Chapter 23
Stand, Soil and Nutrient Factors Determining the Functioning and Management of Beech Forest Ecosystems: A Synopsis

R. Brumme and P.K. Khanna

23.1 Background and Issues

The three European beech ecosystems described in this volume differ in their soil chemical properties which are related to the differences in their soil parent materials. The ecosystems are located in an undulating landscape primarily formed by different geological formations of Triassic limestone (Göttinger Wald) and sandstone (Solling) with locally interspersed tertiary volcanic materials (Zierenberg) and loess. The difference in elevation between the three sites is less than 100 m and the distance is about 70 km, which provided comparable climatic conditions at the three sites. *Fagus sylvatica* L. is the dominating tree species at all three sites. *F. sylvatica* possesses wide physiological amplitude and can occupy a variety of sites, though its growth performance varies depending upon a number of factors such as genetics, climate and soil. The chemical state of a forest soil affects decomposition and bioturbation processes through its effects on the litter quality and faunal activity, and thus is the main driving variable for nutrient availability, acidity related stress, the productivity and stability of beech ecosystems.

The natural development of soils has, however, undergone significant changes in recent times due to atmospheric depositions which have accelerated soil acidification processes, have changed the activity of soil biota, have affected decomposition and nutrient turnover processes (short-term changes) and may have led to long-term changes in the soil organic matter content. High inputs of nitrogen by atmospheric deposition have increased forest growth. These inputs together with the increased application of dolomitic lime to improve soil acidity may have further affected the forest productivity. Emission control measures have reduced the deposition of H, S, N and base cations since the late 1980s causing additional impact on the future development of forest ecosystems (Meesenburg et al., Chap. 15). Considering these recent changes and their interactions, it still remains very difficult to predict the future development with respect to the productivity and stability of these forests.

R. Brumme and P.K. Khanna (eds.), *Functioning and Management of European Beech Ecosystems*, Ecological Studies 208,
DOI: 10.1007/b82392_24,

We envisioned that the wide differentiation in various ecosystem characteristics among the three beech sites described in this volume might provide ample background material to describe the functioning of these and other similar beech ecosystems. Therefore, data on N status from these three beech sites were compared with those of other beech forests in Germany, providing useful information on future trends in ecosystem development and relationships for developing site and stand management strategies. This synthesis section deals with some of these relationships where site factors and nutrient turnover processes are used to describe productivities (health and vitality) of these three ecosystems under the following headings:

(1) Productivity, C stocks, C balances, and their relations to soil chemical state of the three beech ecosystems
(2) N stocks and N balances at the three beech ecosystems
(3) Nutrient status and productivity of European beech ecosystems in a changing environment
(4) N-status and its significance for European forest ecosystems
(5) Dynamics of C and N sequestration in European forests
(6) Bioturbation as a central process of C and N dynamics: role of soil biota
(7) Forest management strategies – future perspectives

23.2 Productivity, C Stocks, C Balances, and Their Relations to Soil Chemical State of Three Beech Ecosystems

The three *F. sylvatica* stands are of similar age and have accumulated 520–690 m^3 ha^{-1} of merchantable wood in the above ground biomass (>7 cm diameter; Rademacher et al. Chap. 8). Annual increments in the long-lasting tree biomass compounds (branches, bark, wood and coarse roots) at the three sites were 1.15 Mg C ha^{-1} (Solling), 1.7 Mg C ha^{-1} (Zierenberg) and 3.3 Mg C ha^{-1} (Göttinger Wald) (Table 23.1). The annual net primary production (NPP) which included the annually recycled biomass compounds was lower at the Solling and Zierenberg sites (5.1 and 5.0 Mg C ha^{-1} per year) compared to the Göttinger Wald site (6.5 Mg C ha^{-1}). These NPP values are in the range reported for four beech forests (>100 years old) along a transect from Denmark to Italy (4.4–6.5 Mg ha^{-1} per year, Scarascia-Mugnozza et al. 2000). Differences in the carbon allocated to the leaves did not explain long-lasting biomass increment differences among the three beech sites, as their contribution to the NPP of the trees was similar (2.6–2.7 Mg C ha^{-1} per year) (Table 23.1). However, the production of fine roots on the three sites was different, it was about 1.3 Mg C ha^{-1} per year at the acid Solling site, and that compared to 0.6 Mg C ha^{-1} per year at the calcareous Göttinger Wald site. Positive effects of base cations on the growth and functioning of roots (Murach et al., Chap. 9) is expected to increase the uptake of nutrients and water, and to decrease the C-allocation to

Table 23.1 Net primary production (NPP) (Mg C ha^{-1} per year), annual C-balances (tree litterfall, Khanna et al., Chap. 11; tree fine roots, Murach et al., Chap. 9; herb litter, Schulze et al., Chap. 10), and changes in C-pools per ha at Solling, Göttinger Wald, and Zierenberg (DOC losses, Brumme et al., Chap. 16; above ground increment, Rademacher et al., Chap. 8; C-changes in soil, Meiwes et al., Chap. 4). (sd or range in parenthesis)

		Solling	Zierenberg[a]	Göttinger Wald
NPP of vegetation		5.1	5.4	6.7
NPP of trees		5.1	5.0	6.5
		Soil C-Balances		
Litter production	Tree litterfall	2.6 (0.7)	2.7	2.6 (0.8)
	Fine-roots from trees	1.3	ND	>0.6[b]
	Herb[e]	0.01	0.42 (0.36–0.82)	0.22 (0.04–0.43)
	Total	3.9	≈3.7	>3.4
Decomposition[d]		2.6/1.6	−/2.1	−/2.4
DOC losses		0.01	0.02	0.02
Total C-production – decomposition		+1.3/+2.3	−/+1.6	−/+1.0
		C-pool changes		
Tree increment[c]		+1.15	+1.7[f]	+3.3
O-horizon increment (1966–2001)		+0.35	ND	ND
Mineral soil increment (1966–2001)		0	ND	ND

[a]Assuming a fine-root litter production similar to that at Göttinger Wald
[b]This value could be higher since it considers only 0–20 cm soil depth (Solling 0–50 cm) due to high stone content
[c]Including branches, bark, wood and coarse roots
[d]Decomposition refers to field measurements of soil respiration at rooted and nonrooted locations (Brumme et al., Chap. 17) and to C-mineralisation studies (values given behind the slash; Brumme et al., Chap. 13)
[e]Weighted mean values and range of means of different facies calculated by the use of C-concentrations of 45% for Göttinger Wald and Solling and 42% for Zierenberg (Bolte 2006)
[f]Calculated by using an average of the functions between biomass of various tree components and tree basal area for Göttinger Wald and Solling (Chap. 8, personal communication, Rademacher)

the fine root biomass by increasing the longevity of fine roots. The higher amount of NPP required for the production and the maintenance of fine roots at the Solling site may partly explain the relatively low carbon gain for aboveground growth at this site. The high soil acidity at this site may create additional soil chemical stress for the aboveground growth by limiting the availability of base cations. Low soil availability of base cations has resulted in very low content of Ca, Mg and K in the leaves, whereas high values of leaf N content indicated its luxurious nutrition (Khanna et al., Chap. 11). Relationships between N uptake for growth increment, an index of NPP, soil pH and the content of Mg in leaves of 17 beech forests in Germany indicated that growth rates were low on soils with low base saturation (Fig. 23.3). However, the low NPP value at the base-rich Zierenberg site may be the result of low tree density in comparison with the Göttinger Wald site (Rademacher et al., Chap. 8) which in turn favoured the growth of ground vegetation by providing high light intensity below the tree stands (Schmidt, Chap. 5). The luxuriant growth of ground vegetation has increased the NPP of the Zierenberg site by about 0.4 Mg C ha^{-1} per year and of the Göttinger Wald site by 0.2 Mg C ha^{-1} per year.

Data on balancing of C fluxes and on periodic inventories of soil C (Table 23.1) indicated that the soil at the Solling site was accumulating C. The total carbon input to the soil at the Solling site was 3.9 Mg C ha^{-1} per year and consisted primarily of litterfall (67%) and fine-root litter (33%). The litter input by ground vegetation is low. The total carbon loss by decomposition processes ranged from 1.6 to 2.6 Mg C ha^{-1} per year and the remaining 1.3–2.3 Mg ha^{-1} would have accumulated annually. Soil inventories conducted periodically at the Solling site partly confirmed these results. The organic carbon stock in the surface organic layer increased by about 0.35 Mg ha^{-1} per year over a period of 35 years (Meiwes et al. 2002, Chap. 4). No change in the carbon stocks of the mineral soil layer at the Solling site was observed due to large spatial variation primarily in the 0–10 cm of the mineral soil. Amount of leaffall, however, appears to be constant at the Solling site as shown by the data since 1990 despite the temporal annual variation in these values (Khanna et al., Chap. 11). However, fructification has more than doubled the total litterfall and frequency of fructification has increased during the last few decades. Thus, litter production and its decomposition may not be in equilibrium. Additional factors reducing decomposition are related to atmospheric depositions. Many studies on N fertilisation has shown that fertilisation leads to retarded decomposition (e.g. Fog 1988; Berg and Matzner 1997; Olsson et al. 2005). Therefore, high N depositions are expected to have a similar effect in retarding litter decomposition. However, Sjöberg et al. (2004) suggested that humus accumulation under high acid depositions might result from more than one factor.

The carbon dynamics at the Göttinger Wald and Zierenberg sites differed from that at the Solling site due to higher productivity of the vegetation on the former sites. At the Göttinger Wald and Zierenberg sites, the surface organic layer was small and was mostly covered by ground vegetation. Ground vegetation produced about 0.2 and 0.4 Mg C ha^{-1} per year litter at these sites (Table 23.1). Production of high amounts of ground vegetation litter and low amount of fine root litter may commonly occur on less acid soils (Murach et al., Chap. 9 and Schulze et al., Chap. 10). Amounts of C retained when assessed from soil-C balance indicated values of +1.0 Mg at Göttinger Wald and +1.6 Mg C ha^{-1} per year at Zierenberg site.

Amounts of C retained annually by the soils of the three beech sites was similar to the value estimated by Schulze (2000) (1.44 Mg C ha^{-1} per year) for a European transect. The values obtained by using models indicated that 100–600 kg C ha^{-1} per year were retained in soils which were primarily related to differences in litterfall and thus tree growth (Nabuurs and Schelhaas 2002; Liski et al. 2002). Our estimates of C retention are not confirmed by the nitrogen balance measured on these three beech sites (see Sect. 23.3) suggesting that C mineralisation rates may be underestimated which would overestimate the C sequestration in the soils. Our C mineralisation estimates are based on differences between rooted and root-free areas at the Solling site which would depend on a number of factors, e.g. the dynamic of roots and associated root exudates after clearing (Brumme et al., Chap. 17). Incubation studies may under- or overestimate C mineralisation, e.g. by excluding root related inputs of C or by causing higher decomposition through physical soil disturbance (Brumme et al., Chap. 13). However, N balances seem to be a useful alternative to estimate C sequestration in forest ecosystems (Holland et al. 1997; Nadelhoffer et al. 1999; deVries et al. 2006). Based on calculated N retention rates in soils (N deposition minus net N uptake minus N leaching) and their C/N ratios, deVries et al. (2006) estimated an annual net C sequestration of 143 kg ha^{-1} for forest soils in Europe. Berg et al. (2007) reported similar values of between 96 and 180 kg C ha^{-1} per year for Sweden which they estimated with three different methods. Since an annual sequestration rate of 120 kg C ha^{-1} equals only 3% of litter production which is lower than the error involved in such measurements, for example, by soil respiration measurements, it illustrates the performance of using soil N changes as a useful method.

