Chapter 4
Changes in C and N Contents of Soils Under Beech Forests over a Period of 35 Years

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4.1 Introduction

Soil organic matter (SOM) contributes significantly to many vital ecosystem processes by affecting physical, chemical and biological properties of soils. Among the many ecosystem processes, SOM contributes significantly to the retention of water and nutrients, maintenance and functioning of soil biodiversity and cycling of nutrients and organic C. SOM is primarily a store of soil organic C (SOC) and plant nutrients and can therefore be considered as a suitable surrogate of fertility for many soils.

SOC occurs in many different forms in a soil and any change in its amount is the consequence of a balance between inputs and outputs of organic matter. A continuous increase in SOC is expected when the decomposition (output) pattern of the litter fall is impeded. This may occur due to a change in the type of litter fall (an increase in the proportion of more woody litter than leafy type) or to a change in its chemical composition (e.g. high C/N ratio) or a change in environmental and microbial factors (e.g. changes in the soil temperature and moisture conditions due to management practices or changes in the microbial activity due to population changes) (Schulze et al. 2000).

A number of theories have been postulated on the changes in SOC in forest ecosystems, which may occur during the development of a stand. Covington (1981) suggested that C in soils would undergo a decrease during the initial phases of stand development after clearfelling, which is then followed by a phase of C accumulation and finally reaching a phase in old growth stands of no further change. A decrease in soil C after clearfelling may, however, occur depending upon the type of the stand and status of stand structure and the amount of woody debris. For example, a breakdown of the stand structure will lead to a decrease in soil C in mature stands. The 'no change' or quasi-steady state situation will occur when the input of C balances the output despite further changes in stand growth. Berg and Matzner (1997) have described that various phases of decomposition are affected differently by climatic factors and N levels in the system. For example, an increase

in the N concentration of the litterfall from conifer stands will decrease the total amount of litterfall decomposed probably due to chemical changes in the lignin fraction in the presence of high N.

Nitrogen, phosphorus, sulphur and many other nutrients are intricately related with soil C, and any change in organic C in soils will affect their accumulation or release. Inputs of nitrogen through atmospheric depositions or fixation may allow a significant fraction of N to be retained as part of SOC at constant or near constant C:N ratios (De Vries et al. 2006). Any nutrient with limited supply or input will be depleted in the organic matter indicating a widening of its ratio with soil C and probably a reduction in its uptake and an increase in its retention (retranslocation processes) during litter fall. For example, Knoepp et al. (2005) showed in their study on the accumulation of litter layer in the southern Appalachian forests after 20 years that it was associated with changes of leaf litter quality. The leaf litter had decreased in P concentration and showed lower P release on decomposition.

This study provides two aspects of changes in soil C and N in beech stands at Solling, Zierenberg and Göttinger Wald. Firstly, a comparison will be made for the three mature beech stands for their soil C and N contents to find if there are common factors to explain the differences among the three sites. Secondly, the long-term data on soil C and N and other nutrients measured periodically over a period of 35 years at one of the sites will be used to assess the possible human effects in changing soil C, N and other nutrients and their consequences on ecosystem functioning. The long term analysis of data was restricted to the Solling site as similar long-term data from the other two sites were not available.

4.2 Content and Distribution of C and N in Soils from Three Beech Sites

Distribution of organic C and N in soils. Organic C concentration decreased with soil depth in all the three beech sites in an expected manner, when the depth from surface organic layer to 80 cm was considered (Table 4.1). C concentration of the LF layer ranged from 400 to 460 g kg^{-1} whereas it was about 300 g kg^{-1} in the H layer. L layer from the Zierenberg site had low C values indicating some mixing of L layer with the organic matter from deeper layers. In the mineral soil, C concentration ranged from 42–68 g kg^{-1} in the 0–10 cm depth to 5–21 g kg^{-1} in the 40–80 cm depth. Of the three sites, the highest values of organic C were observed at Göttinger Wald for all the comparable depths. For example, at 40–80 cm depth of the Solling and Zierenberg sites organic C concentration was 5 g kg^{-1} as compared to 21 g kg^{-1} in Göttinger Wald, which would be regarded as a high value for this depth of any soil.

