CHAPTER 12

Past and Future Effects of Atmospheric Deposition on the Forest Ecosystem at the Hubbard Brook Experimental Forest: Simulations with the Dynamic Model ForSAFE

Salim Belyazid, Scott Bailey and Harald Sverdrup

12.1 INTRODUCTION

The Hubbard Brook Ecosystem Study presents a unique opportunity for studying long-term ecosystem responses to changes in anthropogenic factors. Following industrialisation and the intensification of agriculture, the Hubbard Brook Experimental Forest (HBEF) has been subject to increased loads of atmospheric deposition, particularly sulfur and nitrogen. The deposition of these elements, also referred to as acidic deposition because of its acidifying effect on the soil, has inevitably affected the forest ecosystem and streams at HBEF. A particular characteristic of great relevance for studying the effects of acidic deposition at HBEF is the existence of long time-series of field measurements, including forest biomass, soil and runoff water. This study builds on the available data for HBEF to validate the dynamic ecosystem model ForSAFE, with the aim of using the model to reconstruct the historical state of the forest as it has been gradually affected by the increasing atmospheric deposition, and to make future predictions about changes in the forest ecosystem at HBEF.

12.2 A SHORT DESCRIPTION OF THE ForSAFE MODEL

The ForSAFE model (Wallman *et al.*, 2005; Belyazid, 2006) is theoretically based on the physical cycles of matter in a forest ecosystem as they were presented by Kimmins

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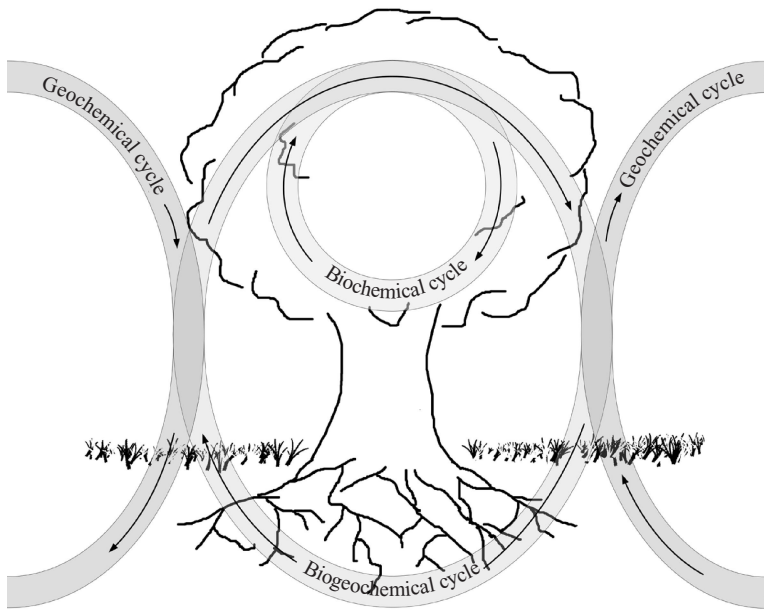
Any numbers in boxes in the left hand margin of the pages refer to the numbered list of queries on the last page of the chapter.

(1997) (Figure 12.1). The biochemical cycle represents the flows of carbon, nutrients and water within the biological compartment of the forest ecosystem. In the context of the ForSAFE model the biological compartment is represented by the trees. The biochemical cycle includes the allocation of carbon and nutrients to the tree parts, which, in the model, are grouped into foliage, wood and fine roots (roots with a diameter of less than 2 mm used for water and nutrient uptake). The biochemical cycle also includes the retranslocation process, which restores part of the nutrients from the roots and foliage destined for litterfall back into the living biomass.

The biogeochemical cycle links the living biomass to the soil (Figure 12.1). This cycle comprises the uptake of water and nutrients, litterfall, and the decomposition of the litter. In ForSAFE this cycle is the crucial link between the soil and the vegetation. It is through the biogeochemical cycle that water and nutrients are removed from the soil by the trees, and nutrients and carbon are introduced into the soil through litterfall and decomposition. If changes occur in the soil chemistry, it is through the biogeochemical cycle that they affect the living biomass and vice versa. The geochemical cycle includes the input of matter through weathering of soil minerals and atmospheric deposition of gases and particles, as well as precipitation, soil leaching and soil erosion. In the model the weathering and leaching processes are simulated dynamically, while the mineral composition of the soil, the deposition and the precipitation

Figure 12.1: The biochemical, biogeochemical and geochemical cycles involved in the nutrient dynamics in a forest ecosystem (adapted from Kimmins, 1997). The ForSAFE model attempts to re-create a system where the three cycles are integrated.



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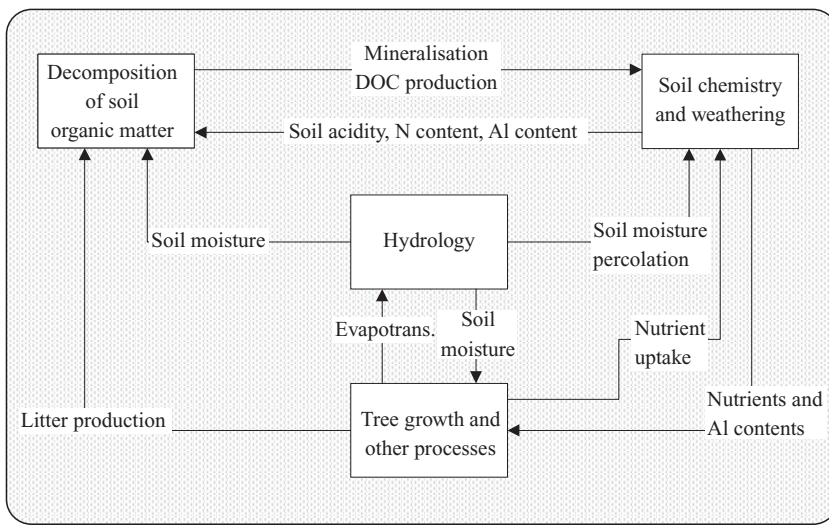
are taken as environmental inputs. Soil erosion is not considered in the model, nor is the depletion of the soil minerals through weathering.

The three cycles are closely related, and overlap with each other. When translated into the model, the focus is turned from keeping a clear distinction between the three cycles to tracing the flow of the elements. Carbon, nutrients and water are transferred between the three cycles at different stages of their flow within the modelled forest ecosystem, and the boundaries between the cycles become ephemeral. The apparent structure of the model becomes an integrated web of flows between the tree parts, the trees and the soil, and within the soil (Figure 12.2).

ForSAFE (Figure 12.2) simulates the biogeochemical cycles of carbon, nitrogen, base cations and water in a forest ecosystem, with focus on tree growth, soil chemistry and soil organic matter accumulation and decomposition (Wallman *et al.*, 2005; Belyazid, 2006; Belyazid *et al.*, 2006). The module for tree growth simulates the dynamics of photosynthesis, nutrient uptake, nutrient and carbon allocation and evapotranspiration. This module is based on the PnET model (Aber *et al.*, 1992), and uses the nitrogen content of leaves or needles to estimate a potential photosynthesis rate from the solar radiation. The photosynthesis rate is in turn corrected according to nutrients (from the soil chemistry module) and water (from the hydrology module) availability.