23.3 N Stocks and N Balances at Three Beech ecosystems

Atmospheric depositions of N at the three beech sites ranged from 21 to 25 kg N ha^{-1} per year in the period 1990–2002 and were not significantly different among the sites (Table 23.2). However, N-balance on these sites indicated a completely different fate of the atmospheric deposited nitrogen. Losses of N by seepage water at the three sites were 1.7 kg ha^{-1} per year (Solling), 21 kg ha^{-1} per year (Zierenberg) and 4.5 kg N ha^{-1} per year (Göttinger Wald). The gaseous N-losses as nitrous oxide were of the same magnitude as the leaching losses at the Solling site but were negligible at theGöttinger Wald and Zierenberg sites. Therefore, about 84 and 76% of the atmospheric deposited nitrogen were retained at Solling and Göttinger Wald sites, respectively, with much lower values (13%) at the Zierenberg site.

When the N-balance method is employed to calculate the amount of N retained at the Solling site, the value was quite high, being 21 kg N ha^{-1} per year for the period 1990–2002 and 36 kg N ha^{-1} per year for 1981–1989 (Table 23.2). Similar values were obtained by periodic soil N-inventories conducted on the site since 1966. The amount of N-retention in the surface organic layer was large (about 21 kg N ha^{-1} per year) and was three to four times higher than that observed in the long-lasting tree components (branches, bark, wood and coarse roots) at the Solling site (6 kg N ha^{-1} per year). During the period 1969–2002, the total N deposition decreased from 40 (1969–1989) to 25 kg N ha^{-1} per year (1990–2002) (mean for the whole period was 35 kg N ha^{-1} per year). The mean value was close to the amount that was calculated (27 kg N ha^{-1} per year) to accumulate in the tree growth and the surface organic layer increments during the same period. The decrease in atmospheric N depositions has resulted in an equivalent reduction in the amount retained by the soil while the leaching losses did not change during this period (Fig. 23.1). The soil N-balance conducted by the amount of annual nitrogen input by litter minus the net N-mineralisation confirmed the observation from the ecosystem N-balance that nitrogen is sequestered in this soil at the Solling site.

Table 23.2 N-balances on the three beech sites for the period 1990 – 2002 (period 1981–1989 in parenthesis for Solling and Göttinger Wald). Values were taken for input (Meesenburg et al., Chap. 15); output (Brumme et al., Chap. 16); N_2O (Brumme and Borken, Chap. 18); tree litterfall (Khanna et al., Chap. 11); tree fine roots (Murach et al., Chap. 9); herb litter (Schulze et al., Chap. 10); uptake by trees (Rademacher et al., Chap. 8, for Zierenberg Brumme et al., Chap. 16); and C-changes in soil (Meiwes et al., Chap. 4). All values are given in kg N ha^{-1} per year

		Solling	Zierenberg	Göttinger Wald
		Ecosystem N-Balances		
Uptake by trees		110–113	98–110[a]	99–107
Input	Wet and dry deposition	25 (40)	24	21 (26)
Output	Leaching losses	1.7 (2.0)	21	4.5 (9.5[b])
	N_2O losses	1.9	0.4	0.2
Input – Output		+21 (+36)	+3	+16 (+16)
		Soil N-Balances		
Litter-N input	Tree litterfall	68	75	63
	Fine roots from trees[d]	36–39	ND	18–26
	Herb	<0.4	36	21–31
	Total	104–107	129–137[a]	102–120
NMM[e]		74/90	80/128–167	99/ND
		N-Pool Changes		
Tree increment[c]		6.0	5–9	18
O horizon increment		21	ND	ND
Mineral soil increment		0	ND	ND

[a]Assuming a fine-root production similar to that on the Göttinger Wald site
[b]First year of measurements with untypical high N losses (see Chap. 16) was excluded
[c]Including branches, bark, wood and coarse roots
[d]Range refer to dead and living roots containing different N concentrations
[e]NMM (net N mineralisation, is given for “long-term soil column field experiment” and the “in situ sequential coring method,”; Brumme et al., Chap. 13)

The sequestration of N in the surface organic layer provided an estimate of C sequestration at the Solling site. Assuming a C/N ratio of the sequestrated organic matter to be 19, the same as in the surface organic layer, the annual amount of C sequestration was calculated to be 580 kg ha^{-1} for the period 1981–1989 and 313 kg ha^{-1} for 1990–2002. The mean C sequestration value for the whole observational period is thus 422 $\pm$ 170 kg ha^{-1} which comes close to the amount estimated by soil inventories (347 kg C ha^{-1}; Meiwes et al., Chap. 4). It also suggests that the sequestered organic matter may have a lower C/N ratio. A C/N ratio of 15.5 in the sequestrated organic matter would meet the amount of carbon estimated by inventories.

The amount of N retained annually (input-output) at the Göttinger Wald site for the period 1990–2002 was 16 kg N ha^{-1} which was 2 kg N ha^{-1} lower than the annual amount of N retained by the aboveground tree increment (18 kg N ha^{-1} Table 23.2). For the period 1981–1989, total N-deposition was about 5 N ha^{-1} per year higher. The higher depositions during 1981–1989 led to equivalently higher leaching losses indicating that the capacity to immobilise additional N in the soil and through plant uptake at this site is independent of the amount of N present in atmospheric depositions (Fig. 23.1). This is quite a different result from that observed at the highly acid Solling site where the amount of N input by depositions was nearly completely retained in the soil.

At the Zierenberg site, a small fraction (13%) of the total N deposited as atmospheric inputs was retained (3 kg N ha^{-1} per year) because most of it was lost by leaching (Table 23.2). Considering the amount of N required for plant growth at the Zierenberg site, stored soil N remains the main source of nitrogen supply (2–6 kg N ha^{-1} per year). Nitrate leaching increased with an increase in precipitation suggesting that the general trend to higher precipitation during the non-growing season (Panferow et al., Chap. 2) is expected to increase leaching losses at this site. Assessing N-retention from litter production and mineralisation studies does not always provide reliable values. By using the leaching method, low

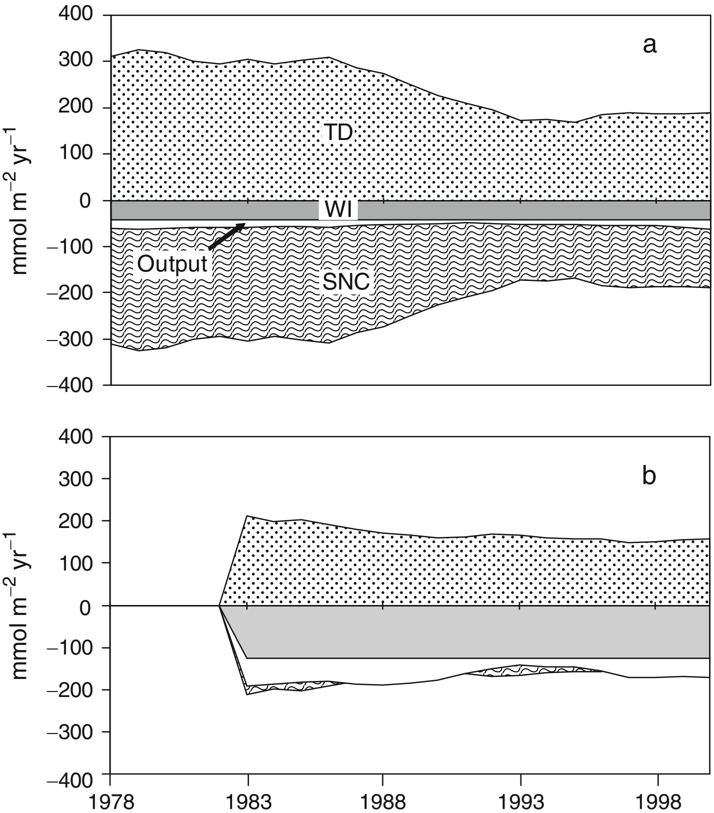

Fig. 23.1 Time series of budgets (5-year moving average) of *TD* (total deposition, dry and wet deposition), soil-N-change (*SNC*), output with seepage (*output*) and wood increment (*WI*) at (**a**) Solling and (**b**) Göttinger Wald (mmol$_c$ m^{-2}) (adopted from Meesenburg et al. Chap. 15 and Brumme et al. Chap. 16)

mineralisation rates (74 ± 14 kg N ha^{-1} per year) suggest an accumulation of N at Zierenberg site. The high mineralisation rates of 128–167 kg N ha^{-1} per year measured with the in situ sequential coring method would cover the amount of N-input by litterfall. Ulrich (1987) suggested that high N mineralisation rates might result from humus degradation in this soil. The degradation would occur when soil is acidified and is shifted from the silicate type of proton buffer range to the exchanger type of proton buffer range (see Sect. 23.4 for more information).

23.4 Nutrient Status and Productivity of European Beech Ecosystems in a Changing Environment

Atmospheric depositions of acidity and nitrogen have changed the soil chemical and nutritional status of forests, particularly of those having low buffering to soil acidification changes. The trend of increasing atmospheric depositions peaked in 1980–1985 across Europe (Ferrier et al. 2001). By that time, it has reduced soil pH by up to 2 units and base saturation by up to 50% and has increased the N content in the litter layer (Brumme et al., Chap. 21). Long-term monitoring at the Solling and Göttinger Wald sites indicated that atmospheric depositions have declined when emission control measures were introduced in Europe and structural changes in the industry had occurred. Total depositions decreased for sulphur (-60% at the Solling and Göttinger Wald sites) and H (−72% at the Solling and Göttinger Wald sites) between the 1981–1989 and 1990–2002 periods (Meesenburg et al., Chap. 15). These changes in the atmospheric inputs caused an increase in the dissolution of aluminum sulphate stored in soils and led to the release of stored acids in the drainage water. However, this decrease in acid inputs also simultaneously decreased the inputs of base cations (−60% at Solling and Göttinger Wald). Long-term annual budgets indicated that the Solling soil which was previously a sink for Ca and sulphate became a net source of these elements during the last three decades (Fig. 23.2), and thus delayed the recovery of this soil from acidification.

The nutritional status of 17 beech forests in Germany (Haußmann and Lux 1997), which belonged to the intensive forest monitoring programme (Level II) of the international cooperative program on assessment and monitoring of air pollution effects on forests, ICP Forests, indicated that Ca was insufficient at seven beech sites, Mg at four sites, P at three sites and K at two sites, whereas no forest site had insufficient nutrition of N (Table 23.3). Among these sites, eight had moder type humus, of which five sites had Ca deficiency. Similar results were observed, with an exception for P, for the German forest inventory sites (Wolff and Riek 1997a, b) which included a higher number of beech stands ($n = 75$) in Niedersachsen, Brandenburg, and Bayern States. Among these stands, about 54% of the beech forests were described as P-deficient. Despite a reduction of N deposition caused by emission control in Europe (−38% at Solling and −20% at Göttinger Wald), N deposition was in excess of the demand for plant increment at

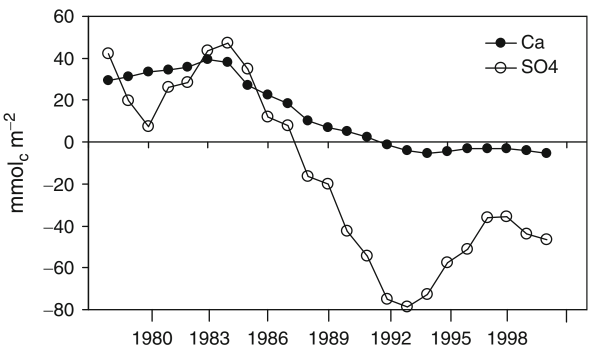

Fig. 23.2 Time series of Ca budgets (total deposition + weathering – plant increment – seepage losses) and sulfate budgets (total deposition – seepage losses) (5-year moving averages, mmol$_c$ m^{-2}) at the Solling site (adopted from Brumme et al. Chap. 16)

Table 23.3 Number of beech forests (17 German forest sites (Level II) including Solling (*SO*), Göttinger Wald (*GW*), Zierenberg (*ZB*), Haußmann and Lux 1997) with element content (1996–2003) in leaves in the ranges of insufficient, sufficient, or luxurious plant nutrition for N (<20.3, 20.3–23.8, > 23.8 mg g^{-1}), Ca (<5.8, 5.8–8.6, 8.6 mg g^{-1}), Mg (<0.99, 0.99–1.43, > 1.43 mg g^{-1}), P (<1.14, 1.14–1.52, > 1.52 mg g^{-1}), K (<5.4, 5.4–7.3, > 7.3 mg g^{-1}), according to Krauß and Heinsdorf (2005)

	N	Ca	Mg	P	K
Insufficient	0	7, SO	4, SO	3, GW	2
Sufficient	10, ZB	6	6, GW	13, SO, ZB	9, SO, ZB
Luxurious	7, SO, GW	4, GW, ZB	7, ZB	1	6, GW

all stands of the Level II sites by up to 27 kg N ha^{-1} per year. The net N retention by beech trees ranged from 6 to 20 kg N ha^{-1} per year (mean value of 13 kg N ha^{-1} per year, Becker et al. 2000). The Solling site thus has N retention value at the lower end (6 kg N ha^{-1} per year), whereas the Göttinger Wald site is at the upper end (18 kg N ha^{-1} per year), and the Zierenberg site is between the two (5–9 kg N ha^{-1} per year), of the range of values given for annual amounts of N retained (Table 23.2).

