92	32.64	5.12	1.91	137.85	29.29	19	134.80
B	5.56	83	1.75	0.33	0.20	85.74	2.79	15	13.38
C		37	1.03	0.19	0.15	38.67	3.90	14	6.78

$$A = A_{\text{Ullstorp}} + X_{\text{Clay}}, *8$$

where A is the surface area at Björnstorp Estate, $A_{Ullstorp}$ is the surface area at Ullstorp with no clay, X_{Clay}, is the Björnstorp Estate clay content, calculated as a fraction, and 8 is the multiplying factor used for Swedish soils. The units are 10^6 m^2 m^{-3}. It is assumed that A_{Ullstorp} has the value 0.5×10^6 m^2 m^{-3}.

Root depth and root distribution are used to estimate the cation and nitrogen uptake in percent of the maximum of each layer. The data for beech, oak and Norway spruce on cambisol were obtained from Leuschner et al. (1998), Rosengren and Stjernquist (2004) and Südhaus (1999) (Table 6). The root depth and root morphology of maple, larch and Douglas fir are reported in Köstler et al. (1968). As they all have a heart root system, the root system is estimated to have the same distribution pattern as beech. Grandis fir is estimated to have the same root distribution as Douglas fir. Data were adapted to a four-layer

Table 3 Composition of the atmospheric deposition in units of kEq ha^{-1} year^{-1} and for phosphorus in kg ha^{-1} year^{-1}

Stand	Ca	Mg	K	Na	Cl	SO_4–S	NO_3–N	NH_4–N	P
Spruce	0.186	0.261	0.133	1.020	0.917	0.839	0.883	0.963	0.14
Douglas fir	0.186	0.261	0.133	1.020	0.917	0.839	0.883	0.963	0.14
Grandis fir	0.186	0.261	0.133	1.020	0.917	0.839	0.883	0.963	0.14
Beech	0.258	0.195	0.215	0.739	0.698	0.548	0.634	0.651	0.11
Maple	0.258	0.195	0.215	0.739	0.698	0.548	0.634	0.651	0.11
Larch	0.258	0.195	0.215	0.739	0.698	0.548	0.634	0.651	0.11
Oak	0.243	0.200	0.198	0.729	0.739	0.538	0.666	0.654	0.12

Table 4 Soil mineralogy, in percent weight, obtained with the UPPSALA model

Mineral	Beech	Maple	Larch	Oak	Norway spruce	Grandis fir	Douglas fir
K-feldspar	24.86	25.37	25.68	21.53	23.78	20.57	21.27
Plagioclase	17.46	20.24	16.11	15.24	17.45	14.51	15.79
Apatite	0.17	0.16	0.22	0.29	0.12	0.13	0.13
Hornblende	0.35	0	0	0	0	0.57	0
Muscovite	8.79	9.03	9.08	7.62	8.41	7.28	7.52
Chlorite	0	0	0	0	0	0	0
Epidote	0	0	0	0	0	0	0
Quartz	32.12	21.69	24.84	34.77	27.77	36.82	35.46
Vermiculite	16.24	23.50	24.06	20.56	22.47	20.11	19.84

Table 5 Surface area, in 10^6 m^2 m^{-3}, for each tree stand and layer

Layer	Beech	Maple	Larch	Oak	Spruce	Grandis fir	Douglas fir
1	0.50	0.50	0.50	0.50	0.50	0.50	0.50
2	1.14	1.44	1.46	1.32	1.40	1.30	1.29
3	1.78	2.34	2.42	2.14	2.29	2.11	2.08
4	1.78	2.34	2.42	2.14	2.29	2.11	2.08

calculation in the PROFILE model. It was assumed that the nutrient uptake in each layer is proportional to the root distribution of each layer. With regard to the nitrogen, it was assumed that 80% of the nitrogen uptake takes place in the upper 10 cm of the soil.