The soil chemistry module is based on the SAFE model for soil chemistry processes and weathering (Alveteg *et al.*, 1995; Alveteg, 1998). This module estimates the soil solution contents of different chemicals (nitrogen, base cations, aluminium, hydrogen, chloride, sodium) based on the balance between the processes of uptake (estimated in the growth module), mineralisation (estimated in the decomposition

Figure 12.2: ForSAFE is made up of four main central modules, to which the VEG module is annexed. The five modules communicate continuously on a monthly basis.



module), precipitation, weathering, leaching (estimated in the hydrology module) and cation exchange.

The decomposition module, based on the DECOMP model (Walse *et al.*, 1998; Wallman *et al.*, 2006), simulates the accumulation and decomposition of the soil organic matter and litter. The incoming litter (produced by the growth module) is sorted into four different pools with different dispositions to decomposition, and each pool is decomposed at a rate that depends on the soil temperature, moisture content (from the hydrology module), acidity and nitrogen content (from the chemistry module).

Finally, the hydrology module, derived from the PULSE model (Wallman *et al.*, 2005), estimates the rates of vertical water percolation and evapotranspiration based on the water-holding capacity and the wilting point of different soil layers.

12.3 INPUT

The model simulation was carried out for watershed 6 (W6) at the Hubbard Brook Experimental Forest, New Hampshire. In accordance with the concept presented in Figure 12.1, the model requires input about the state of the soil and the vegetation, and time-series inputs for the geochemical flows. The soil input data were based on field measurements at W6, available at the Hubbard Brook Ecosystem Study website.[1] The soil was stratified into six layers representing the six existing horizons at the site, and input for each layer was specified according to measurements (Table 12.1). The values for gibbsite solubility were based on the value reported in Dahlgren *et al.* (1989).

The mineral composition of the soil (Table 12.2) was reconstructed using the normative back-calculation model UPPSALA (Sverdrup and Warfvinge, 1993; Warfvinge and Sverdrup, 1995), based on the total analysis of the soil bulk chemistry available at HBEF (Scott Bailey, personal communication). The O horizon was assumed to contain no weatherable minerals. Feldspar and plagioclase are the dominant minerals through the mineral soil profile, and the E horizon contains important amounts of these two minerals.

Table 12.1: Layer specific input at the low-level elevation site at HB.

	Thickness/ cm	Density/ ($kg\,m^{-3}$)	Field capacity/ $m^3\,m^{-3}$	Weatherable area/ $m^2\,m^{-3}$	CEC	BS/%	Gibb-site constant
O	4.0	300.0	0.32	1.0×10^5	17.5×10^{-5}	50.0	6.5
A	3.0	400.0	0.38	2.5×10^6	5.8×10^{-5}	16.0	7.6
E	3.0	1000.0	0.23	8.0×10^5	3.4×10^{-5}	18.0	7.6
Bhs	4.0	1400.0	0.44	1.5×10^6	7.5×10^{-5}	13.0	8.2
Bs	75.0	1400.0	0.25	1.0×10^6	5.8×10^{-5}	7.0	9.1
C	11.0	1800.0	0.20	1.0×10^6	2.1×10^{-5}	6.0	9.2

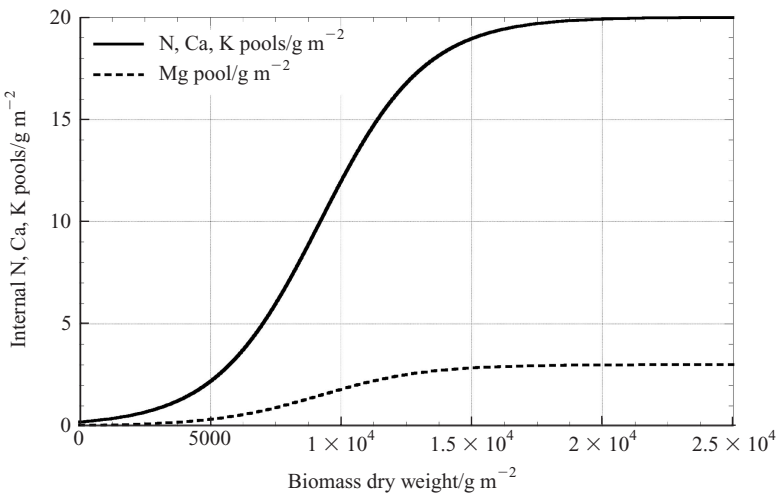
Table 12.2: Mineral contents per layer. Quartz makes up the remaining fraction not presented in the table.

	Minerals/%												
	Fld	**Plg**	**Hrn**	**Pyr**	**Epd**	**Grn**	**Btt**	**Msc**	**Chl**	**Ver**	**Apt**	**Klt**	**Clc**
O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A	9.43	8.83	0.62	0.00	0.03	0.00	0.23	0.06	0.00	2.18	0.35	0.00	0.00
E	13.59	14.62	1.28	0.00	0.27	0.00	0.00	0.00	0.00	3.01	0.10	0.00	0.00
Bhs	11.65	14.51	2.15	0.00	0.35	0.00	0.18	0.29	0.00	3.53	0.18	0.00	0.00
Bs	13.36	17.68	2.15	0.00	0.45	0.00	0.43	0.38	0.00	4.18	0.33	0.00	0.00
C	15.52	20.25	3.39	0.00	0.65	0.00	0.57	0.73	0.00	0.84	0.36	0.00	0.00

Fld, K-feldspar; Plg, plagioclase; Hrn, hornblende; Pyr, pyroxene; Epd, epidote; Grn, garnet; Btt, biotite; Msc, muscovite; Chl, Fe-chlorite; Ver, Mg-vermiculite; Apt, apatite; Klt, kaolinite; Clc, calcite.

The parametric input for the forest cover was based on the data used for PnET model simulations (Aber *et al.*, 1997, 2002), which were specifically parameterised for the northern hardwoods at HBEF-W6. These data describe the photosynthesis, growth rates, evapotranspiration, litterfall and nutrient allocation in trees in response to light intensity and the nitrogen content of the foliage. A modification was made to this part of the input data, whereby the internal pools of nutrients in the trees were changed from static values to dynamic sizes dependent on the size of the biomass (Figure 12.3). The necessity for modelling the internal nutrient pools dynamically comes from the fact that these pools are used to create an uptake gradient that reflects the deficit between the tree's nutrient need and the actual nutrient availability in the

Figure 12.3: The internal nutrient pools are modelled to dynamically increase or decrease following respectively a growth or decline of the biomass.



tree for allocation. This gradient is in turn used to create an uptake requirement, which should fill the gap in the trees.

The model uses an average root distribution (Figure 12.4) based on field measurements for root uptake and HBEF-W6 (Fahey, personal communication). Root density is highest in the forest floor, while the majority of roots in total are found in the lower mineral soil (Bhs, Bs and C horizons). Root density is lowest in the E horizon. The root distribution is used in the model to direct the uptake distribution of nutrients and water, and to partition root growth, respiration and litter. At this stage, the root distribution is assumed to be constant with respect to time.