The retention of N at the German Level II beech forests is correlated significantly with Mg (r^2 = 0.45) and Ca contents (r^2 = 0.33) in leaves and with the soil acidity given as pH in soil solution (r^2 = 0.41), pH in humus layer (r^2 = 0.48) and the base saturation in the surface mineral soil layer (r^2 = 0.36) (Fig. 23.3). Since plant N increment is not correlated with indices of N availability (total N depositions, N content in the foliage and soils, C/N of surface organic layers, N content in soil solutions), base cations may be considered as an important factor determining plant growth in these high N ecosystems. This would suggest the need for an additional supply of Ca and Mg by liming the forest sites. Liming has significantly increased

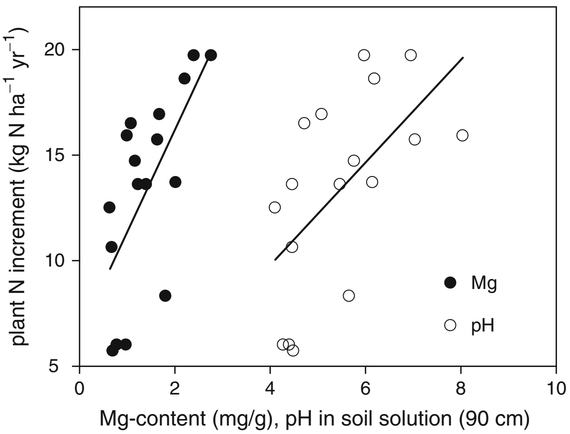

Fig. 23.3 N increment (kg N ha^{-1} per year) in plant growth components (Becker et al. 2000) in relation to Mg content in leaves and soil pH($CaCl_2$) in 20–40 cm depth for 17 beech forests of Level II sites in Germany

the Ca and Mg content in foliage at several sites in the Solling area which received dolomite (Rademacher et al., Chap. 8) and has contributed to an increase in growth (Fig. 23.3). The mean foliage level of the 17 beech sites indicates sufficient N concentrations (23.9 mg g^{-1}) indicating clearly that atmospheric N depositions have removed the N limitation in these forests.

In recent decades, aboveground growth of trees has increased (Spiecker 1999; Kauppi et al. 1992), with values of 25–30% increase in Europe during 1971–1990 (Kauppi et al. 1992). For most cases, tree growth increments since the 1950s have much higher values than could be predicted by common yield tables (Pretzsch 1996). Forest inventories have indicated an increase of 10–20% in the standing volume during 1971–1987 in southern Germany which exceeded the yield table values by 12–43% (12% for broadleaved, 27% for oak, 31% for spruce and fir, 43% for pine and larch). A weighted mean growth increment considering the proportions of tree species showed an annual increase of 29% in Germany. By assuming an annual aboveground wood increment of 2.6 Mg C ha^{-1} per year between 1987 and 1993 (Dieter and Elsasser 2002), the additional C-sequestration can be calculated to be about 0.58 Mg C ha^{-1} per year in Germany. This increase in the growth of wood may be due to many reasons. Firstly, N status of European forests has improved due to high atmospheric inputs. Availability of some other nutrients in soils may have been reduced by acid depositions, but depositions of base cations prior to emission control measures were implemented might have compensated for any losses. Secondly, dolomitic lime has been extensively applied to many forests in Germany to improve the calcium and magnesium availability in soils. Thirdly, an increase in the concentration of atmospheric CO_2 and nitrogen depositions may have increased the photosynthetic activity to compensate for losses of foliage and fine roots turnover due to acid depositions.

23.5 N-Status and Its Significance for European Forest Ecosystems

N enrichment of forest ecosystems has a number of consequences relating to their productivity, vitality, soil acidification, N use, N losses via different means and effects on neighboring systems. Input–output analysis has been shown to be a useful tool to quantify small changes of elements which occur in large stocks of elements in soils (Ulrich 1992; Matzner 2004) that could otherwise remain undetected by repeated sampling commonly done in ecological studies. Brumme and Khanna (2008) used 8-year records (1996–2003) of input–output analysis to evaluate changes in the N status of 53 German forest sites (Haußmann and Lux 1997; Block et al. 2000) belonging to the intensive forest monitoring program (Level II) of the international cooperative program on assessment and monitoring of air pollution effects on forests (ICP Forests) operating under the UNECE Convention on Long-range transboundary air pollution. Of the 53 forest sites, 17 sites are occupied by beech, 15 by spruce, 12 by pine and nine by oak. Trees are 60 to more than 130 years old. Some important site and stand characteristics are given in Table 23.4. Of the 17 beech forests, nine had mull type humus and eight had moder type humus with C/N ratios of 14–21 in the upper mineral soil (mull type humus) and 19–39 in the surface organic layer (moder type humus).

These forest sites were distinguished into three groups based on the following criteria where total deposition (TD) referred to the annual amount of total N deposition including wet and dry depositions, WI to the amount retained by wood increment and O to the amount lost by nitrate leaching.

$TD - WI = O$	(quasi-) Steady-state type	(I)
$TD - WI > O$	Accumulation type	(II)
$TD - WI < O$	Degradation type	(III)

Amounts of gaseous N-losses were not included here because estimates of fluxes of all gases (N_2O, NO, N_2) do not exist on the regional scale. High fluxes of gaseous N losses are estimated to occur at only a few sites (Barton et al. 1999; Brumme et al. 2005; Kesik et al. 2005) and are assumed to be equal to atmospheric N fixation at most of the sites. Considering this uncertainty and other errors in the estimates of water fluxes, total N deposition, wood increment and leaching losses, an annual uncertainty of ±5 kg ha^{-1} above and below the 1:1 line in Fig. 23.4 was used to distinguish the patterns of N changes among different sites.

Forest sites between the two parallel lines in Fig. 23.4 represent those where the excess of total deposition (TD_{ex}) is balanced by nitrate leaching assuming an uncertainty of ±5 kg N ha^{-1} per year. Such forest sites are considered to be of the (quasi-) Steady-State Type with respect to N ($n = 23$ of which eight were occupied by beech). Sites located on the outside to the left of the lines lose nitrogen in excess of total N-deposition larger than 5 kg N ha^{-1} per year suggesting that soil

Table 23.4 Stand characteristics of forests at different N states (means, min and max in parenthesis) (three sites of the degradation type are not shown)

	N	Total deposition	Plant N-increment	N leaching	Soil N change	pH 20–40 cm	base sat. 20–40 cm	N 0–5 cm	C/N[a]	Foliage N	Precipitation	Mean annual temperature
	0–5 cm	kg N ha^{-1} per year				(CaCl$_2$)	%	%		%	mm per year	°C
Beech forests												
All beech sites	16	21 (18–31)	13 (6–20)	5 (0–25)	3 (−24–11)	4.4 (3.7–7.3)	39 (4–99)	0.43 (0.09–0.7)[b]		2.4 (2.2–2.7)	850 (700–1,200)	8.0 (6.4–9.9)
(quasi-) steady state												
Mull	4	20 (19–22)	17 (14–20)	1 (0–5)	2 (−2–5)	4.9 (4–7.3)	65 (14–99)	0.41 (0.2–0.7)	17 (14–21)	2.3 (2.2–2.6)	720 (700–780)	8.2 (7.6–8.9)
Moder	4	21 (18–24)	14 (8–17)	8 (2–16)	−1 (−5–4)	4.1 (4–4.2)	13 (4–21)	0.25 (0.2–0.3)[b]	22 (20–23)	2.5 (2.4–2.6)	920 (820–1,040)	7.8 (6.4–9.9)
Accumulation type												
Mull	4	21 (19–27)	10 (6–16)	3 (1–6)	8 (6–10)	4.3 (3.7–4.9)	59 (11, 84)	0.50 (0.3–0.7)	17 (16–18)	2.5 (2.3–2.7)	850 (760–980)	7.9 (7.1–8.6)
Moder	4	22 (15–31)	11 (6–15)	2 (0–7)	9 (6–11)	4.1 (3.9–4.2)	12 (4, 24)	0.27 (0.1–0.5)	27 (19–36)	2.3 (2.2–2.4)	930 (740–1,200)	8.2 (6.5–9.1)
50 forest sites												
(quasi-) steady state	23											
Mull	8	18 (12–23)	15 (9–20)	2.3 (0.1–7.6)	1.1 (−3–5)	5.2 (4–7.6)	70 (8–100)	0.43 (0.2–0.7)	16 (13–21)	2.3 (1.9–2.7)	780 (700–1,080)	8.7 (7.6–11)
Moder-mor	15	17 (7–33)	10 (5–17)	5.8 (0.1–19)	0.7 (−5–4.5)	4.2 (4–4.4)	13 (4–29)	0.35 (0.1–0.9)[b]	25 (20–29)	spruce: 1.5 (1.3–1.6) deciduous: 2.5 (2.4–2.6)	780 (490–1,200)	7.9 (6.0–9.9)
Accumulation type	27											
Mull	6	21 (19–27)	10 (6–16)	2.5 (0.9–5.8)	9.1 (7–14)	4.1 (3.7–4.9)	53 (8–84)	0.49 (0.3–0.7)	16 (14–18)	deciduous: 2.4 (2.1–2.7)	850 (620–1,080)	8.1 (7.1–9.1)
Moder-mor	21	23 (10–37)	8 (4–15)	3.8 (0–13)	11 (6–21)	4.1 (3.2–4.6)	6.4 (2–16)	0.22 (0.02–0.6)	26 (19–36)	spruce: 1.4 (1.2–1.5) deciduous: 2.4 (2.2–2.6)	935 (560–1,320)	7.5 (5.5–9.7)

[a]C/N is given for the top mineral soil (mull) and the litter layer (moder)
[b]Excluded is one unusually high value of 1.4%

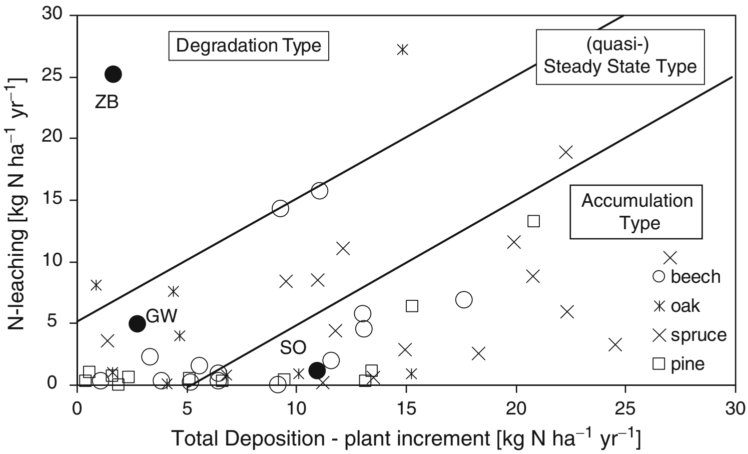

Fig. 23.4 Nitrate leaching (Block et al. 2000) versus total nitrogen deposition (Gehrmann et al. 2001) in excess of N-uptake by aboveground wood increment (Becker et al. 2000) of 53 Level II forests in Germany occupied by beech, oak, spruce and beech trees. The *lines* divide forests into three N-states, forests with decreasing amount of soil organic matter and N losses from soil organic matter (degradation type), forests with additional N-sinks in the soil (accumulation type), and forests showing no change [(quasi-) steady-state type] (*lines* provide estimates of uncertainties of ±5 kg ha^{-1} above and below the 1:1 *line*). Beech sites at Solling (*SO*), Göttinger Wald (*GW*), and Zierenberg (*ZB*) are highlighted by *solid circles*. (Figure adopted from Brumme and Khanna 2008, modified)

N loss is associated with a decrease of the amount of soil organic matter (Degradation Type, $n = 3$, one site with beech) whereas those on the right of the lines accumulate more than 5 kg N ha^{-1} per year (accumulation type, $n = 27$, eight sites with beech).