Nitrogen concentration of soils decreased with depth in an expected way similar to that of organic C in these soils. Nitrogen values in the organic layer of 13–24 g kg^{-1} in the LF and of 15 g kg^{-1} in the H layers decreased to 2.5–5.4 g kg^{-1}

Table 4.1 Concentration of organic carbon and nitrogen in soils under European beech stands at Solling (*SO*) (*n* = 6; 1993), Göttinger Wald (*GW*) (*n* = 6; 1995) and Zierenberg (*ZB*) (*n* = 4; 1996); mean values and standard deviation (in parentheses) are given

Soil layer	Organic carbon (g kg^{-1})						Nitrogen (g kg^{-1})					
	SO		GW		ZB		SO		GW		ZB	
L + F	450.0	(9.0)	445.1	(14.0)	397.3	(16.0)	23.6	(0.3))	12.9	(0.5)	20.0	(1.3)
H	285.1	(65.0)	–	–	–	–	15.2	(0.3)	–	–	–	–
0–10	48.0	(17.0)	68.5	(9.0)	41.9	(3.0)	2.5	(0.7)	5.4	(0.7)	3.6	(0.4)
10–20	24.8	(4.0)	42.9	(8.0)	27.0	(1.0)	1.5	(0.2)	3.7	(0.7)	2.5	(0.2)
20–40	13.9	(1.0)	23.2	(4.0)	15.3	(3.0)	1.0	(0.1)	2.1	(0.3)	1.4	(0.3)
40–80	5.2	(1.0)	21.2	(3.0)	5.3	(1.0)	0.5	(0.1)	1.7	(0.3)	0.6	(0.1)

Table 4.2 Mean values of C:N ratio (g/g) in soils under European beech stands at Solling (*SO*) (*n* = 6, 1993), Göttinger Wald (*GW*) (*n* = 6, 1995) and Zierenberg (*ZB*) (*n* = 4, 1996); standard deviation in parentheses

Soil layer	C:N ratio (g/g)					
	SO		GW		ZB	
L + F	19.5	(0.39)	34.5	(2.28)	20.0	(0.99)
H	18.9	(0.82)	–	–	–	–
0–10	18.8	(2.05)	12.6	(0.40)	11.8	(0.85)
10–20	17.0	(1.21)	11.6	(0.44)	11.1	(0.83)
20–40	14.2	(0.52)	11.2	(0.94)	10.9	(1.07)
40–80	9.8	(1.33)	12.9	(1.70)	8.7	(0.90)

in the 0–10 cm depth and further to 0.5–1.7 g kg^{-1} in the 40–80 cm soil depth. Similar to C concentration, N concentration in Göttinger Wald soil was the highest of the three soils.

In the L + F layer, the C:N ratio was 35 at Göttinger Wald and about 20 at Solling and Zierenberg (Table 4.2). The C:N ratios decreased with soil depth of the mineral soil (0–10 compared with 40–80 cm), but the decrease was slight in Göttinger Wald when compared with the other two stands. A steeper gradient in the C:N ratio was observed in Solling. These differences in the C:N ratios indicate differences in the quality of SOM produced in these stands and probably in association with the differences in C and N cycling of these stands.

Total content of soil C and N in the three beech forests. Total organic C contents for 0–80 cm soil depths were similar at Solling (172 ± 31 Mg ha^{-1}) and Göttinger Wald (179 ± 22 Mg ha^{-1}) sites, whereas much lower contents were observed for Zierenberg (109 ± 9 Mg ha^{-1}) (Table 4.3). For the whole profile (0–80 cm), the amount of N was, however, about 20% higher at Göttinger Wald (14.2 ± 1.7 t Mg ha^{-1}) than at Solling (11.2 ± 1.5 Mg ha^{-1}) and Zierenberg (10.0 ± 1 Mg ha^{-1}). In order to compare organic C and N in these soils with similar soils in the area, soil survey data compiled for Lower Saxony (Bartens and Büttner 1997) and Hesse (Hocke, personal communication) were evaluated. The survey data

Table 4.3 Mean content of soil organic carbon and nitrogen in European beech stands at Solling (*SO*) (*n* = 6, 1993), Göttinger Wald (*GW*) (*n* = 6, 1995) and Zierenberg (*ZB*) (*n* = 4, 1996); standard deviation in parentheses