Finally, the geochemical cycle inputs to the model – precipitation, light intensity, temperature and deposition – were derived from the data available on the Hubbard Brook website.[2] Bulk deposition data were modified to account for dry deposition. Throughfall deposition was first modified for chloride by increasing bulk deposition by a factor of 1.3, which was extended to the other elements. The data report a larger increase in the atmospheric deposition that started in the middle of the 1800s (Figure 12.5), and while the deposition of sulfur, chloride and base cations was considerably reduced by the early 2000s, that of nitrogen continues to be elevated.

Figure 12.4: The average root distribution through the soil profile as used in the model.

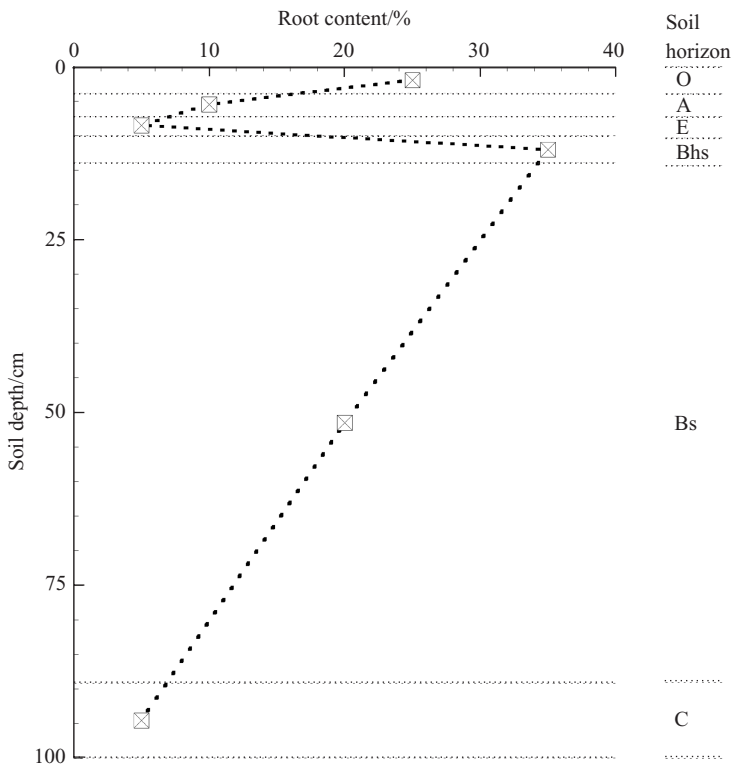
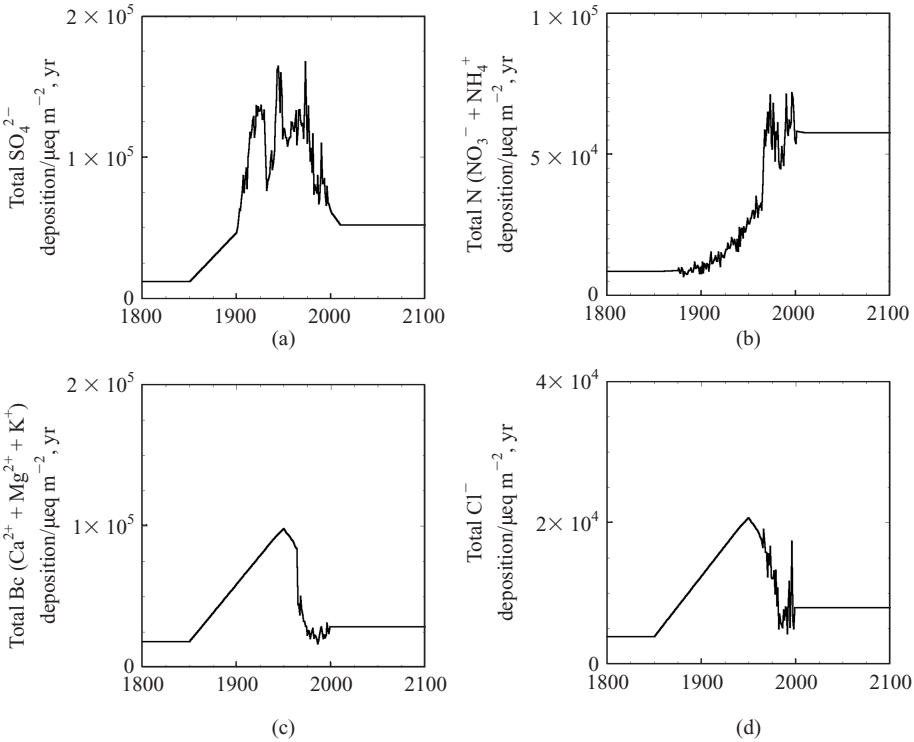


Figure 12.5: Deposition trends of (a) sulfate, (b) nitrogen, (c) base cations and (d) chloride as used in input for the ForSAFE simulation. Note that the scales are not similar on all graphs.



12.4 MODEL CALIBRATION

The ForSAFE model is calibrated on base saturation, soil organic carbon and the C/N ratio in the humus exclusively. The base saturation calibration estimates the size of the exchangeable pool of base cations at the start of the simulation, a value usually unknown, since it lies around the year 1800 or earlier. Calibration of the soil carbon pool estimates the size of the organic pool of carbon in the soil at the start of the simulation. The C/N ratio calibration estimates the retention potential of mineralised nitrogen in the soil organic matter

- *Base saturation*: The base saturation at the first year (1800) is adjusted up or down until the line passes through the 1983 value.
- *Carbon*: The calibration target value was the measured soil organic carbon value for 1983 in the forest floor (corresponding in Table 12.1 to the O horizon) (Huntington *et al.*, 1988). The calibration was carried out by varying the initialisation period to allow the soil carbon to accumulate to the measured point.

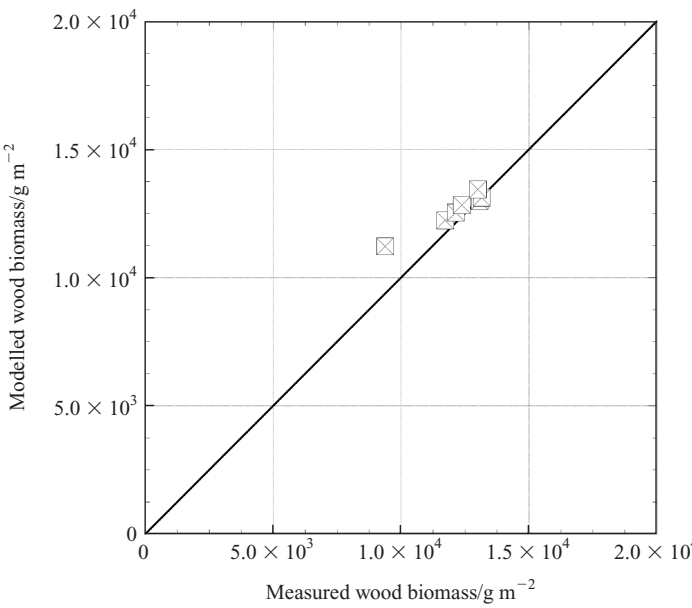
- *Nitrogen*: The C/N ratio was calibrated by modifying the nitrogen retention coefficient after mineralisation using target C/N ratio values for 1983 in the forest floor (corresponding in Table 12.1 to the O horizon) (Huntington *et al.*, 1988).