23.5.1 Forests of the Accumulation Type

Of the 53 forest sites, 27 sites accumulated nitrogen in the soil and annual accumulation values ranged from 6 to 21 kg N ha^{-1} (Table 23.4). Plants accumulated 4–16 kg N ha^{-1} for annual plant increment which is lower than the amount required for the soil. Out of 21 sites with moder type humus, 11 had C/N ratio values <25 (two were occupied by beech) and showed the same mean annual N retention in the soil (11 kg N ha^{-1}) as those with C/N ratios >25 (two of these sites were occupied by beech) indicating that factors other than C/N ratio are responsible for N retention in these soils. The C/N ratio has often been shown to be a potentially useful predictor of the level of nitrate leaching from forest ecosystems (Matzner and Grosholz 1997; Dise et al. 1998a, b; Gundersen et al. 1998; MacDonald et al. 2002; Borken and Matzner 2004). A new analysis by van der Salm et al. (2007) revealed that N deposition by

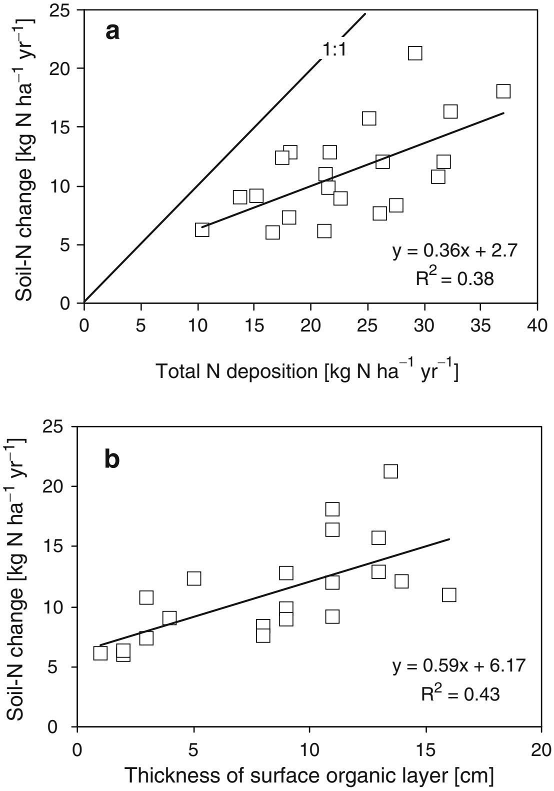

Fig. 23.5 Soil-N change (kg N ha^{-1} per year) versus (**a**) total depositions (kg N ha^{-1} per year) and (**b**) thickness of surface organic layer (cm) for 21 Level II sites retaining annually more than 5 kg N ha^{-1} deposited N in moder–mor type humus soils (accumulation type)

throughfall was more important than C/N ratio of the organic layer. However, the sinks in plant and soil have not been studied exclusively on these sties.

Accumulation type forests of the moder–mor type humus showed a significant correlation between N retention and total N deposition ($r^2 = 0.38$; Fig. 23.5a). Factors affecting organic matter accumulation in mature stands are not well known but may probably relate to the high N depositions (Fog 1988; Berg and Matzner 1998). A decrease in decomposition activity following the addition of ammonium fertiliser to the litter layer was reported in the literature review (Berg and Matzner 1997) suggesting the stabilisation of the humus in the surface organic layer in the presence of high N content. Decomposition studies by Berg et al. (1995) showed that high N content of the litter accelerated its decomposition in the beginning, but reduced the decomposition in the long-term leading to the accumulation of litter. It therefore implies that high N depositions may probably stabilise the organic matter of moder and mor humus after its enrichment in leaves and needles or by microbial immobilisation during decomposition. Whether N stabilises organic matter or changes the microbial community or the litter quality cannot be deduced from the literature (Fog 1988; Berg and McClaughterty 2003; Olsson et al. 2005). However, positive correlations between N retention and the thickness of the surface organic layer ($r^2 = 0.43$), and the atmospheric depositions of nitrogen ($r^2 = 0.38$) (Fig. 23.5) of the 21 forests of the accumulation type suggest that factors other than N depositions might also be involved.

One such factor may be soil acidity. Soil pH has decreased during the last decades by up to 2 units in Europe, especially in soils of low proton buffer capacities. This decrease in soil pH may have caused an imbalance in the processes of decomposition and sequestration of soil organic matter since the thickness of the surface organic layer generally increased with soil acidity (Brumme et al., Chap. 21). Soils of the accumulation type showed positive correlations between surface organic layer thickness and pH in soil solution ($r^2 = 0.43$). Additional N sequestration may occur in the H-horizon when its amount in L and F horizons remains unchanged when moder type of litter layer is being formed (Fig. 23.12). Moreover, acid deposition might directly be involved in N sequestration as is suggested by the correlation between N retention and sulphate deposition ($r^2 = 0.39$) and has been shown to reduce C-mineralisation in experimental acidification studies when pH was reduced with diluted sulphuric acid (Persson and Wirén 1993).

Solling beech site presents itself as a typical accumulation type. It accumulated in the soil annually by 36 kg N ha^{-1} from 1981 to 1989 and by 21 kg N ha^{-1} from 1990 and 2002 (Table 23.2) following a decrease in total depositions of similar amounts. However, during this period, leaching losses of N remained low and unchanged at about 2 kg N ha^{-1} per year and point to the potential for further sequestration of atmospheric deposited nitrogen. N retention in the Solling soil significantly increased with N deposition with a rate of 0.96 kg per kg deposited N (Fig. 23.6). Since the beginning of Solling project in 1968, the C/N ratio of the litter layer has remained unchanged but surface organic layer mass has increased as indicated by the repeated inventories during the last 35 years of the observation period (Meiwes et al., Chap. 4). The same process may have caused N retention in other moder type humus soils as 11 sites of the accumulation type have C/N ratio <25. At sites of the accumulation type with high C/N ratio >25 ($n = 10$), additional

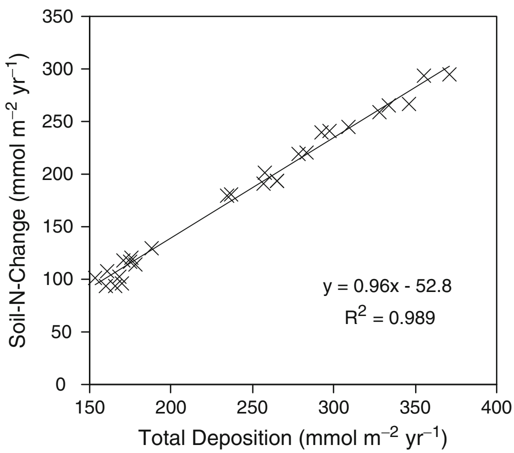

Fig. 23.6 Annual soil-N change versus annual total N deposition for the Solling site for 1976–2002

N sequestration may occur through an increase in N concentration in the organic layer. Repeated inventories conducted between 1974 and 2004 indicated that C/N ratios had decreased and C stocks increased in two Scots pine ecosystems in Southern Germany (Prietzel et al. 2006). On the two pine sites, carbon had increased by about 210 and 400 kg ha^{-1} per year and nitrogen by 13 and 18 kg ha^{-1} per year, respectively, while C/N ratio declined from about 36 in 1974 to 23 and 29 in 2004. These changes were attributed to a recovery of the degraded ecosystems through former litter-raking practices.

Of the 27 forest sites of the accumulation type, six had mull type humus, and four of them were occupied by beech which retained 6–10 kg N ha^{-1} per year (Table 23.4). These beech forests had high soil N content and high base saturation in the mineral soil. However, soil pH values were as low as were observed on soils with moder type humus. Such conditions are considered typical for soils where humus degradation may be occurring. It is not clear if this process is active in these soils as the amount of humus accumulation in the surface organic layer may exceed that of humus degradation in the mineral soil.

N balance has been shown to be a highly sensitive parameter for calculating changes in C content in soils (Holland et al. 1997; deVries et al. 2006). Annual N retention in soils of the accumulation type with moder–mor type humus (n = 21) ranged from 6 to 21 kg N ha^{-1} (mean 11 $\pm$ 5 kg N) which would mean C sequestration of 150–590 kg C ha^{-1} per year (mean 290 $\pm$ 113 kg C) assuming no change in N to C ratios. For the whole of Germany, forest soils with moder–mor type humus will sequester about 1 Tg C per year when 66% of the forested area of 10.15×10^6 ha in Germany are considered to have such soils and of these 51% of sites accumulate N. The total C sequestration rate in German forest soils may diverge from the calculated value as other soils such as those with mull type humus may also accumulate N or accumulate N without C sequestration (constant C/N ratio). However, Hyvönen et al. (2008) reported a mean increase in soil C-stock of 11 $\pm$ 1.7 kg C per 1 kg added N in long-term fertilisation experiments in northern European forests. This number is close to the value of 13 $\pm$ 5 kg C (sequestered) kg N^{-1} (added) calculated for the accumulation type with moder–mor type humus by C sequestration divided by total N deposition.

23.5.2 Forests of the Degradation Type

Of the 53 forests presented in Fig. 23.4, three sites belonged to the Degradation type where the amount of N loss exceeded the inputs in excess of plant increment. Two of these sites are occupied by oak and have untypical thick surface organic layers of a moder-humus type. Commonly, the oak forests have thin mull humus type litter layers. Low C/N ratios <20 in the surface organic layer material suggest degradation of humus in this layer. The third site which is losing N from the soil through degradation in the mineral soil is the beech Zierenberg site (see Sects. 23.2 and 23.3).

23.5.3 Forests of the (quasi-) Steady State Type

Among this collective of forest sites, 23 sites are of the (quasi-) Steady-State Type (Table 23.4). Eight forests of this type with mull humus type had higher N content in mineral soil than those of the moder humus type ($n = 15$). They also had a higher pH and a much higher base saturation in the mineral soil. Mg and Ca contents in the leaves were also higher by about 30 and 60%, respectively, than in the leaves of trees on moder humus type soils. Uptake of N by forest trees which have developed on mull humus type soils is higher than on moder humus type soils at the (quasi-) Steady State Type sites and higher than by forest trees at the accumulation type sites. The negative relationship between soil N change and plant N increment of pine, spruce, oak (Brumme and Khanna 2008) and beech trees (Fig. 23.7) in the (quasi-) Steady State and the accumulation types is explained by soil acidity which positively influenced the retention of N in the soil with increase in surface organic layer thickness (Fig. 23.5b) and negatively influenced the plant growth with decreasing base cations (Fig. 23.3).