Uptake and nutrient cycling

For base cation and nitrogen both net total uptake and circulation amounts are considered. Nutrients are taken up by the root system but are also immobilized and exported in biomass. In multi-layer models, such as the PROFILE model, nutrient cycling redistributes elements in the profile. Base cation and nitrogen litter fall were not measured in this study. The litter nutrient fluxes are estimated to be four times the corresponding uptake value (Warfvinge and Sverdrup 1995). We made the assumption that canopy leaching is included in litter fall. Net mineralization was set to zero. Net uptake is based on site-specific estimates of net long-term harvested forest growth. Each tree species is considered separately and it is calculated for each base cation. The long-term accumulated growth of the stem was obtained from the production rate of each stand. Thinning and clear-felling data from the site of the study have been used (Table 7). These were taken from the management plan for Björnstorp Estate forests. The total accumulated harvest, a large part of the accumulated growth, is divided by the length of the rotation, and the result is the annual production rate. The element content in percent of the weight and wood densities were obtained from Sverdrup et al. (1990),

Table 6 Root depth and soil layer height in metres for the tree species used in the PROFILE model, as well as root distribution in percent of total for each species and each layer

Tree species	Root depth (m)	1	2	3	4	1	2	3	4
Beech	0.55	0.10	0.30	0.10	0.05	21	63	13	3
Maple	0.60	0.15	0.35	0.05	0.15	31	63	3	3
Larch	1.00	0.05	0.35	0.10	0.50	10	64	16	10
Oak	1.20	0.10	0.35	0.05	0.70	36	39	15	10
Spruce	0.45	0.10	0.30	0.05	–	60	35	5	0
Grandis fir	0.90	0.05	0.40	0.05	0.40	13	71	10	6
Douglas fir	0.50	0.10	0.30	0.05	0.05	22	61	10	7

Table 7 Thinning and clear felling data, in m^3sk, for each tree species during a rotation time

Year	Beech	Maple	Larch	Oak	Norway spruce	Grandis fir	Douglas fir
15			25			35	20
20			30		35	40	25
23		7					
25	7	8	40	10	45	50	37
27	11	10		16			
30	15	16	37	25	30	45	40
33				30			
35	15	19	35	35			35
40	33	15		33			
45	37	13		30			
50	33	10		30		650	35
55	33			27			
60	30	10		30	590		
65	27			25			
70			803				908
75	25			25			
80		512					
85	25			25			
90							
95							
100	309						
120				309			
Sum	552	610	970	620	695	820	1100
G	5.5	7.6	13.9	5.2	11.6	16.4	15.7

Sverdrup et al. (2002) and Stjernquist et al. (2002). It was assumed that the nutrient concentration for Grandis fir is the same as for Douglas fir and for larch and Sycamor maple the same as for European beech (Table 8). The soil has a low stone content and a rather high content of clay. The soil moisture was standardized to 0.25 $m^3\ m^{-3}$ in the upper layer and 0.2 $m^3\ m^{-3}$ in the lower layers.

Leaching

The leaching was calculated from the observed soil solution concentrations and an estimate of the minimum leaching. The concentration of ions in the soil solution was derived from the analysis of water suspensions of soil from the lower layer samples (Table 9). The runoff was interpolated from the Ullstorp site and was set to 0.35 m $year^{-1}$. The trees are not active in uptake during the winter; however, leaching is small during the winter because of low percolation rates. For P and N the minimum leaching was set using the root efficiency. Root distributions as well as root depth of the different tree species are very difficult to identify. They are not only dependent on the tree species but also on the soil moisture and soil texture. Another assumption is based on the idea that the nutrient uptake in each layer appears to follow approximately the fine root distribution, and so the

Table 8 Growth rate, stem wood density and concentration of nutrients for each tree stand as percentage of dry weight

Stand	Growth rate ($m^3\ ha^{-1}\ year^{-1}$)	ρ_{stem} (kg m^{-3})	x_i nutrients				
			Ca	Mg	K	P	N
Beech	6.0	700	0.11	0.03	0.10	0.0055	0.10
Maple	7.8	700	0.11	0.03	0.10	0.0055	0.10
Larch	13.9	560	0.11	0.03	0.10	0.0055	0.10
Oak	5.4	705	0.11	0.02	0.13	0.0100	0.18
Spruce	11.7	350	0.14	0.02	0.07	0.0055	0.10
Grandis fir	17.0	380	0.07	0.01	0.04	0.0044	0.08
Douglas fir	15.7	530	0.07	0.01	0.04	0.0044	0.08