12.5 MODEL VALIDATION

To establish the validity of the model predictions at the site, data reproduced by the model were compared with those from field measurements. Time-series of measured data from HBEF-W6 were available through the HBES website. The validation carried out covers aspects of the biomass, soil solution chemistry, and runoff water.

The model reproduces the standing wood biomass reasonably well over the period from 1965 to 2002 over which measurements were available (Figure 12.6), although it does not replicate the observed slowdown and levelling off of biomass observed in W6 beginning about 1980, nor the slight decline of about −1.1% between 1997 and 2002 (Figure 12.10). The decline in the standing biomass was reported in the field as being driven largely by an increase in mortality of sugar maple (Juice *et al.*, 2006), indicating that species-specific responses may be very important to forest dynamics and model performance (see also Hawley *et al.*, 2007). The ForSAFE model

Figure 12.6: Comparison between modelled and measured values for the standing wood biomass (all trees greater than or equal to 2 cm dbh). Measured values are from the lower half of watershed 6 at the HBEF. Dead trees are not included in the comparison.



as currently configured does not account for species-specific responses, because of its reliance on Pnet for its forest growth component. In cases where forests are co-dominated by species especially sensitive to nutrient imbalances or other environmental factors, this limits the applicability of the model results. Because the decline between 1997 and 2002 is so small, it would be very relevant to pursue the comparison in the future to see whether the decline will persist and, if so, to identify the causes behind it and explain why the decline is not reproduced by the model. A thorough comparison of the measured nutrient contents in the tree parts and the modelled values would also give very valuable information about the change in the trees' nutrient balance, and give indications about their vulnerability to stresses.

The soil solution concentration of chloride and sulfate is indirectly used as a quality control on the deposition input data. A usual assumption is that there is no long-term net source of chloride and sulfate in the soil. For Hubbard Brook, the deposition was adjusted upwards (Figure 12.5c) until the chloride soil solution concentrations matched those observed. The model then reproduced the variation over time of chloride concentrations in the soil solution (Figure 12.7).

Because Cl is relatively inactive, its concentrations are dependent largely on the water content at the different soil depths. After modifying the deposition of Cl and finding that a good agreement with the measured values could be found, this gave an indication that sulfate deposition might also have been underestimated, and the modified deposition in Figure 12.5a was therefore adopted.

Soil solution pH is reproduced reasonably well by the model, as the measured and modelled values lie within close range of each other (Figures 12.8a and 12.8d). While the slight downward trend in measured pH in the Bs horizon is reproduced by the model, the model produces an upward trend in the Oa horizon, unlike the measured trend between 1983 and 1993 but similar to the measured trend thereafter.

Figure 12.7: Modelled and measured chloride concentrations in the soil solution at two different depths.

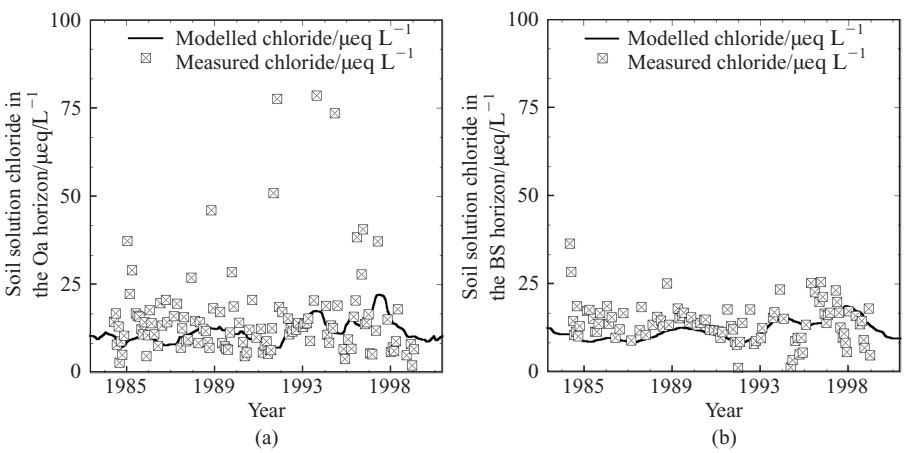
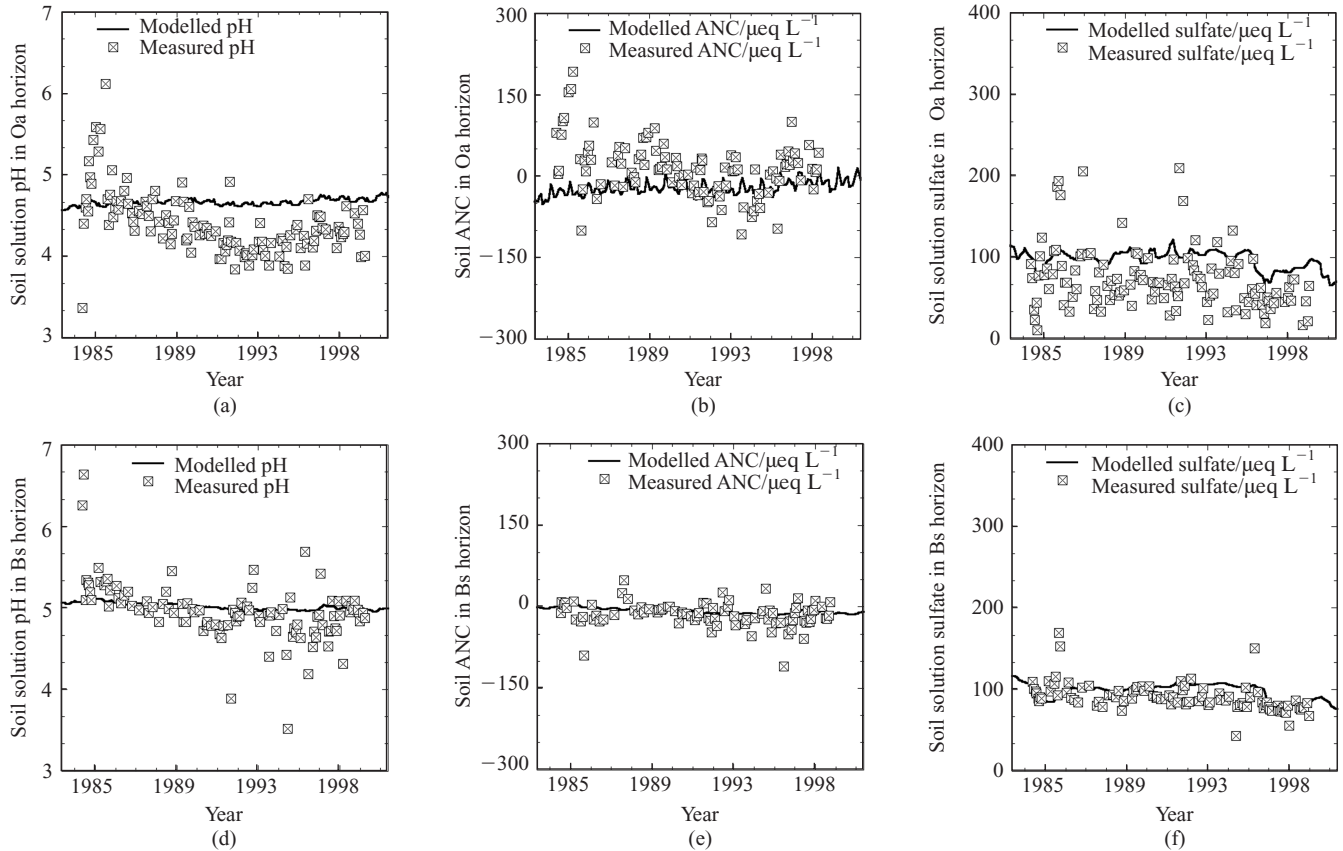