The Göttinger Wald site is a typical case of the (quasi-) Steady-State Type (see Sects. 23.2 and 23.3). N dynamics on this site followed the amount of N deposited annually. A decrease in total N depositions after emission control measures were introduced decreased the leaching losses which were in equivalent amounts to the decrease in depositions (Table 23.2). This indicates that the soil at the Göttinger Wald site has a limited capacity to retain any more nitrogen. It is not clear why those forests with mull humus type very low base saturation did not accumulate organic matter in the surface organic layer.

Low mineral N content values in forest soils of moder humus type (Table 23.4, $n = 15$) indicate that these forests had gone through the phases of humus degradation and N accumulation in the surface organic layer and have approached the (quasi-) Steady State phase through a decrease in C/N ratio of about 25 in the surface organic layer (Fig. 23.10). The beech forests in this group currently lose deposited N in excess of plant increment of up to 16 kg N ha^{-1} per year indicating that N accumulation in such forests is of a transient nature.

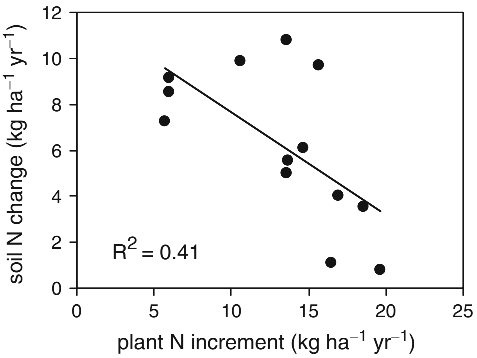

Fig. 23.7 Soil N change in relation to plant N increment (kg N ha^{-1} per year) in beech forests of the (quasi-) steady state and accumulation type

23.6 Dynamics of C and N Sequestration in European Forests

Chemical status of soils may affect the soil C- and N-stocks in a forest. Temporal changes of C- and N-stocks of soils are difficult to follow because the mechanisms involved in the sequestration of C and N and humus degradation processes are not well understood.

The Göttinger Wald site has a thin surface organic layer and contains 115 Mg C ha^{-1} in the surface soil (L layer to 30 cm depth, pH(H_2O) 6.7) which compares well with the mean C-stock of German forest soils with pH(H_2O) >5.5 (110 Mg C ha^{-1}). The N-stock in the surface soil of Göttinger Wald site is about 30% more than the mean for German sites of similar pH (7 Mg N ha^{-1} in German forest soils at pH(H_2O) >5.5). Soils in the carbonate buffer range had the highest carbon and nitrogen stocks in the mineral soil layer (Figs. 23.8, 23.9). This is related to high earthworm and decomposer activity and the stabilisation processes through clay-humus complex formation in the mineral soil. Although the carbonate content in the surface mineral soil of the Göttinger Wald site occurs as small gravels, and the surface soil layer at Göttinger Wald lies between the carbonate and silicate buffer ranges, further acidification of this soil is expected to be a slow process. This slow process may be related to root uptake of bases from deeper soil depths and to the bioturbation by earthworms, and to the relatively high clay content of the surface soil. The input–output balance of the Göttinger Wald site, a typical representative

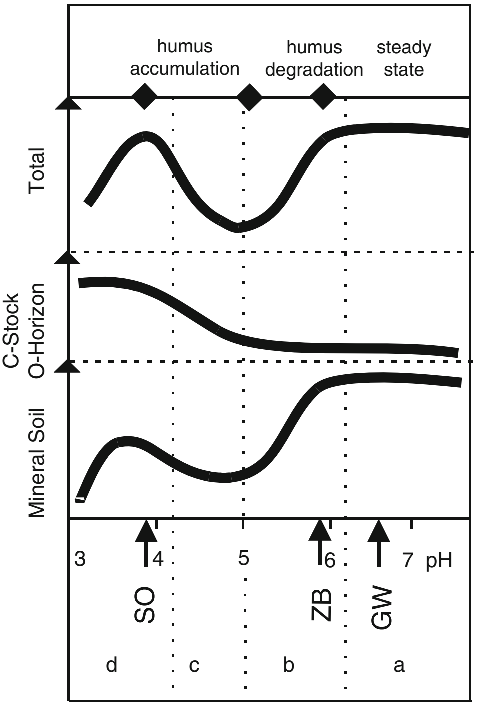

Fig. 23.8 Schematic diagram showing C-stock in the mineral soil, the surface organic layer (O horizon), and the total C-stock of German forest soils along the soil pH (H_2O) gradient (adopted from Brumme et al., Chap. 21, by smoothing the curves). The beech forests at Göttinger Wald, Zierenberg and Solling are arranged according to their soil pH. The buffer ranges are indicated by *dotted lines:* **a** carbonate buffer, **b** silicate buffer, **c** exchanger buffer, **d** Al/Fe buffer. The ranges of humus states "humus accumulation, humus degradation," and "steady-state" are indicated at the *top* of the figure

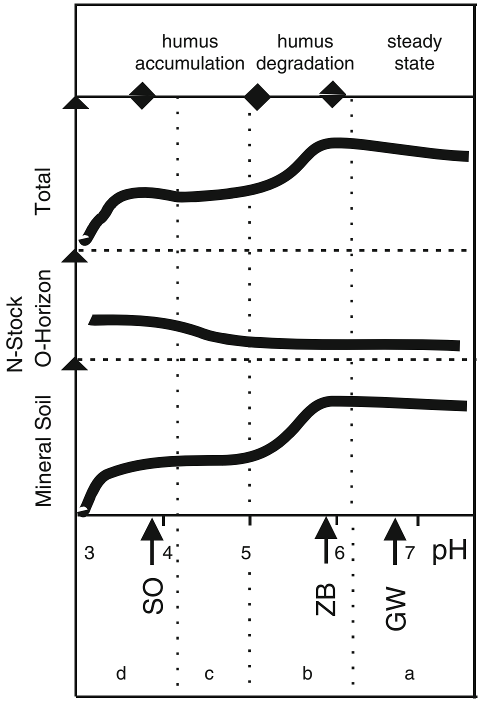

Fig. 23.9 N-stock in the mineral soil, the surface organic layer (O horizon), and the total in German forest soils with changes in soil pH(H_2O) (adopted from Brumme et al., Chap. 21, by smoothing the curves). The beech forests at Göttinger Wald, Zierenberg, and Solling are shown on pH scale. The buffer ranges are indicated by *dotted lines*: **a** carbonate buffer, **b** silicate buffer, **c** exchanger buffer, **d** Al/Fe buffer. Stages of "humus accumulation, humus degradation," and "steady-state" are indicated at the *top* of the figure

of the (quasi-) Steady-State Type, indicated that nitrogen was not retained in the soil (Table 23.2). Thus, soils in the carbonate buffer range may show the (quasi-) steady-state conditions where decomposition of organic matter equals litter production and the amount of soil organic matter does not change with time.

In an earlier study by Wittich (1952), similar values of N content as reported here were observed in the surface mineral soil which had developed on calcareous or basaltic bedrock. Thus, atmospheric N depositions did not change N levels in such soils. Wittich (1952) reported that, in two Rendzic Leptosol soils, total N values of 4% and 4.8% were observed which were in the similar range (3.9%) as observed at the Göttinger Wald site. Similarly, for a Eutric Cambisol developed on basaltic bedrock (Meißner site), Wittich (1952) reported a value of 4.03% which was also close to that for the Zierenberg soil (4.3%).

Soil at the Zierenberg (0–30 cm depth, pH(H_2O) of 5.5) site occurs in the transitional range of high and low C- and N-stocks among the soil collective of different pH values (Figs. 23.8, 23.9). Below soil pH value of 5.7, the C- and N-stocks in soils decreased with a minimum value approaching in soils of pH 4.4 to 5.2. Zierenberg soil occurs in the silicate buffer range which, due to moderate buffer rate, has undergone acidification through high atmospheric acid loads (Eichhorn and Hüttermann 1994, 1999). Acidification would reduce exchangeable base cations and increase the content of aluminum. Ca-humates are not stable as Al inhibits polymerisation of low to high molecules through formation of soluble complexes of organic matter and Al. Consequently, the humus in the mineral soil starts to degrade (humus degradation or humus disintegration) as indicated by high nitrate leaching (Table 23.2) causing further acidification (Ulrich 1984; Eichhorn and Hüttermann 1994). The C-stock at Zierenberg (76 Mg C ha^{-1} for L-30 cm depth) equals the minimum value of C-stocks observed in Germany for soils at pH 4.4–5.2; but the amount of N-stock (6.6 Mg N ha^{-1} for L–30 cm depth) is about 35% higher than the mean for forest soils in Germany.

C-stock at the Solling site is slightly higher than the overall mean observed for German forest soils at pH(H_2O) 3.9 (126 Mg C ha^{-1} at Solling compared to mean of 110 Mg C ha^{-1} for German sites), and the N-stock is 35% higher (7.2 Mg N ha^{-1} at Solling compared to 5.3 Mg N ha^{-1} in German sites for L–30 cm depth) (Figs. 23.8, 23.9). At this site, high retention of nitrogen by the surface organic layer causes very low nitrate leaching despite high N depositions (Table 23.2). The high N-input of 40 kg ha^{-1} per year during the period 1981–1989 resulted in only a slight increase in N-leaching of 0.3 kg N ha^{-1} per year when the values are compared with the period 1990–2002. Organic matter accumulation on such sites which have moder type of litter layer may therefore retain high amounts of N caused through an increase in the thickness of the surface organic layer.

Of the forested area in Germany, 86% of sites have soils with pH(H_2O) < 5 (Wolff and Riek 1997b). They may have undergone soil acidification, humus degradation or organic matter accumulation in the surface organic layer, and some have reached a new (quasi-) Steady-State of moder humus type (Fig. 23.10). Ulrich in his forest ecosystem theory (1984, 1987, 1992, 1994) suggested that most forest soils (except some sandy soils) in Germany, due to the influence of glaciation processes, were not acidified during the Sub Atlantic period (0–2,500 B.P.). At that time, soils had developed mull type humus of litter layers (Puhe and Ulrich 2001) and contained high C and N contents in the mineral soil. Further acidification which moved the soils from the exchanger to the Al/Fe buffer ranges is primarily related to acid precipitation of recent times (Puhe and Ulrich 2001). Soil acidification is accompanied by losses of base cations, nitrogen and carbon in the mineral soil (Humus Degradation Type) (Fig. 23.10). After the degradation phase, there is a small accumulation of C in the mineral soil and a large accumulation in the surface organic layer (accumulation type) as indicated in Figs. 23.8 and 23.11. Nitrogen is accumulated in the surface organic layer together with C while its accumulation in the mineral soil is negligible (Fig. 23.9). This may relate to low nitrogen sources of organic matter in acid mineral soils, such as dissolved organic carbon and roots (Brumme et al., Chap. 21). Acid soils thus lose their retention function for nitrogen in the mineral soil.