Soil layer	Organic carbon (Mg ha^{-1})						Nitrogen (Mg ha^{-1})					
	SO		GW		ZB		SO		GW		ZB	
L + F	24.9	(3.5)	7.8	(3.7)	4.4	(0.2)	1.3	(0.2)	0.2	(0.1)	0.2	(0.0)
H	11.0	(2.3)	–		–		0.6	(0.1)	–		–	
0–10	46.3	(16.4)	54.4	(7.1)	33.5	(2.3)	2.4	(0.7)	4.3	(0.6)	2.9	(0.3)
10–20	26.8	(4.0)	35.0	(6.7)	23.6	(1.2)	1.6	(0.2)	3.0	(0.5)	2.1	(0.2)
20–40	35.0	(2.1)	35.8	(5.8)	29.9	(6.7)	2.5	(0.2)	3.2	(0.4)	2.7	(0.6)
40–80	28.1	(4.6)	46.4	(6.2)	17.6	(4.2)	2.9	(0.4)	3.6	(0.6)	2.0	(0.3)
Sum	172.2	(31.2)	179.4	(21.8)	109.0	(9.5)	11.2	(1.5)	14.2	(1.7)	10.0	(1.0)

Table 4.4 Mean total content of organic C and total N in the soil survey collective from Lower Saxony and Hesse. The values are given for 40 cm soil depth. Data were obtained from Bartens and Büttner (1997) and Hocke (personal communication); standard deviation in parentheses

Sites	*n*	C (Mg ha^{-1})		N (Mg ha^{-1})	
Loess	9	95	(29)	5.6	(1.2)
Lime stone	6	102	(44)	8.3	(3.4)
Basalt	15	55	(19)	4.6	(1.6)

formed part of a study which was conducted on a 8 × 8 km grid to assess temporal changes in soils under forests. For comparing data with the present study, sites with similar parent materials (Solling – loess, Göttinger Wald – limestone and Zierenberg – basalt) were selected from the grid-based soil survey.

Amounts of C and N in those soils are shown in Table 4.4. Amount of C and N in all the three sites studied here showed 30–60% higher values than those found in soils of the same parent material in the region. This was probably due to differences in the altitude of the Solling and Göttinger Wald sites which are located 170 m and 130 m higher than the comparable grid-based soil survey sites. These differences in altitude are expected to affect the mean annual temperature on the sites and thus the stand productivity and the decomposition processes. Wirth et al. (2004) showed a clear increase of SOC with altitude in forest stands in the nearby region of Thuringia. The Zierenberg site has a north aspect and thus also has relatively lower temperatures than the comparable sites of the region. The forest stands of the Solling, Göttinger Wald and Zierenberg sites have not been managed since the investigation was started; this may also have influenced the content of C and N, at least in the top organic layer.

Distribution of C and N at various soil depths was different for the three beech sites depending upon the intensity of faunal activity and thus the presence or absence of H horizon of the top organic layer. In the Solling soil, where mixing
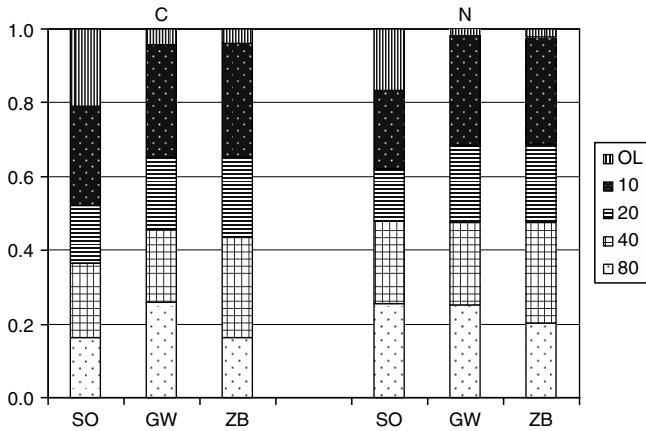
Fig. 4.1 Fractions of total organic C (*left side*) and N (*right side*) in different depths (*OL* organic layer, 10 = 0–10 cm, 20 = 10–20 cm, 40 = 20–40 cm and 80 = 40–80 cm). *SO*, *GW*, and *ZB* refer to three beech sites at Solling, Göttinger Wald and Zierenberg

and turnover of the soil was lacking due to low faunal activity, 36 Mg ha^{-1} of organic C occurred in the organic layer. This accounted for 20% of the total C in the surface 80 cm soil depth. At Göttinger Wald and Zierenberg, the organic C in the organic layer was about 4% of the total C when the 80 cm depth was considered (Fig. 4.1). The fraction of the total soil N in the organic layer of the three sites was less than that of C. At the Solling site, 12% of the total N in the soil to a depth of 80 cm was in the top organic layer whereas at the other two beech sites it was less than 2%.