Figure 12.8: Measured and modelled values of soil solution pH, ANC and SO_4^{2-}.



The cause behind the discrepancy between the measured and modelled pH values in the Oa horizon can be traced back to the ANC (Figure 12.8b). The ANC trends changes towards the early 1990s because of a decrease in the concentration of sulfate, which is not reproduced to the same extent by the model (Figure 12.8c). Chloride is relatively chemically inactive in the soil as it percolates down through the soil profile, entering as deposition and leaving with the runoff water.

The soil solution concentrations of the sum of base cations (Bc) in the Bs horizon are slightly overestimated by the model (Figure 12.9d), but slightly underestimated in the Oa horizon (Figure 12.9a). The overestimation of Bc in the Bs horizon may be due to an overestimation of Bc uptake at that layer. Uptake is assumed to be directly proportional to the root distribution in the model. Aluminium is inversely related to the Bc content, and is slightly underestimated by the model, although it still reproduces the trends seen in the measurements (Figure 12.9e). The aluminium concentrations result from the updated gibbsite solubility coefficients adopted in Table 12.1. The Bc/Al ratio is clearly underestimated for the Oa horizon, but lies in the same range as the measured values in the Bs horizon. The modelled Bc/Al is well framed by the measured points (Figures 12.9c and 12.9f), although slightly towards the lower end in the Oa horizon.

12.6 RESULTS

12.6.1 Changes in the trees' biomass

The forest at W6 has been subject to three consecutive cuttings, visible in Figure 12.10 as vertical dotted lines. Prior to the first cutting, the biomass would have been nearly stable. At this stage, the increasing deposition of nitrogen (Figure 12.5b) was not sufficient to cause any increase in the growth rate of the biomass, probably because the severe nitrogen limitation in the ecosystem meant that nitrogen was rapidly immobilised by the soil biota, and was therefore made inaccessible to the trees. Following the second cutting, the model predicts a rapid recovery of the vegetation, probably as a combination of the increased availability of nitrogen and light as a result of the canopy opening caused by the cutting. The growth after the third cutting is also rapid, and is predicted to slowly approach a plateau significantly higher than the historical level of the 1800s.

The model does not predict any severe or lasting shortages of base cations, and no subsequent limitation to growth. On the contrary, the acidification of the soil caused by the elevated acidic deposition may have increased the availability of the base cations for uptake (Section 12.6.2), a process that has been described in many European forest ecosystems. As a result, the increase in growth may have been supported by soil acidification in the short to medium term (within 100 years in the future covered by the simulation). It may be possible, however, that the parameterised nutrient content ranges used for the model are not accurate, and that the forest would need more nutrients (in terms of base cations) than assumed in the model. Results from the watershed-scale calcium manipulation at Hubbard Brook suggest this may be

Figure 12.9: Measured and modelled levels of Bc and total inorganic aluminium concentrations as well the Bc/Al ratio in the Oa and Bs horizons.

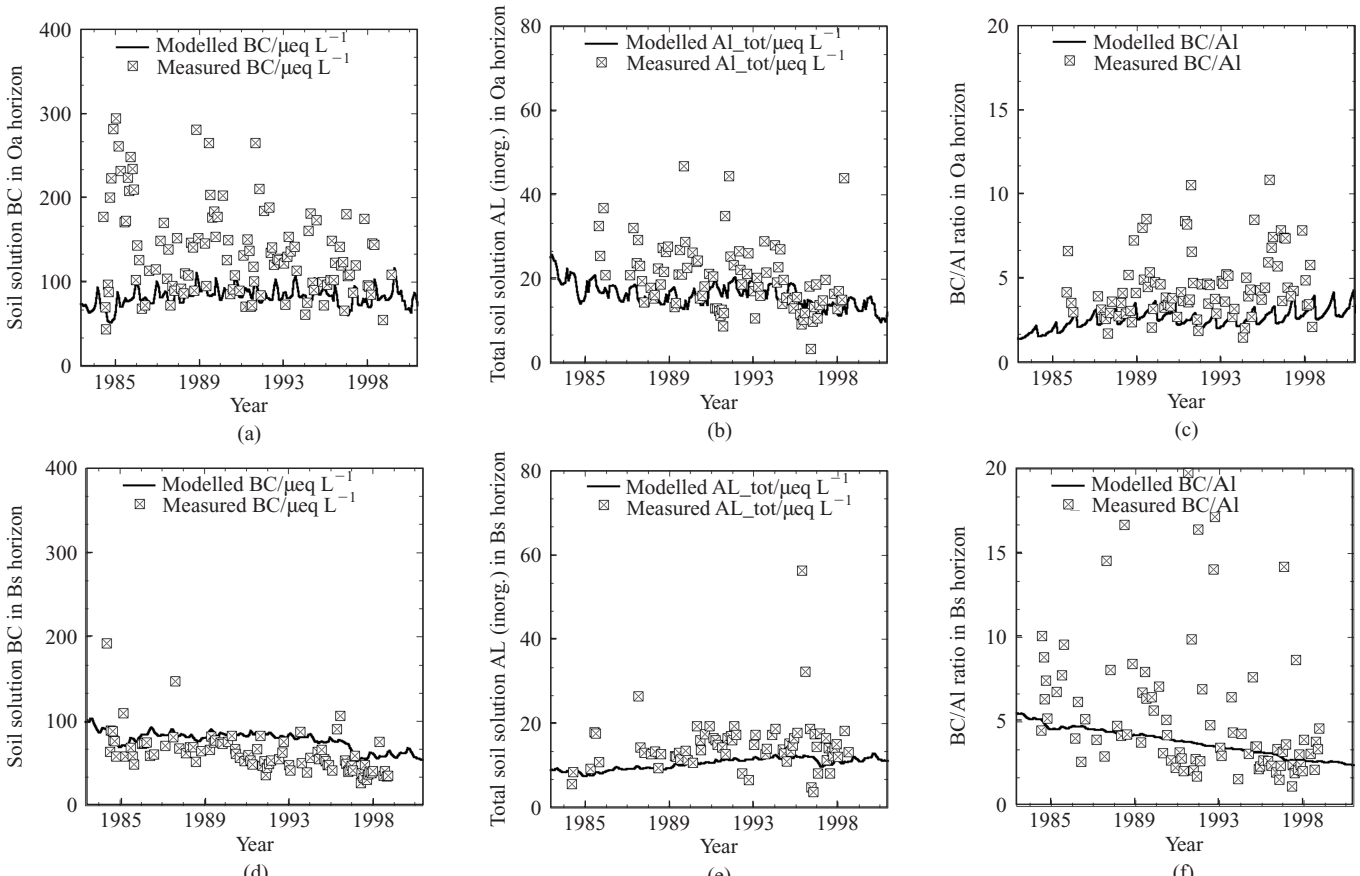
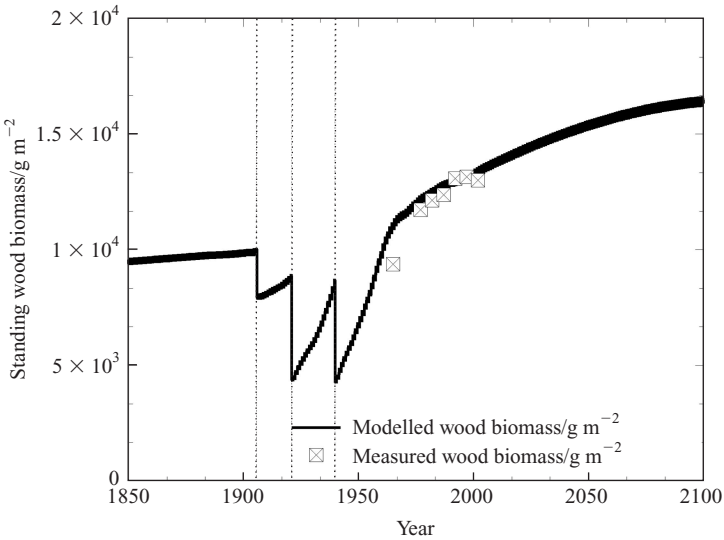