Table 9 The weathering rate in units of kEq ha^{-1} year^{-1}for each tree stand for the specific rooting depth as calculated with PROFILE. The values are the result of the sum of the weathering rate on the different layers

Parameter	Beech	Maple	Larch	Oak	Spruce	Grandis fir	Douglas fir
Ca	0.101	0.153	0.197	0.229	0.073	0.132	0.077
Mg	0.056	0.091	0.126	0.095	0.057	0.091	0.055
K	0.211	0.343	0.484	0.374	0.164	0.263	0.169
Na	0.139	0.306	0.485	0.182	0.146	0.182	0.154
P	0.028	0.037	0.068	0.115	0.013	0.027	0.016
Total weathering	0.507	0.893	1.292	0.880	0.440	0.668	0.455
Rooting depth, m	0.55	0.60	1.00	1.20	0.45	0.90	0.50

percentage of roots in each layer is proportional to the uptake that these roots can capture (Thelin et al. 2002; Holmqvist et al. 2002).

Results

Weathering

The weathering rate was calculated with the PROFILE model and is shown in Table 9. As can be seen, the weathering rate is higher for K in every tree species stand and lower for Mg. The soil has a high content on vermiculite and other minerals with a high content of K, thereby leading to high amounts of K in the soil water content as a product of the weathering process. As rooting depth increases, more weathering becomes available to the tree. This emphasizes the relative supply advantage of the deeper rooted trees. It may be illustrative to compare the base cation weathering rate recalculated in terms of per metre of soil depth: European beech 0.92 kEq ha^{-1} year^{-1}, Sycamore maple 1.48 kEq ha^{-1} year^{-1}, larch 1.29 kEq ha^{-1} year^{-1}, oak 0.73 kEq ha^{-1} year^{-1}, Norway spruce 0.98 kEq ha^{-1} year^{-1}, Grandis fir 0.73 kEq ha^{-1} year^{-1} and Douglas fir 0.91 kEq ha^{-1} year^{-1}. The soils of the European beech, European oak, Grandis and Douglas stands are similar; the soils of the Sycamore maple and larch stands are richer. This is also reflected in the release values for P.

Mass balance and sustainable yield

The nutrient sustainability was assessed from the results of mass balance calculations for each of the nutrients. The results of the mass balance calculations are shown in Tables 10, 11, 12, 13 and 14. Almost every stand shows some degree of deficiency, suggesting that the growth is close to being nutrient limited. For Mg and K the balances are positive except for European beech and larch stands. Negative mass balance values imply that removal by growth and leaching is larger than supply, and, thus, the situation is not sustainable in the long term. Deposition is higher than the weathering in almost every case except for K. European oak is the deciduous tree that has the most positive mass balance values, mainly because of its potential for deep rooting. With regard to the coniferous trees, the most negative mass balance is at the Douglas fir stand, followed by Norway spruce and Grandis fir. The Douglas fir stand has high leaching compared with the other stands, which results in a very negative mass balance. The larch stand has the highest uptake, and leaching is also very high. It also sets its roots deeply, but if we assume the same depth for larch as for Norway spruce, its balance would be very negative. As compared to the other sites, the observed leaching at the Douglas stand stood out as particularly high. As we have no replicate samples, we will have to accept the value as it is. A comparison between deciduous and coniferous mass balances shows noticeable differences, but these are mostly attributable to deeper rooting. Comparing all, one can seen that European beech, larch and Douglas fir stands have the most negative mass balance values. Sustainable yield was also calculated with respect to Ca, Mg and K, and it was assumed that no nutrients were added. Two sustainable yields were calculated. The first was calculated from the actual leaching, and the second with minimal leaching. In both cases the

Table 10 Calculation of mass balances of Ca, Mg and K for European beech and Sycamore maple at Björnstorp Estate. Units are in kEq ha^{-1} $year^{-1}$