In the 0–10 cm mineral soil, higher amounts of C and N occurred at Göttinger Wald and Zierenberg sites than at Solling, which was again related to the high earthworm activity in the former two soils. N content of the 0–10 cm mineral soil was 29% of the total at the Göttinger Wald and Zierenberg sites but only 21% at the Solling site when the whole soil depth of 80 cm was considered. Also, the subsoil (40–80 cm) at the Göttinger Wald site was richer in organic C and N than the subsoils at the Solling and Zierenberg sites. A quarter of the total soil C at the Göttinger Wald site was present in the subsoil which compared with 16% in soils at the Solling and Zierenberg sites, whereas the respective values for N in the subsoil were: Zierenberg 20%, Solling 26% and Göttinger Wald 25%.

Important factors determining the amount of organic C and N in forest soils are their inputs, the decomposition factors (substrate quality, temperature and moisture conditions) and the immobilisation factors (physical protection through clay content, chemical protection through Al content). Litterfall, including root litter, is the main input of C in these stands, whereas both litterfall and atmospheric depositions are important inputs for N. Annual litterfall values of these stands are, however, different, and are primarily related to the productivity of these stands. The annual litter production at Solling was 4.9 Mg ha^{-1} aboveground and 1.3 Mg ha^{-1}

fine roots. At Göttinger Wald, 5.1 Mg ha^{-1} originated from aboveground litter and 0.6 Mg ha^{-1} from fine roots. At Zierenberg, 5.8 Mg ha^{-1} came from aboveground litter and 0.6 Mg ha^{-1} from root litter.

The N inputs in these stands through litterfall and atmospheric deposition are (kg ha^{-1}): 68 and 36 (Solling), 64 and 25 (Göttinger Wald) and 75 and 23 (Zierenberg) (Meesenburg et al., Chap. 9, this volume, and Khanna et al., Chap. 5, this volume). Therefore, the differences in the inputs of C and N in the three sites can only partly explain the observed differences in the contents of C and N in these soils.

The decomposition factors, soil temperature and moisture, are similar on these three sites. The three sites are located at 400–500 m a.s.l., the mean annual air temperature at Solling is 7.0°C, at Göttinger Wald 7.7°C and at Zierenberg 7.6°C (1997–1998, Panferov et al., Chap. 1.2, this Volume). The annual precipitation values are, however, different: Solling 1168 mm, Göttinger Wald 525 mm and Zierenberg 644 mm (1990–1998). Despite the differences in precipitation, the climatic factors do not seem to be the main cause of different decomposition rates of organic C and N at these three sites.

Clay contents of the soils, as an indicator of physical protection to SOM decomposition, are different at these three sites with Göttinger Wald showing the highest value. Soils at the Solling site had 18–23% clay, Zierenberg 11–13% and Göttinger Wald 36–54% in the 0–30 cm depth and 23–30% in the 30–90 cm depth (the subsoil at the Göttinger Wald site had 49–61% stone content on a volume basis). Chemical protection as reflected by Al content or soil acidity in these soils is expected to be highest in Solling soil (lowest soil pH). It therefore seems that the physical protection of organic C by high clay concentration at the Göttinger Wald site and chemical protection at the Solling site are the major factors contributing to high SOC in these soils. Soil N contents of these soils follow soil C contents.

4.3 Long-term Periodic Measurements of C and N Contents in the Soil at Solling Site

Solling soil was periodically sampled and measured for organic C, N and other element contents during 1966–2001. Some of the data have been published previously (Ulrich et al. 1979; Matzner 1988; Tiktak et al. 1995; Meesenburg et al. 1999). In addition to the data from the beech site, some data from the spruce site at Solling will also be included as a comparison between the two sites. The combined data on soil C and N are presented as a sequence of temporal changes, the consequences of measured changes, and the methodological problems associated with such long-term measurements. Data on organic C and N for mineral soil and top organic layer are treated separately.