Thus, the soil chemical state, which is closely linked to the stabilisation processes of soil organic matter, has changed on the majority of the sites during decades by atmospheric deposition, and has caused C and N dynamics of transient nature (accumulation and degradation phase) in 9 of 17 beech sites (29 of the total of 53 sites) (Table 23.4). There are only four beech sites (in total eight forest sites) which have resisted these constraints [(quasi-) steady state phase with mull humus type]. These forests are saturated with nitrogen and are losing atmospheric-deposited

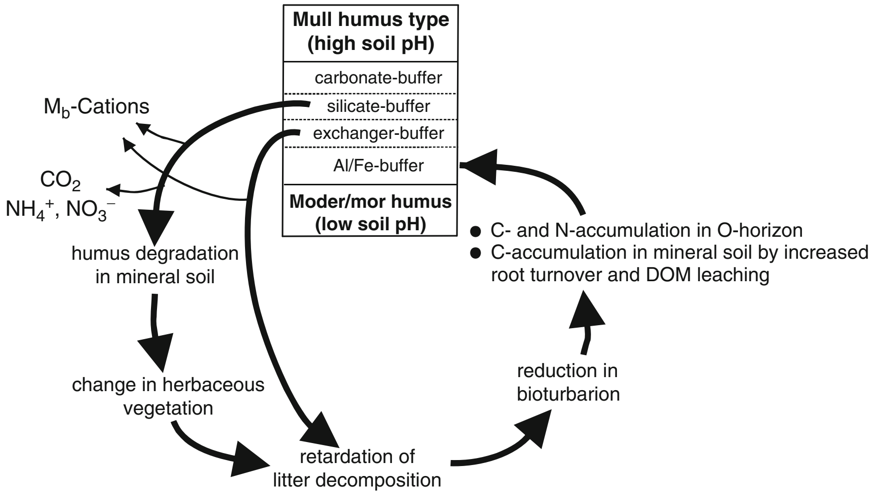

Fig. 23.10 Effects of acid load on ecosystem processes affecting the organic matter and N dynamics in forest soils in relation to the chemical state of the soils (M_b cations: Ca^{2+}, Mg^{2+}, K^+, Na^+) (Ulrich 1992, modified)

nitrogen in excess of that taken up by plants. In addition to these sites, there are four beech forests (in total 15 forest sites) which have a moder or mor type humus in the (quasi-) steady state phase and which are also losing any additional nitrogen deposited in excess of that taken up by plants. However, they differ in the dynamics of C and N sequestration. The sites with mull humus type may not have changed much by atmospheric deposition. They have not gone through the phase of N accumulation as proposed by Aber et al. (1998) and have been enriched with nitrogen since the Sub Atlantic times. The (quasi-) steady state phase of the moder humus type sites results from humus degradation followed by C and N sequestration in the surface organic layer.

23.7 Bioturbation as a Central Process of C and N Dynamics: Role of Soil Biota

The soil chemical state has been suggested here as one of the main driving variables which determines forest productivity and the carbon and nitrogen sequestration in the soil. It controls the cycling and distribution of nutrients in forest ecosystems, the availability of plant nutrients, the activity and growth of fine roots, distribution of soil biota species and activity of soil biota (Fig. 23.11). However, the key process relating to element cycling in the temperate biomes appears to be the bioturbation by earthworms. Earthworms together with termites and ants are sometimes described as soil engineers because of their role in soil-forming processes through soil bioturbation. Soil pH is one of the important factors determining the presence

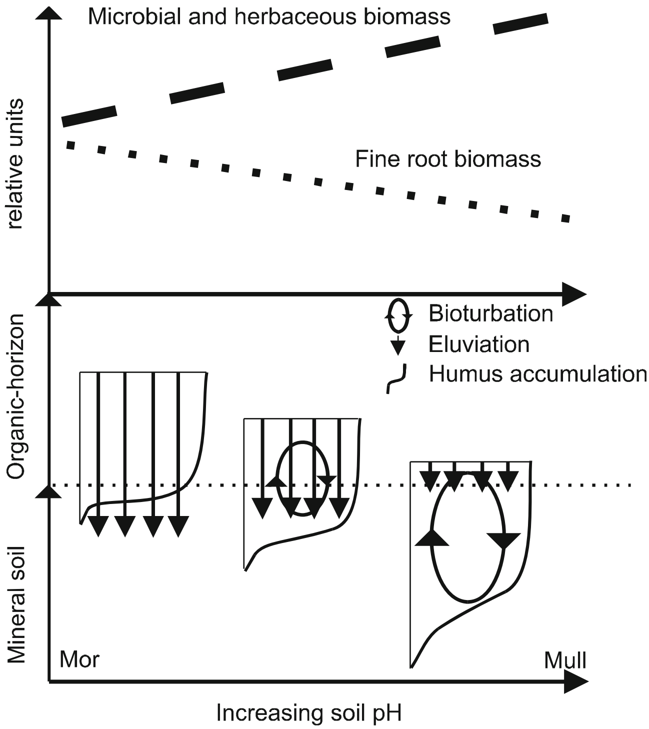

Fig. 23.11 Three states of forest soils at less acid (mull humus), intermediate and acid conditions (mor humus) as affected by faunal bioturbation, eluviation of dissolved organic carbon from top organic horizon to mineral soil, by litter layer accumulation, and by production of microbial, herbaceous and fine root biomass. (adopted from Beese, personal communication)

or the absence of earthworms in soils. Acid-intolerant species of earthworms have usually been absent from acid soils (Edwards and Bohlen 1996). In addition to low soil pH, reduced availability of energy resources for earthworms due to low quality of tree litter and the absence of herbaceous species may form another factor affecting the type and density of earthworm populations. The faunal studies at the three experimental sites showed that the three sites have varying amount and activity of soil biota.

The soils with high pH contained 205 individuals m^{-2} at Göttinger Wald and 114 individuals m^{-2} at Zierenberg of *Lumbricidae* whereas the acid soil at the Solling site had only 19 individuals m^{-2} (Schaefer and Schauermann, Chap. 7). The absence of *Lumbricidae* at the Solling site reduced the litter incorporation into the mineral soil causing the litter to accumulate on the surface of the mineral soil forming a moder humus type (Fig. 23.12).

The soil chemical state at the Göttinger Wald and Zierenberg sites acts positively on the microbial and herbaceous biomass, and thereby increases the activity of deep-burrowing anecic and surface-burrowing endogeic earthworms. The soils at the two sites are completely covered by herbaceous species which provide diverse

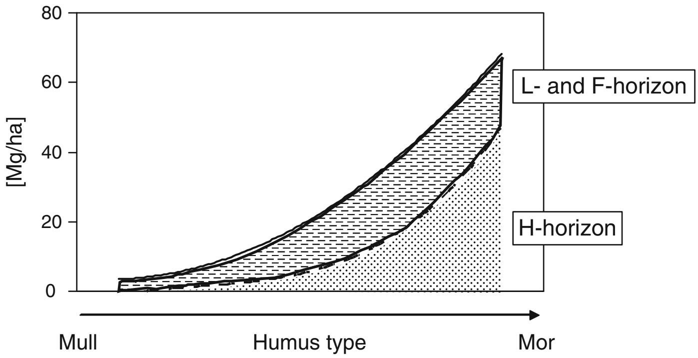

Fig. 23.12 Theoretical build-up of total surface organic layer, the L/F horizon and in the H horizon stratified from mull to mor humus in Germany (from Chap. 21)

and energy-rich resources of 0.2 Mg at Göttinger Wald and 0.4 Mg C ha^{-1} per year at Zierenberg (Schulze et al., Chap. 10) (Table 23.1). Through the activity of soil biota, the total aboveground litter fall of 2.6 Mg at Göttinger Wald and 2.7 Mg C ha^{-1} per year at Zierenberg (Khanna et al., Chap. 11) is consumed during a year from the soil surface (Schaefer et al., Chap. 12). At both sites, a thick A_h-horizon and a thin litter layer of mull-humus type were formed through earthworm activity. Incorporation of plant litter by earthworms produces high amount of microbial biomass in the mineral soil (Brumme et al., Chap. 6). Thus, soil micro-organisms have access to diverse and readily available energy source at these sites. Mixing plant litter with mineral soil while passing through the guts of earthworms may accelerates the stabilisation process of soil organic matter (Edward and Bohlen 1996) and the formation of organo-mineral complexes (Zech and Guggenberger 1996). Organo-mineral complexes consist of high proportions of less humified organic carbon in soils with mull humus layer and provide a much better nutrient source for microorganisms than C present in the mineral layers of soils of the mor humus type. Available C sources in acid mineral layers of soils are dead roots and some amounts of dissolved organic carbon through eluviation of the surface organic layer, as is the case at the Solling site. Lack of easily available C sources in the mineral soil at the Solling site and the presence of high acidity have reduced the microbial biomass to half the amount present at the Göttinger Wald and Zierenberg sites.

Moreover, soils with mull humus have a higher cation exchange capacity, a higher proportion of essential plant available base cations, a higher N-stock and more plant-available water than those with the mor humus. Deep burrowing anecic and endogeic earthworms form stable soil aggregates in the mineral soil and establish permanent burrows with high C and N contents accumulating in the burrow linings (Don et al. 2008). Vertical burrows increase the gas exchange between deeper soil layers and atmosphere. At the Göttinger Wald site, high gas diffusivity in the mineral soil was observed which promoted the methane and oxygen diffusion from the atmosphere into the mineral soil causing high methane oxidation (Borken and Brumme, Chap. 19) and low N_2O emissions (Brumme and

Borken, Chap. 18). In contrast, the low diffusivity in the mineral soil of the Solling site reduced the methane diffusion and increased the N_2O emissions. The soil pH is a good indicator for the trace gas exchange between the soil and atmosphere because there is a positive relationship between soil pH and soil diffusivity.

Diversity of the soil biota is higher at the forest sites with high degree of bioturbation and mull humus type of litter layer. For example, shell-bearing *Gastropoda* are lacking at the Solling site in contrast to 487 individuals m^{-2} at the Zierenberg and 120 individuals m^{-2} at the Göttinger Wald site (Schaefer and Schauermann, Chap. 7). *Gastropoda glomeris* feeds on intact litter material without much digestion and assimilation and provides a highly attractive food substrate for endogeic earthworms and microbes. However, the litter material at the Solling site may be of low quality (low Ca content) for the shell-bearing *Gastropoda*. Under highly acid soil conditions, populations and activity of earthworms are low and fungi dominate the microbial population (Anderson, Chap. 20). This specifically affects the production and loss of nitrate from ecosystems. For example, the highly efficient autotrophic nitrifiers may be replaced by less efficient heterotrophic nitrifiers under highly acid conditions reducing the nitrification in soils. Under such conditions, mineral nitrogen may remain in the ammonium form and the nitrate losses through leaching and denitrification are reduced.

The central role of faunal bioturbation in beech soils is evident from the many nutrition and soil-related processes. Appropriate management measures are thus required to develop soil conditions which are conducive to the establishment of active faunal populations.

23.8 Forest Management Strategies: Future Perspectives

European beech (*F. sylvatica* L.) has regained its importance in the last few decades mainly due to its wide ecological amplitude enabling it to grow under a range of site conditions, which under possible future changes of the climate and other environmental and social factors would provide it with an advantage over other tree species for forests of Germany. In future, beech may be replacing some of the mono-species stands of pine and spruce. The aim of the forest management in Germany is to increase the proportion of beech, especially as mixed stands, to achieve higher diversity and stability of forest stands in the long-term. This change in the stand structure through regeneration or planting is one of the most difficult tasks that forest management is facing today. In managed beech forests of Central Europe, natural regeneration is the dominant form of stand development. The success of any silvicultural treatment is measured in terms of a quick and problem-free conversion of mature stands into younger stands. From an ecological stand point, any conversion of stands should have minimum effects on the neighbouring ecosystems such as through leaching of nitrates or emission of greenhouse gases. It is, however, difficult to predict changes in the site and environmental factors during the course of a single rotation of a forest stand, such as, for example, changes in soil acidity, increase in N supply, amelioration practices and climate change phenomenon. There is also another unknown factor which is the lack of experience with regard to management decisions taken on a stand. For given climatic conditions, the regeneration of beech stands will primarily depend upon the soil conditions and other vegetation components as well as on the protection measures taken against deer browsing. Each of the three beech stands represents a different soil and site condition and can thus be viewed as a unique set for describing and developing silvicultural options (Bartsch and Röhrig, Chap. 22).