Parameter	Beech			Maple		
	Ca	Mg	K	Ca	Mg	K
Weathering	0.101	0.056	0.211	0.153	0.091	0.343
Deposition	0.258	0.195	0.215	0.258	0.195	0.215
Leaching	–0.444	–0.238	–0.266	–0.283	–0.124	–0.121
Uptake	–0.231	–0.104	–0.107	–0.298	–0.134	–0.139
Balance	**–0.316**	**–0.090**	0.043	**–0.170**	0.028	0.298
Available, best case	0.259	0.181	0.307	0.300	0.209	0.467
Available, now	**–0.085**	0.013	0.160	0.128	0.162	0.437
Limestone per rotation, ton/ha	1.6	0.34		0.68		

Table 11 Calculation of mass balances of Ca, Mg and K for European oak and larch at Björnstorp Estate. Units are in kEq ha^{-1} $year^{-1}$

Parameter	Larch			Oak		
	Ca	Mg	K	Ca	Mg	K
Weathering	0.197	0.126	0.484	0.229	0.095	0.374
Deposition	0.258	0.195	0.215	0.243	0.200	0.198
Leaching	–0.423	–0.196	–0.149	–0.274	–0.112	–0.083
Uptake	–0.426	–0.192	–0.198	–0.210	–0.063	–0.128
Balance	**–0.394**	**–0.067**	0.352	**–0.012**	0.120	0.361
Available, best case	0.387	0.272	0.594	0.448	0.280	0.543
Available now	0.032	0.125	0.550	0.198	0.183	0.489
Limestone per rotation, ton/ha	0.8	0.2				

Ca is in deficit in every stand. For the first case, the current growth rate (Table 8) is higher than the sustainable yield just in larch, Norway spruce and Douglas fir and only for Ca. For K and Mg, the sustainable yield is higher than the growth rate, which means that the harvest applied is sustainable.

When actual leaching is used to calculate the sustainable yield, it has lower values, reaching even zero for European beech and Douglas fir. The harvest applied is, in every stand, higher than the sustainable yield for Ca, but the other ions are mostly in balance with the harvest applied. In addition to the case using present-day values for the input parameters, a best case has been constructed. The best case assumes that no acidification happens at all as the rate of leaching is low. The mass balance was calculated with the minimum rate of leaching instead of the real leaching measured. The mass balances change substantially as Ca reaches positive mass balances, and Mg and K acquire higher positive values for almost every stand. Only Norway spruce, Douglas fir and Larch stands still have negative balances values for Ca.

Table 12 Calculation of mass balances of Ca, Mg and K for Norway spruce, Grandis fir and Douglas fir at Björnstorp Estate. Units are in kEq ha^{-1} $year^{-1}$

Parameter	Norway spruce			Grandis fir			Douglas fir		
	Ca	Mg	K	Ca	Mg	K	Ca	Mg	K
Weathering	0.073	0.057	0.164	0.132	0.091	0.263	0.077	0.055	0.169
Deposition	0.186	0.261	0.133	0.186	0.261	0.133	0.186	0.261	0.133
Leaching	–0.176	–0.071	–0.062	–0.232	–0.099	–0.062	–0.636	–0.177	–0.208
Uptake	–0.285	–0.067	–0.074	–0.226	–0.053	–0.066	–0.291	–0.069	–0.085
Balance	**–0.200**	0.180	0.161	**–0.140**	0.200	0.268	**–0.664**	0.070	0.090
Available, best case	0.172	0.210	0.196	0.204	0.307	0.278	0.179	0.147	0.100
Available now	0.083	0.247	0.235	0.086	0.253	0.334	**–0.373**	0.139	0.094
Limestone per rotation, ton/ha	0.6			0.4			2.3		

Table 13 Calculation of mass balances of P and N for European beech, Sycamore maple, European oak and larch at Björnstorp Estate. Units are in kg ha^{-1} year^{-1}

Parameter	Beech		Maple		Larch		Oak	
	P	N	P	N	P	N	P	N
Deposition	0.110	18.0	0.110	18.0	0.110	18.0	0.120	18.5
Weathering	0.896	–	1.187	–	2.184	–	3.684	–
Leaching	–0.098	–1.3	–0.071	–1.3	–0.023	–1.3	–0.044	–0.7
Uptake	–0.686	–4.2	–0.887	–5.4	–1.266	–7.8	–1.127	–6.9
Balance	0.222	12.5	0.339	11.5	1.015	9.2	2.633	10.9