Methodological issues of long term field measurements. As is evident from Fig. 4.2, the C content of the top organic layer measured periodically for 35 years

Fig. 4.2 Content of C in the
organic layer of beech (B1)
and spruce (F1) stand at the
Solling site measured
periodically since 1966; mean
and standard deviation
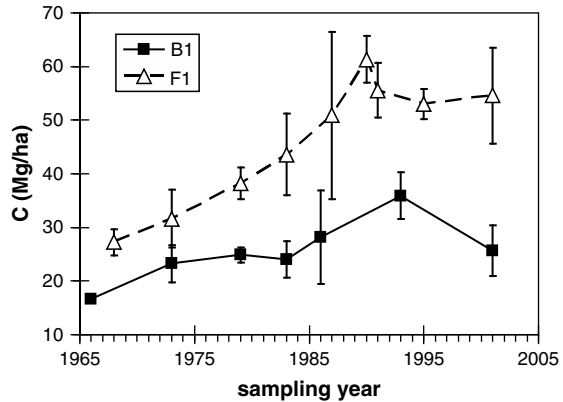
showed high variability and some unexpected short-term trends. Many field and laboratory conditions influenced the type of data obtained, which are outlined below:

1. Changes in the study aims during the sampling period: Objectives of the initial soil sampling were not to set up a chronosequence study and therefore the number of replicates collected for each sample, preparation of soil and organic layer samples, and the use of field and laboratory methods were not the same nor standardised during the study period. In general, two to six mixed samples were collected and, for each mixed sample, three to six individual samples were combined. The diameter of soil corer varied from 8 to 27 cm. Some details of the field and laboratory methods are provided by Meesenburg et al. (1999).
2. The samples were collected by different persons and under different meteoro-logical conditions which resulted in high variability associated especially in identifying the boundary between organic layer and mineral soil.
3. Chemical analysis of the soil changed over the period. Prior to 1979, C concentration of the organic layer was determined by subtracting the amount of oxides of elements in the ash (loss on ignition) from dry matter which was then divided by a factor of 1.81. This factor of 1.81 (standard deviation = 0.11) was obtained from a collective of samples ($n = 342$), which were analysed for C concentration by the dry combustion method, and these values were compared with the C concentration values calculated by the above method of using oxides in the ash. After 1979, C was determined by dry combustion using an organic carbon analyser.

Changes in the mineral soil. For the evaluation of time trends, the mean values of element contents were regressed against time (1966–2001) and a linear regression was fitted. Presence of any linear trend in time of the data was tested by using product moment correlations ($p < 10\%$) to find out if organic carbon contents measured at various times showed any linear trend. It was observed that soil C and N data from the mineral soil did not show any significant trend in time (Table 4.5).

Table 4.5 Contents of C and N (Mg ha^{-1}) of 0–50 cm mineral soil measured periodically at the Solling beech site; standard deviation in parentheses

Year	No. of samples	C		N	
1966	2	97	(3.6)	6.5	(0.3)
1973	3	98	(10.8)	6.7	(0.7)
1979	3	128	(11.9)	7.8	(0.5)
1981	4	66	(7.8)	4.4	(0.3)
1983	4	78	(8.8)	5.1	(0.8)
1986	3	103	(4.5)	6.5	(0.1)
1993	6	122	(22.0)	7.6	(1.1)
2001	6	127	(18.7)	7.1	(0.9)
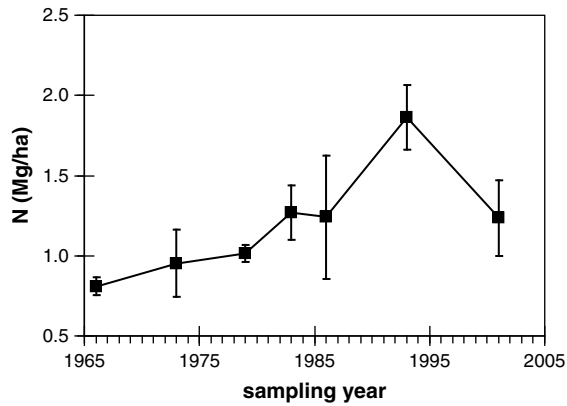
Fig. 4.3 Accumulation of N in the top organic layer of beech stand at Solling measured periodically since 1966; mean and standard deviation

The high content of C on this site and the associated variability were probably the reasons for the lack of any clear trend in the changes, if there were any to be detected.