Usually, the amount of element losses during the conversion phase of a stand depends upon the degree of disturbance on the site and the period required for reversing the disturbance. Harvesting of a mature stand leads to a decrease in the uptake of water and nutrients. This may cause additional leaching losses of nitrate which is commonly turned over as leaf litter and fine roots annually prior to harvesting. Moreover, additional amounts of organic matter may be mineralised due to environmental changes in the surface soil. Additional losses of nitrate may also occur through denitrification as soils become wetter and contain excessive amounts of nitrates. Any amount of N_2O produced during denitrification will be of special concern due to its greenhouse gas character (Brumme and Borken, Chap. 18). There may be additional changes in the soil which act as a natural sink of methane gas due to changes in moisture status reducing the oxidation processes associated with the methane uptake (Borken and Brumme, Chap. 19). Also of major concern is the compaction of soils with harvesting machines which will create high emission areas of greenhouse gases, the so-called "hot spots."

For the regeneration of a stand, a rational approach would be to provide additional exposure of organic layer to sunlight for the growth of the saplings, but this rational management practice goes against the demand for minimum site disturbance on many regeneration sites. However, this is not a major requirement for the light-tolerant beech saplings. Recent experiments have shown that beech could be regenerated successfully by creating small gaps in the mature stand. This has led to replacing the commonly practiced shelterwood harvesting and group selection methods of regeneration with the single tree selection and target diameter harvesting of beech stands (Bartsch and Röhrig, Chap. 22). One single important factor for obtaining successful regeneration of beech is the control of browsing by deer. Moreover, it has been observed on the Göttinger Wald site that the presence of calcareous bedrock causing high biological activity in the soil would not need any soil tillage (disturbance) or liming for the regrowth. The high density of herb under-storey does not provide any specific hindrance to the germination and growth of beech saplings. Shelterwood harvesting assists the shade-tolerant beech saplings to develop and form pure species stands whereas group selection would also help the growth of other light-loving noble hardwood trees and can be employed to increase the proportion of these trees in the mixed species stands. Rapid growth of young noble hardwood trees (e.g., *Fraxinus excelsior, Acer pseudoplatanus, Ulmus glabra, Acer platanoides*) leads to strong competition for light and rooting volume of the soil to reduce ground vegetation and shrubs. The establishment of these species is highly restricted due to deer browsing, and insufficient regulation of deer populations.

On the nutrient-rich sites, as at Zierenberg, regeneration of beech has caused problems because of the dense and rapid growth of stinging nettles (*Urtica dioica*) or other under-storey plants. At Zierenberg, dense growth of stinging nettles cannot be kept in check due to the lack of noble hardwood tree species. Moreover, other contributory factors such as high amounts of available nitrogen, phosphorus and magnesium may be important to support thickets of stinging nettles. On such sites, small gaps in the mature stand may be required for successful regeneration. Large gaps should not be created. Small gaps may be achieved by maintaining a sub-canopy layer and understorey. Gas exchange on this site is not restricted due to high proportion of air pore spaces in soils, so the production of N_2O is low and the sink for methane will not be limited.

Regeneration of beech on acid sites, as is the case for the Solling site, requires special silvicultural efforts. The regeneration remains restricted on such acid sites due to the thick litter layer and highly acid mineral soils. Creating large-sized gaps in the canopy of the mature stand would lead to leaching losses of nitrate, emissions of N_2O and reductions in methane uptake. A surface application of lime would be required to improve the conditions for germination and initial growth of beech sampling but may also increase the growth of strongly shading shrub layer (e.g. *Rubus idaeus, R. fruticosus*). Through the competition by the dense shrub layer, beech seedlings may be completely lost in due course. However, the losses of N would be reduced and the uptake of methane enhanced. For such a site, a slowly advancing shelterwood harvesting and a lime application on the soil surface without soil disturbance should provide the most useful technique for regeneration that would serve both the ecological and silvicultural requirements.

Frequency of fructification has increased in recent decades due to high N inputs and the general vitality of the stands (Khanna et al., Chap. 11). However, the seeds are mostly lost to wild animals and soil fauna. Frequent and heavy fructification has also led to high requirements for other elements especially P, whose concentrations are higher in fruit components than in leaves. Moreover, high N inputs may have led to a decrease in litter decomposition and accumulation of organic matter in the litter layer which would also retain some amount of P in the litter layer, by reducing its turnover rate. The consequences of the high P requirements due to fructification, and high retention due to increase in productivity, and low turnover rates of P may further affect the N to P balance in plants, especially on those sites which are already low in P supply. Further experimental studies are required in future to assess the effect of such changes on the nutrition of beech stands.

23.9 Conclusions

- The three beech forests at Solling, Göttinger Wald and Zierenberg receive similar atmospheric inputs and are growing under similar climatic conditions as the long-term observations indicated. The three beech sites, however, differ in soil chemical conditions. The soils are rich in base contents at the Zierenberg site which is derived from weathered Tertiary basaltic debris and at the Göttinger Wald site which has Triassic limestone as parent material. These two sites are characterised by high soil pH values and a high diversity of plants and decomposers. High levels of decomposer activity developed a mull humus type, a high nutrient turnover and high tree productivity at the two sites. In contrast, the Solling site has an acid moder humus type soil which has developed from loess material overlaying Triassic sandstone. This soil has a very low pH, has low nutrient turnover and low tree productivity.

- The low productivity at the Solling site is caused by low availability of base cations (K, Ca, Mg) and high soil acidity which has increased the belowground allocation of biomass to maintain a high level of fine roots in the acid soil. Production of herbaceous plants is low at the Solling site, whereas it is high at the base-rich Göttinger Wald and Zierenberg sites which therefore act as an additional sink for nutrients and a luxuriant substrate for decomposers.
- Emissions of SO_2 and NO_x have decreased significantly since the end 1980s in Europe through political decisions to control emissions which have led to a noticeable decline in atmospheric depositions of sulphuric acid but to a lesser extent of nitrogen. The long-term observation at Solling and Göttinger Wald indicated that total depositions had decreased for sulphur (−60% at Solling and Göttinger Wald), H (−72% at Solling and Göttinger Wald), and nitrogen (−38% at Solling, −20% at Göttinger Wald) and base cations (−60% at Solling and Göttinger Wald) between the two periods 1981–1989 and 1990–2002.
- Effects of atmospheric depositions differed on each of the three sites. On the Göttinger Wald site with calcareous bedrock material, acid depositions affected slightly the surface soil layer. There was a small effect of acid inputs on the productivity of this stand. It had high soil biological activity and almost closed C and N cycles. However, on the base-rich Zierenberg site, acid depositions and soil acidification caused significant soil changes. This site was experiencing humus degradation where a net loss of N from the mineral soil occurred. At the Solling site, further addition of acidity through acid depositions to the acid soil decreased the availability of base cations. Prior to the 1980s, there were some inputs of base cations through atmospheric depositions which helped to reduce nutrient imbalances. Emission control measures at the end of the 1980s have changed this scenario by decreasing the supply of base cations with atmospheric depositions. Moreover, a decrease in acid inputs initiated a change in soil chemistry where the net release of previously stored sulphate has occurred and caused a delay in any recovery from further soil acidification.
- High atmospheric N inputs have removed any growth limitation due to N on beech forests in Germany (including the Göttinger Wald, Solling and Zierenberg sites). However, foliage levels showed an insufficient supply of Ca, Mg, P and K on some of these sites. Due to the significance of base cations for the optimum growth of N-enriched forests on acid soils, liming will show a positive effect on Ca and Mg contents of leaves and on tree productivity. Under certain conditions, other elements like P and K may become deficient.

- The amount of nitrogen retained in forests is controlled by plant uptake and sequestration in soils. Plant growth has increased during recent decades and will thus act as a sink for deposited N. Moreover, the frequency and the amount of fructification have increased in recent years affecting the plant uptake of deposited N. This is related to very high amounts of nutrients present in the fruit components and to a doubling of mast production compared to earlier studies. Elements transferred through litterfall to the organic layer have more than doubled (nitrogen) during the mast years.
- Forests with less acid soils showed high N retention by plants and low retention by soils whereas those on acid soils had low N retention by plants but high retention by soils, as indicated by 8-year records of input and output analysis of 53 German forests. Base-rich soils promote decomposer activity and improve nutrient cycles, and develop mull type humus with intensive faunal burrowing activity. In such soils, litter production and litter decomposition are in equilibrium and N content in the soil is at a maximum. Thus, any N input in excess of plant increment is leached from forests as is indicated by the long-term observations made at the Göttinger Wald site. Such forests are described as the (quasi-) Steady State Type with mull type humus (8 of 53 forest sites evaluated).
- Another type are forests where a part of atmospherically-deposited nitrogen is accumulated in the soil (accumulation type). The annual retention rates in soils (half of 53 forests sites evaluated) ranged from 6 to 21 kg N ha^{-1} depending upon total N depositions, acid–sulphate depositions, and the thickness and C/N ratio of the surface organic layer (moder-mor type humus). The thickness of the surface organic layer is related to soil acidity which has changed during the last decades and is supposed to be far from a steady state. At the long-term monitoring beech site at Solling (accumulation type), an increase in the mass of the surface organic layer with a constant C/N ratio of 19 over 35 years of observation was noted. This reduced the leaching losses of N, even when total N depositions of more than 40 kg N ha^{-1} per year occurred prior to the introduction of emission control measures.
- Another group of forests is where soils are currently losing C and N from the mineral soil layers by humus degradation (Degradation Type). However, this group has only a few sites due to its transient nature but includes the Zierenberg site, one of the three main sites of this study. However, most soils have crossed this state and are now accumulating N and C in the soil. There are some sites which have recovered to a new (quasi-) Steady State Type with moder–mor type humus (15 of 53 forests sites evaluated).
- The use of N balance has turned out to be a sensitive method of estimating soil C sequestration despite the high amount of C already present in forest soils. Mean annual C sequestration was calculated to be 290 ± 113 kg C ha^{-1} at sites of the accumulation type where moder–mor type humus is developing. Total sequestration rate for such sites may amount to 1 Tg C per year in German forest soils.
- Bioturbation of soil organic matter by earthworms and soil fauna appears to be a key process relating to the element cycling in the temperate biomes. Bioturbation increased C and in particular the N content in the upper mineral soil and

develop a mull humus type. A soil survey of forests in Germany indicated high C and N contents in the mineral soil of mull humus type soils. The lower C content in the mineral soil of moder and mor humus type soils that have occurred through humus degradation is compensated by a higher C content in the surface organic layer. The total N content did not recover from N loss in the mineral soil and is in total lower (2.8 Mg ha^{-1}) in mor than in mull humus type soils. Restricted bioturbation in highly acid soils may be improved by liming which may shift organic matter and N retention from the surface organic layer to the mineral soil in the long-term. Liming may also reduce the load of greenhouse gases (CO_2, N_2O, CH_4) in the atmosphere.

- In future, beech will be replacing some of the mono-species stands of pine and spruce in Germany, especially as mixed stands in order to achieve higher plant diversity and stability of forest stands in the long-term. Any conversion of stands should have minimum effects on the neighbouring ecosystems such as through leaching of nitrates or greenhouse gases exchange with the atmosphere by maintaining closed element cycling. This study of three diverse beech sites with similar climatic conditions indicated that the regeneration of beech stands will primarily depend upon the soil conditions and other vegetation components as well as on the protection measures taken against deer browsing.