Figure 12.10: Evolution of the standing wood biomass at. The vertical lines show cuttings. Measured points represent the biomass of all live trees ⩾ 2 cm dbh on the lower half of watershed 6.



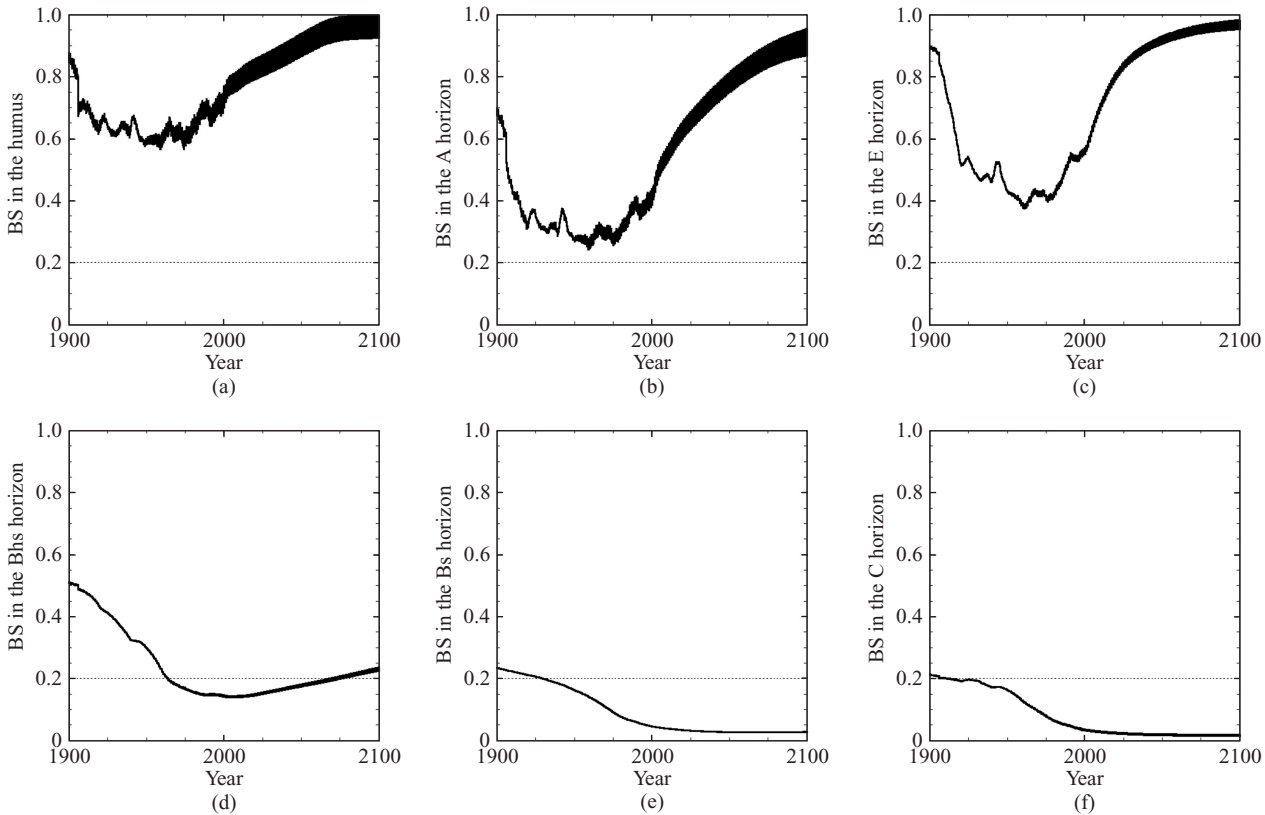
true. After an application of 1.2 tonnes of calcium per hectare in the form of a calcium silicate mineral (wollastonite), sugar maple (the tree species driving the levelling off and decline in biomass observed in W6) has responded with decreased mortality and increased crown condition and seedling survival (Juice *et al.*, 2006).

Another factor of importance is the absence of phosphorus in the model. The model is unable to predict any growth limitations if phosphorus becomes growth limiting, and may in that case overestimate the growth in the future. Also, the model predicts an increase in the biogeochemical cycling of Bc (litterfall, decomposition, uptake), and ignores the fact that the decomposed nutrients are partially available for uptake by the understory vegetation. The Bc made available in the upper layers through this process will in reality not be entirely available for uptake by the trees, suggesting that the model may overestimate the growth in the future. The foliage Bc requirement has been increased in this simulation, providing even more material to fuel the biogeochemical cycle, but still the model indicates only short-lived shortages of base cations that do not affect growth in the long term. It should be noted, though, that because of the increased nitrogen availability, the trees may become vulnerable to pathogen attacks, possibly explaining the decline seen in the measurements, but not reproduced by the model.