Table 14 Calculation of mass balances of P and N for Norway spruce, Grandis fir and Douglas fir at Björnstorp Estate. Units are in kg ha^{-1} year^{-1}

Parameter	Norway spruce		Grandis fir		Douglas fir	
	P	N	P	N	P	N
Deposition	0.140	25.8	0.140	25.8	0.140	25.8
Weathering	0.404	–	0.878	–	0.512	–
Leaching	–0.023	–0.3	–0.071	–1.0	–0.013	–1.8
Uptake	–0.667	–4.1	–0.843	–5.2	–1.088	–6.7
Balance	**–0.110**	21.5	0.104	19.6	**–0.449**	17.4
Phosphorus fertilization need, per rotation kg ha^{-1}	7.7				25	

Negative balances are shown in bold

In this assessment, some of the leaching values were very high, causing some concern about their validity. If they represent the real situation, then all these stands have a problematic supply situation. We cannot exclude, however, that the leaching may have been overestimated for some unknown reason, as replicate sampling could not be done because of resource limitations.

The available amounts of base cation nutrient were converted to production rates, which are shown in Table 15. The values represent estimated sustainable growth, shown in bold type when this is lower than present growth. For comparison, we have entered the present production value according to the forest management plan and as estimated at the sites by the forester. These values are probably valid for a soil situation without acid pollution. It can be seen that most sites are, at present, overproducing with respect to natural sustainability; that is, growth is, at present, significantly higher than sustainable harvest volumes. The implication is that all

Table 15 Assessment of production sustainability under present conditions, including acidification of the soil at present levels of pollution, in m^3 ha^{-1} year^{-1}. For P, the best case and present case is the same, assuming no net leaching of P from the system

Nutrient	Beech	Maple	Larch	Oak	Norway spruce	Grandis fir	Douglas fir
	Production limitation at present leaching rate (m^3 ha^{-1} year^{-1})						
Ca	**0.0**	**3.3**	**1.0**	**5.1**	**3.4**	**6.5**	**0.0**
Mg	**0.8**	9.4	**9.0**	16.0	43.0	81.0	32.0
K	9.1	25.0	39.0	21.0	38.0	86.0	**8.9**
P	7.9	11.0	25.0	18.0	**9.8**	19.0	**9.2**
N	24.0	24.0	30.0	14.0	73.0	82.0	57.0
	Production limitation at best case leaching, m^3 ha^{-1} year^{-1}						
Ca	**6.7**	8.0	**13.0**	11.4	**7.1**	**15.3**	**9.7**
Mg	10.4	12.1	19.7	24.0	33.2	98.0	33.4
K	17.2	26.2	41.7	22.9	31.0	71.7	18.5
	Present growth						
	5.5	7.6	13.9	5.2	11.6	16.4	15.7

growth cannot be harvested if sustainability is to be maintained. The only site that is approximately at its sustainability limit, where all growth available can safely be harvested, is the European oak site. Here, the lowest sustainable level, 5.1 m^3 $ha^{-1}year^{-1}$, is indistinguishable from present growth rate, 5.2 m^3 ha^{-1} $year^{-1}$. This stresses the point that, in a sustainable world, not necessarily all growth that occurs can safely be harvested.

The difference between best case leaching and present case leaching can be interpreted to show the impact caused by acid deposition. In several cases the difference is significant. If the best case is applied, then the actual growth of all species except Norway spruce, Grandis fir and Douglas fir are within the sustainability limit.

Critical loads of acidity and excess

Critical loads of acidity have been calculated for each tree stand and are shown in Table 16, as is the critical load based on no excess of acidity after neutralization in the soil. If the excess of acidity (EA) is higher than zero, it will mean that the soil is acidified. Table 16 shows several aspects of the acidity situation and where the acidity originates from, as well as the fraction of the input derived from acid produced in the growth process. The values in bold type show the lowest critical load, indicating which criterion is limiting. EA and critical load of acidity (CL) are estimated in two different ways for each tree stand in units of kEq ha^{-1} $year^{-1}$. The most affected are the stands of Norway spruce, Grandis fir and Douglas fir. The critical load based on no excessive leaching is almost equal to the weathering rate. Larger values of EA cause more excess of CL_{Acid}. The $CL_{BC/Al}$, has been included for comparison in Table 16.