Acknowledgment For developing this chapter we have extensively used the data and information provided by various authors of the preceding chapters of this book, to whom we wish to express our sincere thanks. We are grateful to the Johann Heinrich von Thünen Institute (Eberswalde, formerly Federal Research Centre for Forestry and Forest Products, BFH) and the various Forest Research Institutes of different federal States of Germany for providing the data in Chapter 23.4 to 23.6. We acknowledge with gratitude the contributions by Prof. Dr F. Beese who provided many useful ideas on various topics and his general encouragement and support.

References

Aber J, McDowell W, Nadelhoffer K, Magill A, Berntson G, Kamakea M, McNulty S, Currie W, Rustad L, Fernandez I (1998) Nitrogen saturation in temperate forest ecosystems. BioScience 48:921–934

Barton L, McLay CDA, Schipper LA, Smith CT (1999) Annual denitrification rates in agricultural and forest soils: a review. Aust J Soil Res 37:1073–1093

Becker R, Block J, Schimming CG, Spranger T, Wellbrock N (2000) Critical Loads für Waldökosysteme – Methoden und Ergebnisse für Standorte des Level II-Programms, Arbeitskreis A der Bund-Länder Arbeitsgruppe Level II. Bundesministerium für Ernährung, Landwirtschaft und Forsten, Bonn, Germany

Berg B, McClaugherty C, de Santo AV, Johansson MB, Ekbohm G (1995) Decomposition of litter and soil organic matter – Can we distinguish a mechanism for soil organic matter builtup? Scand J For Res 10:108–119

Berg B, Matzner E (1997) Effect of N deposition on decomposition of plant litter and soil organic matter in forest systems. Environ Rev 5:1–25

Berg B, McClaugherty C (2003) Plant litter. Springer, Berlin
Berg B, Gundersen P, Akselsson C, Johansson MB, Nilsson A, Vesterdal L (2007) Carbon sequestration rates in Swedish forest soils: a comparison of three approaches. Silva Fennica 41:541–558
Bolte A (2006) Biomasse- und Elementvorräte der Bodenvegetation auf Flächen des forstlichen Umweltmonitorings in Rheinland-Pfalz. Ber Fosrschungszentrum Waldökosysteme B 72, Universität Göttingen
Block J, Eichhorn J, Gehrmann J, Kölling C, Matzner E, Meiwes KJ, v. Wilpert K, Wolff B (2000) Kennwerte zur Charakterisierung des ökochemischen Bodenzustandes und des Gefährdungspotentials durch Bodenversauerung und Stickstoffsättigung an Level II-Waldökosystem-Dauerbeobachtungsflächen. Bundesministerium für Ernährung, Landwirtschaft und Forsten, Arbeitskreis C der Bund-Länder Arbeitsgruppe Level II, Bonn, Germany
Borken W, Matzner E (2004) Nitrate leaching in forest soils: an analysis of long-term monitoring sites in Germany. J Plant Nutr Soil Sci 167:277–283
Brumme R, Verchot LV, Martikainen PJ, Potter CS (2005) Contribution of trace gases nitrous oxide (N_2O) and methane (CH_4) to the atmospheric warming balance of forest biomes. In: Griffiths H, Jarvis PG (eds) The carbon balance of forest biomes. Taylor&Francis, Oxon, New York, pp 293–318
Brumme R, Khanna PK (2008) Ecological and site historical aspects of N dynamics and current N status in temperate forests. Glob Chang Biol 14:125–141
deVries WD, Reinds GJ, Gundersen P, Sterba H (2006) The impact of nitrogen deposition on carbon sequestration in European forests and forest soils. Glob Chang Biol 12: 1151–1173
Dieter M, Elsasser P (2002) Carbon stocks and carbon stock changes in the tree biomass of Germany's forests. Forstw Cbl 121:195–210
Dise NB, Matzner E, Forsius M (1998a) Evaluation of organic horizon C:N ratio as an indicator of nitrate leaching in conifer forests across Europe. Environ Pollut 102:453–456
Dise NB, Matzner E, Gundersen P (1998b) Synthesis of nitrogen pools and fluxes from European forest ecosystems. Water Air Soil Pollut 105:143–154
Don A, Steinberg B, Schoening I, Pritsch K, Joschko M, Gleixner G, Schulze ED (2008) Organic carbon sequestration in earthworm burrows. Soil Biol Biochem 40:1803–1812
Edwards CA, Bohlen PJ (1996) Biology and ecology of earthworms. Chapman & Hall London
Eichhorn J, Hüttermann A (1994) Humus disintegration and nitrogen mineralization. In Godbold DL, Hüttermann A (eds) Effects of acid rain on forest processes. Wiley, New York, pp 129–162
Eichhorn J, Hüttermann A (1999) Mechanisms of humus dynamics and nitrogen mineralisation. In: Rastin N, Bauhus J (eds) Going underground – ecological studies in forest soils. Research Signpost, Trivandrum, India, pp 239–277
Ferrier RC, Jenkins A, Wright RF, Schöpp W, Barth H (2001) Assessment of recovery of European surface waters from acidification 1970–2000: an introduction to the Special Issue. Hydrol Earth Syst Sci 5:274–282
Fog K (1988) The effect of added nitrogen on the rate of decomposition of organic matter. Biol Rev 63:433–462
Gehrmann J, Andreae H, Fischer U, Lux W, Spranger T (2001) Luftqualität und atmosphärische Stoffeinträge an Level II-Dauerbeobachtungsflächen in Deutschland. Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft, Arbeitskreis B der Bund-Länder Arbeitsgruppe Level II, Bonn, Germany
Gundersen P, Callesen I, de Vries W (1998) Nitrate leaching in forest ecosystems is related to forest floor C:N rations. Environ Pollut 102:403–407
Haußmann T, Lux W (1997) Dauerbeobachtungsflächen zur Umweltkontrolle im Wald, Level II, Erste Ergebnisse. Bundesministerium für Ernährung, Landwirtschaft und Forsten, Bonn, Germany
Holland EA, Braswell BH, Lamarque JF et al (1997) Variations in the predicted spatial distribution of atmospheric nitrogen deposition and their impact on carbon uptake by terrestrial ecosystems. J Geophys Res 102:15849–15866
Hyvönen R, Persson T, Andersson S, Olsson B, Agren GI, Linder S (2008) Impact of long-term nitrogen addition on carbon stocks in trees and soils in northern Europe. Biogeochemistry 89:121–137

Kauppi PE, Mielikäinen K, Kuusela K (1992) Biomass and carbon budget of European forests, 1971 to 1990. Science 256:70–74

Kesik M, Ambus P, Baritz R, Bruggemann NB, Butterbach-Bahl K, Damm M, Duyzer J, Horvath L, Kiese R, Kitzler B, Leip A, Li C, Pihlatie M, Pilegaard K, Seufert G, Simpson D, Skiba U, Smiatek G, Vesala T, Zechmeister-Boltenstern S (2005) Inventories of N_2O and NO emissions from European forest soils. Biogeosciences 2:353–375

Krauß HH, Heinsdorf D (2005) Ernährungsstufen für wichtige Wirtschaftsbaumarten. Beitr Forstwirtsch u Landsch ökol 39:172–179

Liski J, Perruchoud D, Karjalainen T (2002) Increasing carbon stocks in the forest soils of western Europe. For Ecol Manage 169:159–175

MacDonald JA, Dise NB, Matzner E, Armbruster M, Gundersen P, Forsius M (2002) Nitrogen input together with ecosystem nitrogen enrichment predict nitrate leaching from European forests. Glob Chang Biol 8:1028–1033

Matzner E, Grosholz (1997) Beziehung zwischen NO3--Austrägen, C/N-Verhältnissen der Auflagen und N-Einträge in Fichtenwald (*Picea abies* Karst.)-Ökosystemen Mitteleuropas. Forstwiss Centralbl 116:39–44

Matzner E (2004) Biogeochemistry of forested chatchments in a changing environment. Ecological Studies 172, Springer, Berlin

Meiwes KJ, Meesenburg H, Bartens H, Rademacher P, Khanna PK (2002) Akkumulation von Auflagehumus im Solling, Mögliche Ursachen und Bedeutung für den Nährstoffkreislauf. Forst und Holz 57: 428–433

Nabuurs GJ, Schelhaas MJ (2002) Carbon profiles of typical forest types across Europe assessed with CO2FIX. Ecol Indic 1:213–223

Nadelhoffer KJ, Emmett BA, Gundersen P et al. (1999) Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests. Nature 398:145–148

Olsson P, Linder S, Giesler R, Högberg P (2005) Fertilization of boreal forest reduces both autotrophic and heterotrophic soil respiration. Glob Chang Biol 11:1745–1753

Persson T, Wirén A (1993) Effects of experimental acidification on C and N mineralization in forest soils. Agric Ecosyst Environ 47:159–174

Pretzsch H (1996) Growth trends of forests in Southern Germany. In: Spiecker H, Mielikäinen K, Köhl M, Skovsgaard J (eds) Growth trends in European forests. European Forest Institute Research Report No 5, Springer, New York

Prietzel J, Stetter U, Klemmt HJ, Rehfuess KE (2006) Recent carbon and nitrogen accumulation and acidification in soils of two Scots pine ecosystems in Southern Germany. Plant Soil 289:153–170

Puhe J, Ulrich B (2001) Global climate change and human impacts on forest ecosystems. Ecological Studies 143, Springer, Berlin, Germany

Scarascia-Mugnozza G, Bauer GA, Persson H, Matteucci G, Masci A (2000) Tree biomass, growth and nutrient pools. In: Schulze ED (ed) Carbon and nitrogen cycle in european forest ecosystems. Ecological Studies 142, Springer, Berlin, pp 49–62

Schulze ED (2000) Carbon and nitrogen cycle in european forest ecosystems. Ecological Studies 142, Springer, Berlin

Sjöberg G, Knicker H, Nilsson SI, Berggren D (2004) Inpact of long-term N fertilization on the structural composition of spruce litter and mor humus. Soil Biol Biochem 36:609–618

Spiecker H (1999) Overview of recent growth trends in European forests. Water Air Soil Pollut 116:33–46

Ulrich B (1984) Stability and destabilization of central European forest ecosystems – A theoretical, data based approach. In: Cooley JH, Golley FB (eds) Trends in ecological research for the 1980s. Plenum, New York, pp 217–237

Ulrich B (1987) Stability, elasticity and resilience of terrestrial ecosystems with respect to matter balance. In: Schulze ED, Zwölfer H (eds) Ecological Studies 61. Springer, Berlin, pp 11–49

Ulrich B (1992) Forest ecosystem theory based on material balance. Ecol Model 63:163–183

Ulrich B (1994) Process hierarchy in forest ecosystems: An integrative ecosystem theory. In: Godbold DL, Hüttermann A (eds) Effects of acid rain on forest processes. Wiley, New York, USA, pp 353–398
van der Salm C, de Vries W, Reinds GJ, Dise NB (2007) N leaching across European forests: Derivation and validation of empirical relationships using data from intensive monitoring plots. For Ecol Manage 238:81–91
Wittich W (1952) Der heutige Stand unseres Wissens vom Humus und neue Wege zur Lösung des Rohhumusproblems im Walde. In: Schober R (Hrsg) Schriftenreihe der Forstlichen Fakultät der Universität Göttingen, Band 4, JD Sauerländer's Verlag, Frankfurt am Main, Germany
Wolff B, Riek W (1997a) Deutscher Waldbodenbericht 1996. BMELF, Bd 1
Wolff B, Riek W (1997b) Deutscher Waldbodenbericht 1996. BMELF, Bd 2
Zech W, Guggenberger G (1996) Organic matter dynamics in forest soils of temperate and tropical ecosystems. In: Piccolo A (ed) Humic substances in terrestrial ecosystems. Elsevier, Amsterdam, pp 101–170