12.6.2 Soil acidification and nutrient status

The model simulation shows that the soil solution base saturation (BS) has declined through the entire soil horizon (Figure 12.11). The decline in the deeper layers has

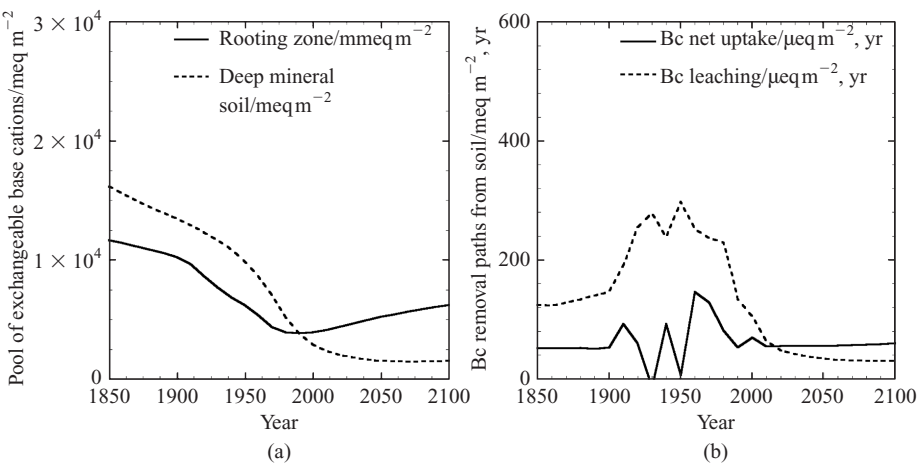
Figure 12.11: Base saturation has declined from historic levels at all the modelled soil depths. While the model shows a relatively rapid recovery in the upper three layers (a, b, c), the Bhs layer is expected to recover slowly (d), and no recovery is predicted for the lower two layers (e, f).



taken the BS below the critical line of 20%, indicating that the soils have been acidified (Figures 12.11d, 12.11e and 12.11f). The decline of BS in the lower three layers is related primarily to the deposition of sulfate. BS in the humus, A and E horizons has declined sharply, but unlike the mineral soil, it is predicted to recover fully within the next 100 years. The high availability of Bc, allowing for the replenishment of BS in the upper layers, is closely linked to the increased foliage Bc contents assumed. The Bc is returned to the soil after litterfall, and made available for uptake and adsorption after the litter decomposes. However, the high demand for uptake also means that less Bc is available to percolate down the soil profile, and therefore BS in the lower layers fails to recover. Acidification is typically accompanied by a loss of exchangeable base cations from the soil. This process is the result of an enhanced desorption of base cations from the exchange sites on the soil particles by the acid ions, particularly hydrogen and aluminium, in the soil solution. As the soil acidifies, more hydrogen ions are added to the soil solution and more aluminium ions are mobilised into the soil solution. These acid ions compete with the base cations for the exchange sites on the soil particle, and the net result of an increase in the former is that more of the latter is desorbed from the soil exchange sites. This increases the availability of base cations in the soil solution, where they become available for uptake by the trees or leaching.

Because weathering rates are typically very slow in comparison with the cation exchange process, the exchangeable pool of base cations (EBC) in the soil is considered to be the base cations capital of the soil. A loss of the EBC would mean an impoverishment of the nutrient (base cations) content of the soil. According to the model calculations, the soil has lost most of its exchangeable base cations between the years 1800 and 2000 (Figure 12.12a), primarily because of the acidification process

Figure 12.12: Base cation pools and pathways in the soil. For clarity, to avoid the inter- and intra-annual variations, the values presented are averages over 10 years.



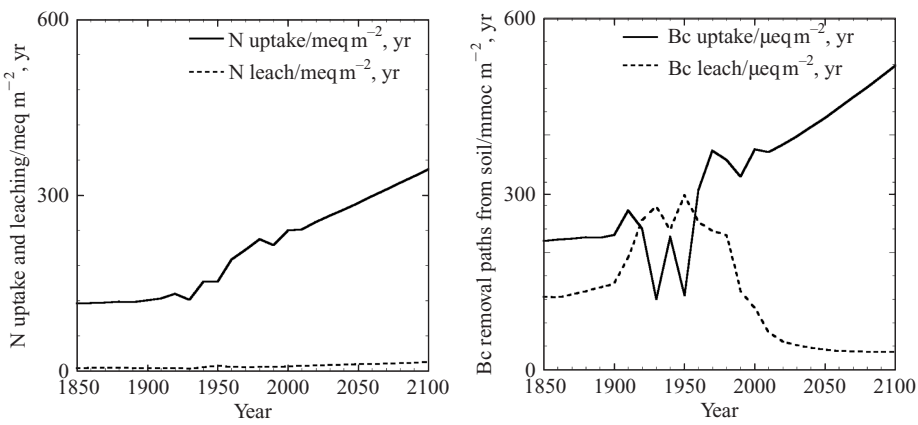
described above, and related to sulfur deposition and, to a lesser extent, nitrogen deposition. Even after a steady recovery between 2000 and 2100, the EBC pool would still remain lower than that at the year 1800 by 2100. The loss of the exchangeable base cations occurred both in the rooting zone and beyond in the deeper mineral soil.

The major pathways for base cation removal from the soil are leaching and uptake. According to the model, more base cations have historically been lost through leaching than through uptake (Figure 12.12b). This difference was even more evident as sulfur deposition increased, driving an amplification of Bc leaching. However, as sulfur deposition was reduced by the end of the 1990s, leaching declined below the level of uptake. Contrary to the past, more base cations will be removed from the soil through uptake than through leaching in the future, suggesting that uptake may become the principal pathway of Bc removal from the soil in the future.

While the net Bc uptake, which is equal to the difference between the gross uptake and mineralisation, may remain unchanged, the gross uptake of Bc will increase considerably (Figure 12.13b). The expected increase in mineralisation will provide most of the Bc for tree uptake in the future, explaining the gradual recovery of the EBC in the future. The increasing gross uptake of Bc will be driven by the increased nitrogen (Figure 12.13a). Nitrogen leaching will remain very low, but will more than double by the year 2100 (Figure 12.13a) as more nitrogen becomes available in the ecosystem.

To assess whether damage from the soil acidification has occurred or will occur, the Bc/Al ratio is a commonly used indicator (Nilsson and Grenfelt, 1988). Bc is the sum of phytoactive base cations: $Ca + Mg + K$ in molar equivalent amounts. Al represents the sum of inorganic positively charged aluminium ions, where Al^{3+} is the most important. The Bc/Al ratio gives an indicator of uptake inhibition, combining root damage by Al and nutrient Bc shortage, which can be directly linked to a

Figure 12.13: The gross uptake of Bc increases (b) following the increased N gross uptake (a). N leaching remains low, although it follows an upward trend.



limitation in tree growth (Sverdrup and Warfvinge, 1993). A value of 1 is used as a reference for Bc/Al, below which damage in the form of growth limitation is superior to 20% (Sverdrup and Warfvinge, 1993). However, in a more specific assessment, the actual response to root function is given by f as a fraction of unimpeded function ($f = 1$ at no effect level):

$$f = \frac{[\mathrm{Bc}]^n}{[\mathrm{Bc}]^n + k[\mathrm{Al}]^m} \tag{12.1}$$

where k is a plant-specific response coefficient; $n = m = 1$ for all conifers and grasses; and $n = 3$, $m = 2$ for most deciduous trees. Values of the coefficient k for about 300 of the most common European and North American trees and plants of the terrestrial ecosystems can be found in Sverdrup and Warfvinge (1993).