The critical load for excess acidity, protecting the site from leaching, is, in most cases, significantly stricter than that for root vitality. The implication is that, even if we reduce deposition enough to protect roots from damage, this is not an adequate protection against excessive leaching. Deciduous species have a higher $CL_{BC/Al}$ than coniferous species, which means that the deposition of acidity on these species has to be very high to be able to produce tree damage. The critical load based on the BC/Al ratio is designed to protect root vitality, whereas the critical load based on the excess acidity is designed for protecting the soil against unnatural leaching of base cations. In Table 17, we have given an overview of the causes of soil acidification at Björnstorp Estate. It can be seen that atmospheric deposition is the overwhelmingly largest contributor to acidity input at all sites. The acidity produced by forest growth is small, on average 8% of the atmospheric input. Thus, pollution is to blame for the soil acidification problems, not forestry. The acid rain problem can only be solved by intergovernment actions. The results suggest that more work and effort in the policy sector is needed. We may conclude that acid depositing causes a problem of sustainable nutrient supply for forest production at the Björnstorp Estate. The issue at stake is not the ecological damage to the trees and their vitality, but rather one of the reducing sustainability potential and, thus, the inflicting of economic damage to the Björnstorp Estate property. We may ask, what is the cost of the damage done by acidification at Björnstorp Estate?

Table 16 Excess of input acidity (EA) critical load of acidity (CL) estimated in two different ways for each tree stand in units of kEq ha^{-1} $year^{-1}$. The exceedance of critical loads is shown for comparison

	Beech	Maple	Larch	Oak	Norway spruce	Grandis fir	Douglas fir
Acid deposition	1.053	1.070	1.086	1.197	2.043	2.015	2.019
Total weathering	0.507	0.893	1.292	0.880	0.440	0.668	0.455
Growth acidity	0.142	0.183	0.262	–0.093	0.134	–0.024	–0.031
Excess Acidity	0.688	0.360	0.056	0.224	1.737	1.323	1.533
CL_{Acid}	**0.365**	**0.710**	**1.030**	**0.973**	0.306	**0.692**	0.486
$CL_{BC/Al}$	2.472	2.771	2.272	1.881	**0**	1.237	**0.176**
BC/Al Limit	0.7	0.7	1	0.6	1.2	1	1
Exceeding of the critical load	0.688	0.360	0.056	0.224	2.072	1.323	1.900

Table 17 Overview of the acidification situation at Björnstorp Estate in units of kEq ha^{-1} year^{-1}. Annual income lost because of acidification in SEK ha^{-1} year^{-1}, assuming a price as for pulpwood, of 250 SEK m^{-3}sk

Parameter	Beech	Maple	Larch	Oak	Norway spruce	Grandis fir	Douglas fir
Acid deposition	1.053	1.070	1.086	1.197	2.043	2.015	2.019
Growth acidity	0.142	0.183	0.262	–0.093	0.134	–0.024	–0.031
Growth acidity fraction (%)	13%	16%	23%	–7.5%	6.4%	–1.1%	–1.5%
Cost SEK ha^{-1} year^{-1}	1,675	1,175	2,900	75	975	2,200	2,425
Restoration cost per rotation and ha SEK ha^{-1}yr^{-1}	3,600	2,680	2,800	2,070	2,600	2,400	4,300
Best case Restoration, SEK/ha	2,450	0	0	0	0	0	3,300