Changes in the top organic layer. During the 35 years of the observation period, organic C content of the organic layer of the beech stand had increased from 20 to 32 Mg ha^{-1} showing a positive linear trend in time (Fig. 4.2). Comparative increase in the spruce stand showed a much higher increase from 29 to 62 Mg ha^{-1}. During the same period, the amount of N in the organic layer of the beech stand increased from 860 to 1600 kg ha^{-1} and that of Ca from 90 to 175 kg ha^{-1} (Figs. 4.3 and 4.4). No significant increase was observed for P. Despite the changes in the C and N contents, the C:N ratios did not show any significant change and probably remained constant during the study period. The annual increase for various elements was calculated to be 347 kg C ha^{-1}, 21 kg N ha^{-1} and 2.5 kg Ca ha^{-1} ($p <$ 0.10) (comparative values of annual increases for spruce stands were 999 kg C ha^{-1}, 42 kg N ha^{-1}, 3.2 kg Ca ha^{-1} and 1.8 kg P ha^{-1}). As the samples collected for the organic layer were not always divided into various horizons, it is not
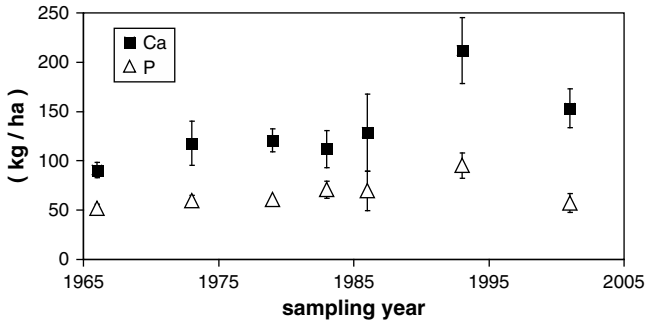
Fig. 4.4 Accumulation of P and Ca in the organic layer of beech stand at Solling measured periodically since 1966; mean and standard deviation

possible to assign this increase to a specific horizon of the organic layer. Moreover, there is a clear reduction in C and N values for the sampling period of 1993–2001 (Figs 4.2 and 4.3). However, the high level of variability in sampling as discussed above makes it mandatory to consider the changes during a single sampling period with caution. For example, a decrease in litter accumulation from 1993 to 2001 would need further verification in future years before any significance can be given to this decrease, which may have resulted from changes in the structure of canopy (removal of trees) or a decrease in atmospheric inputs of acidity and heavy metals.

4.4   Human Impacts and Management Issues at Solling

In order to assess human impacts on the rates of organic matter accumulation in the organic layer of the beech stand, one needs to consider changes in rates during the whole stand development. As no measurements of organic layer were available prior to 1966, the following method was used to calculate the annual accumulation rate.

It was assumed that the litter accumulated on the organic layer was essentially from the existing stand established in 1849 and that the initial 20 years of stand development contributed very little to the accumulated amount measured in 1966. The calculated amount therefore represents a high value for the accumulation of organic matter during the 1869–1966.

Table 4.6 gives the slopes of the accumulation of C, N, P and Ca for the measuring period of 1966–2001 (including r^2 and F significance) and the calculated values for the stand age of less that 20 years until 1966, assuming that at the beginning of this period there was no organic layer. The slopes indicating accumulation rate of C and N on the surface organic layer of the beech stand for 1966–2001 are much higher than those for the period 1869–1966 (Table 4.6). Together with C and N, calcium has also been retained. This accumulation of organic matter is not

Table 4.6 Coefficients (slopes) of the linear regression for C, N, P and Ca contents of the organic layer as a function of time for the period 1966–2001, and slope 1869–1966 based on the assumption of lacking organic layer during stand establishment (1869)

Variable	1869–1966	1966–2001	
	Slope	Slope	R^2 (p value)
C (Mg ha^{-1}a^{-1})	0.124	0.347	0.50 (0.075)
N (Mg ha^{-1}a^{-1})	0.006	0.021	0.51 (0.071)
P (Kg ha^{-1}a^{-1})	0.386	0.562	0.21 (0.295)
Ca (Kg ha^{-1}a^{-1})	0.6	2.461	0.55 (0.057)

related to any change in inputs as the inputs (leaf fall amount) have remained more or less constant as periodic measurements ($n = 13$) during the 35-year period indicated (2890 $\pm$ 510 kg ha^{-1} a^{-1}). Since forest management operations like thinning have not been conducted since 1966, there is no effect of forest management on this accumulation. The increase of the organic layer is presumed to be due to a reduction in the decomposition rate of the litter. A number of hypotheses can be formulated to describe the factors which may have influenced the conditions causing a decrease in litter decomposition on this site.