The model indicates that soil Bc/Al has declined throughout the soil profile (Figure 12.14). The declining pattern is expected to be reversed as sulfur deposition is reduced, and the accelerated biogeochemical cycle of Bc will cause a strong recovery in the A horizon, but a limited recovery in the mineral soil. The model results in Figure 12.14 suggest that the accelerated biogeochemical cycle resulting from a high Bc content in the foliage favours the upper soil layers' alkalinity at the expense of the lower soil layers.

12.6.3 Soil organic carbon and nitrogen

The model indicates that both soil organic carbon and soil organic nitrogen are expected to grow in the future (Figure 12.15a). However, the time-series soil organic

Figure 12.14: The soil Bc/Al ratio has decreased considerably, but is expected to recover slowly in the Bhs and Bs horizons. The weighed Bc/Al is reached by multiplying the ratio for each layer by the fraction of root content in that layer.

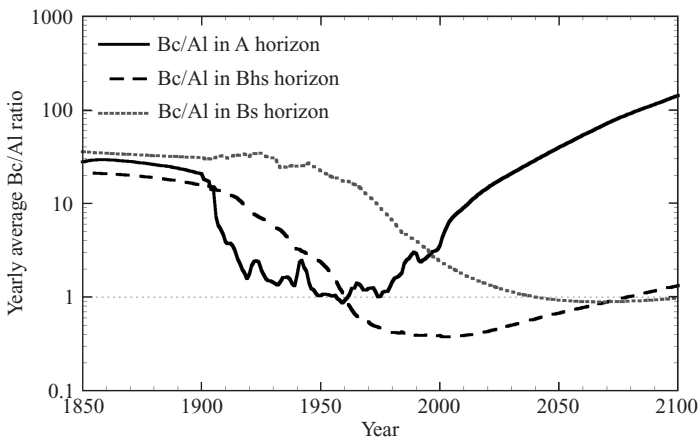
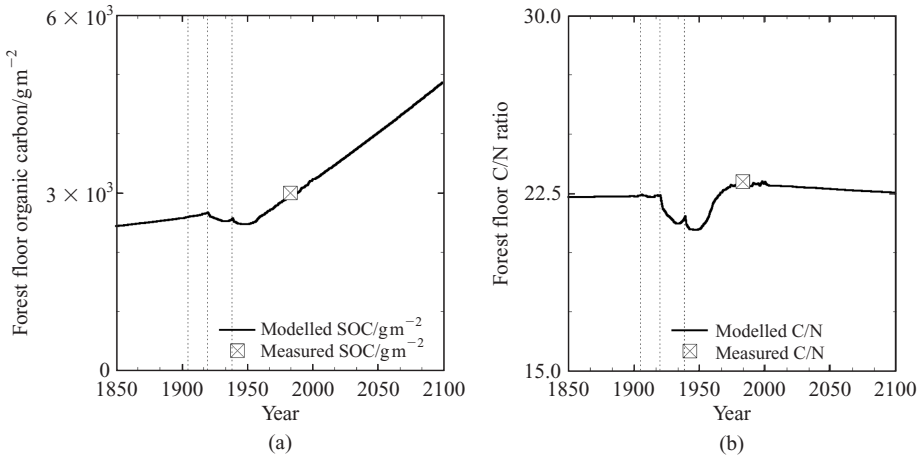


Figure 12.15: Under the assumption that growth is not impeded, both soil organic carbon and nitrogen are expected to accumulate. The C/N ratio would have increased by the year 2000 above its historical level, and is expected to start declining slowly in the second half of the 2000s.



carbon measurements from Hubbard Brook indicate that there has been no increase in soil carbon for the past 30 years, which calls the model predictions into question. The increasing size of the soil organic matter predicted by the model is the result of the increased litterfall, which in turn is a direct consequence of the modelled biomass growth (Figure 12.10). Since the data from watershed 6 appear to depart from the model with a flat or slightly declining biomass over the past 25 years, the reason for the difference between the modelled results and the actual data for soil organic carbon is likely to be the same as that which describes the departure of the modelled biomass from the measured values: that is, nutrient requirements for a nutrient-sensitive dominant species are not being captured by the model.

The C/N ratio puts the relative accumulations of soil organic carbon and nitrogen in perspective to each other (Figure 12.15b). The ratio would not have changed before the cuttings in the early 1900s, which removed part of the standing biomass and thereby part of the litter source. The cuttings caused a reduction in the ratio, but one that recovered as the forest grew back. The model shows a slight downward trends in the C/N ratio in the future as the elevated nitrogen deposition drives the system towards a more nitrogen-enriched state.

The modelled trends of soil carbon and nitrogen are flawed, as explained above. However, these trends point out the potential that the modelled ecosystem has for sequestering carbon in the soil as well as for retaining nitrogen, under the condition that enough carbon is supplied through litterfall. The decline in tree growth, caused by the loss of base cations following soil acidification, also results in a loss of the potential to sequester carbon and retain nitrogen in the soil.

12.7 CONCLUSIONS

The validation of the ForSAFE model at watershed 6 at the Hubbard Brook Experimental Forest (HBEF-W6) shows that the model can be used with reasonable confidence to reconstruct the past and predict the future changes in the soil status at the site. The simulation shows a clear decline in the exchangeable base cations pool in the soil, but fails to reproduce the effect of this decline on forest health.

The results from the model show a clear loss of alkalinity in the soil at HBEF-W6. This acidification of the soil can be linked to the elevated acidic deposition of sulfur and nitrogen. The model shows that the loss of base cations from the soil through leaching, as caused by sulfur deposition, has decreased substantially after the reduction of the latter. However, although the soil alkalinity will gradually recover in the future, it will remain far below the historical levels prior to the acidification, particularly in the lower soil levels. The elevated foliage Bc content assumed produces the effect that the biogeochemical cycle of Bc favours the retention of Bc in the upper layers of the soil. This effect is in accordance with the findings by Schroth *et al.* (2007).

Because of the current limitations in the model related to nutrient balances in the tree species present at the site, the model predicts no decline in tree biomass due to the acidification of the soil in the short and medium term. The measured trends of tree biomass as well as results from a calcium application experiment on an adjacent watershed show that negative effects on tree health due to soil acidification can already be seen. Although erroneous, the predicted growth trend shows a substantial potential for carbon sequestration in the tree biomass, and in the soil, if not hampered by nutrition imbalances caused by deficits in base cations.

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NOTES

1. http://www.hubbardbrook.org
2. http://www.hubbardbrook.org/data/dataset_search.php

1: Aber et al. (1992): not listed in references. Should it be Aber and Federer (1992) (which is not cited)?
2: This is not listed in the References.
3: This is listed in the References as 2006.
4: This is not cited in the chapter.
5: This is not cited in the chapter.
6: This is not cited in the chapter.
7: This is not cited in the chapter.