The damage cost was calculated as the difference between the yield we would have had without any acid rain subtracted by the actual sustainable yield under present conditions, in SEK:

$$\text{Cost} = 250*(\min(Y_{\text{sust-ideal}}, Y_{\text{present}}) - Y_{\text{sust-present}})$$

where *250.–* is the price in SEK per m^3 of pulpwood, and 7 SEK is 1$. In addition would be the cost of restoring the soil to a base saturation of 20–25%; probably this is the absolute minimum of what it once was in the past (Warfvinge et al. 1996). This would add another 15,000 SEK ha^{-1} per stand and rotation period as a one-off repair of the soil. It can be seen that the economic potential lost by pollution damage at Björnstorp Estate is substantial, considering the fact that the estate amounts to 1,250 ha of productive forest. The alternative restoration cost is in SEK per rotation period t_{rotation}:

$$\text{Cost alternative} = 2000 - (\text{t}_{\text{rotation}}*50,000 * \text{balance})$$

The alternative cost can be estimated as the cost of restoration liming and replacement of unduly lost nutrients (Warfvinge and Sverdrup 1989; Brocksen et al. 1990). The results of these calculations in SEK ha^{-1} year^{-1} are shown in Table 17.

Discussion

The outputs presented in this study were created by running input information through a chain of transformations. Each transformation is a model in itself, whether this is computerized or not. In each step, inaccuracies may enter into the information flow. The accuracy of the final result depends on those transformation inaccuracies as well as the inaccuracy that is embedded in the original input information. Some uncertainties also enter the assessment through some of the many simplifications we were forced to make for practical reasons. However, in a world of limited resources, this is perhaps the kind of uncertainty that must be put up with for practical management. The time and costs associated with performing our assessments were in a size feasible for a forest estate. That results are obtained with computer models may be deceptive to some, but is in itself no proof of anything.

We know from experience (Barkman et al. 1995, 1999, Warfvinge and Sverdrup 1995) that the largest uncertainty enters the assessment with the input information. It is difficult, without a very excessive quantitative uncertainty assessment, to quantify this with any accuracy, but we estimate from our earlier experiences that the input information uncertainty in this case represent approximately 75% of the uncertainty encountered in the final result presented here (Sverdrup and Warfvinge 1988a, b, c, 1993b, 1995; Alveteg et al. 1996, 1998; Warfvinge et al. 1992a; Barkman et al. 1995; Barkman and Sverdrup 1996; Barkman et al. 1999). A semi-quantitative assessment of uncertainty of the input information or input terms would be:

Leaching of nutrients. This is the most uncertain in our assessment: ±50%

Deposition of nutrients. This is somewhat uncertain, due to its variability at small scale; however,

it tends to even out over time, we would guess ±20%
Uptake of nutrients. This is also fairly robust in our study, we guess ±15%
Weathering rate. This is perhaps the most robust estimate in our study: ±15%

Depending on the relative weight of these terms in the mass balance, the actual accuracy will vary from case to case. When interpreting the result, one needs to focus on two aspects:

1. The quality of the conclusion made (unsustainable–sustainable)
2. The order of magnitude of the conclusion (a little or a lot of sustainability/unsustainability)

Results from this study show that the acidification of forests soils at the Björnstorp Estate still goes on. All the soil samples have a remarkably low base saturation (Jönsson et al. 2003), and the calculations of critical loads and excess acidity suggest that it has been lost in the past century. In the upper layer the K concentration is below the recommended minimum value of 20 μg g^{-1} for a productive forest soil (Stjernquist et al. 2002; Nihlgård 1999). The base saturation also shows very low values in the deeper layers, suggesting deep penetration of the acidification effects. The overall interpretation is that soil acidification has caused high leaching rates, which explains the present low base saturation in the soil. This is supported by the fact that the values of excess of acidity are positive, and these must have been significantly higher in the past. For a more thorough analysis of future consequences and dynamics of the system, dynamic models such as SAFE or ForSAFE could be used (Belyazid et al. 2006; Sverdrup et al. 1996; Aherne et al. 1998; Alveteg et al. 1996; Martinsson et al. 2005).

With regard to the mass balances, there is a Ca deficit in all tree stands. Considering the uncertainties discussed earlier, determination of the unsustainability of a certain level of harvest at a stand is probably a robust conclusion. Exact how much may be a matter of discussion, but the qualitative aspect of unsustainability is robust. The mass balances for K and Mg are positive in all stands except for the beech and larch, which have a deficit of Mg. K is the only ion with higher weathering input than deposition, due to the high clay content of the soil. For Mg and K the exchange complex, for practical purposes, is now empty. Although the weathering is high for K, they are easily leached and cannot compete with the Al for the exchangeable sites. When minimum leaching is used, the sustainable harvest is larger, and the difference quantifies the damage to nutrient supply sustainability caused by soil acidification. The excess acidity is higher in coniferous species than in deciduous. The net acidity contribution from tree growth at Björnstorp Estate amounts at present to 7% of the total acid input, on average. For some of the sites, phosphorus appears to be able to limit the sustainable harvest (Table 15). Norway spruce and Douglas fir show deficit of P; for Douglas fir it is significant, suggesting that all growth cannot be sustainably harvested without causing long-term deficit. Thus, systematically including P in nutrient sustainability assessments for forest production seems to be necessary.

Conclusions

We may conclude that acid deposition, together with high N deposition and high growth rate, causes a problem of sustainable nutrient supply for forest production at Björnstorp Estate. We may conclude, considering our roughly estimated margins of error as outlined above, that:

1. At present, the acid deposition is above the critical load for the estate by a wide margin and, potentially, will cause damage to the forest productivity at Björnstorp Estate.
   (a) The base saturation is so low that the soil has very little nutrient storage left. Very little buffering against further acidification of the soil is available. The soil has become less fertile for growth than possibly it was in the past. This can be addressed by additions of alkaline substances such as limestone or similar material.
   (b) Work must be initiated by the authorities to significantly further reduce the emission of acidifying compounds contributing to acid deposition in southern

Sweden, as approximately one-tenth of the input acidity is attributed to forest management and growth, and at least 80% is estimated to still come from pollution of foreign origin.

2. Several stands have, under present ambient conditions, need for nutrient support if present production levels are to be sustainably maintained. To be specific:
   (a) Beech would need addition of Ca and Mg.
   (b) Maple would need addition of Ca.
   (c) Larch would need addition of Ca and Mg.
   (d) Oak would need addition of Ca.
   (e) Norway spruce would need addition of Ca and P.
   (f) Grandis fir would need addition of Ca.
   (g) Douglas fir would need addition of Ca, K and P.

   Considering the approximate margins of error, the indicated amounts should be seen as minimum amounts, from a precautionary point of view.
3. The interference of acidification with the sustainability of forest production, as well as the deterioration of the soil quality by leaching, represents a significant potential economic loss for the estate:
   (a) The cost of lost opportunity for production can be estimated, in the worst case, to an order of magnitude of thousands of SEK per hectare annually.
   (b) The alternative restoration cost amounts to approximately the same amount as the opportunity loss described above, in SEK per hectare and rotation period.
4. The restoration cost for repairing the acidification damage caused to the base saturation amounts to approximately 10 tons of pure calcite per hectare, equivalent to a restoration cost of 20,000 SEK per hctare, assuming 80% limestone purity and 75% efficiency of material use. This is the effective cost of soil damage caused to the land property of Björnstorp Estate by acidifying air pollution.

The soils at Björnstorp Estate would, with the absence of acidification and accumulated damage from the past pollution, be soils of excellent forest production properties and good soil chemical status. However, 120 years of acid deposition has taken its toll. The difference between the present yield and the potential sustainable yield may be said to represent a quantification of the damage done by acidification to the soils at Björnstorp Estate. Despite the large decline in deposition of acidifying substances since the 1980s, there has been no improvement in the soil chemical status in forest soils in Skåne (Warfvinge et al. 1993; Jönsson et al. 2003; Barkman et al. 1995). In order to maintain the pool of base cations in the soil at a sufficiently high level, sustainable management should be applied. In this case it would be necessary to add missing Ca, Mg or K. It should be remembered that the leaching may be the most uncertain parameter in this assessment, and the results for Douglas fir and Norway spruce must be taken with some caution because of the larger importance of the leaching term for these particular stands. Although nutrient compensation may improve the situation temporarily, it is of utmost importance that acid deposition to the forest ecosystems should decrease, as it is probably the main factor responsible for the large losses to leaching. In this way the growth rate applied will be sustainable.

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