1. *A change in the micro-climatic conditions has occurred reducing the decomposition of litter.* It is difficult to test this hypothesis as the required long-term data are not available. However, the beech stand was already a mature one in 1966 and its structure did not change during the last 35 years, as is evident from a constant annual leaf litterfall on this site. Therefore, any micro-climatic change in soil temperature or moisture conditions is not expected to affect litter decomposition.
2. *Acid precipitation on the site has caused high acidity in the litter of the organic layer causing a reduction in decomposition rates.* High acidity in atmospheric deposition can reduce the rates of decomposition (CO_2 release) and N mineralisation (Wolters and Schaefer 1994; Schinner and Sonnleitner 1997). For example, Schaefer (1988) measured low CO_2 release from a number of soils which were collected close to the stem of the beech trees (high soil acidity due to stemflow) when compared with the soils collected from less acid areas. Similar results were obtained by Moloney et al. (1983) for conifer needles when studied under laboratory conditions. Wolters (1991) observed a decrease in CO_2 release when litter samples from the litter layer of the Göttinger Wald site were treated with acid rainwater. However, the effects of acidity on the decomposition of litter need to be considered with other accompanying factors such as high levels of soluble heavy metals and Al. For example, soluble Al may affect the litter decomposition directly by causing toxicity to micro-organisms (Jandl and Sletten 1999) or indirectly by complexing the soluble C and thereby reducing the amount of C available for microbial activity (Scheel et al. 2007).
3. *High levels of soluble heavy metals in the litter can slow down litter decomposition.* Contents of heavy metals in the organic layer are shown in Fig. 4.5.

Fig. 4.5 Concentrations of heavy metals (10–90% percentile) in the top organic layer of the beech and spruce stand at Solling (*horizontal lines* indicate concentration levels where impedance of mineralisation is expected according to Tyler (1992)
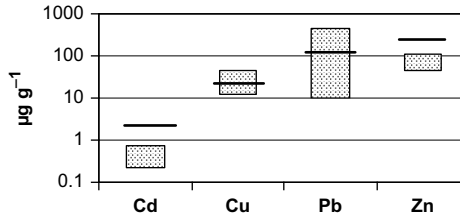
The values presented here provide the data for the whole horizon, whereas it is possible that such values could be much higher when thinner layers of each horizon are considered. Those thin layers may form chemical barrier to microbial activity and C transfer in the soil. For example, Heil (2000) showed that contents of Zn, Cu and Pb, when measured for each cm depth of the organic layer under the adjoining spruce stand to that of beech stand at the Solling site, were highest in H horizons (mean values in mg kg^{-1} were: 500 for Pb, 40 for Cu and 120 for Zn). Considering the critical values of heavy metals indicating toxicity to soil fauna and microbes (Tyler 1992), the high levels of Cu and Pb of the organic layer under the beech stand may have affected its decomposition. Further evidence of the reduction in decomposition due to soil fauna activity was provided by Alberti et al. (1996). In their experiment at Wiesloch in Odenwald, Germany, decrease in litter decomposition due to heavy metal accumulation was primarily related to diminished activity of soil fauna rather than that of microbes. On their site, concentrations of Cd and Zn were much higher and of Pb somewhat higher than those measured in Solling. Schaefer (1988) reported that, in 11 different forest sites under beech located in the south of Lower Saxony, the Pb content of more than 200 mg kg^{-1} in Of horizons caused a decrease in CO$_2$ respiration. Pb concentration in Solling soils lie between 54 mg kg^{-1} and 460 mg kg^{-1}. The heavy metals relevant for toxicity to soil fauna and microbes are monomeric or cationic forms. In a water extract of a loess-derived upper soil (0–10 cm), the percentage of monomeric forms, determined by ion exchange and by the dialysis method, was 72–89% for Cd, 95–96% for Zn, 29–38% for Pb and 2–15% for Cu (König and Ulrich 1986). Similar results were obtained in water extracts of the top organic layer of an oak woodland ecosystem (Martin and Bullock 1994). At the Solling beech site there are no speciation data available, but it can be assumed that the distribution of the heavy metal species may be similar. Although the effects of heavy metal in reducing litter decomposition at Solling cannot be specified, their contribution cannot be ruled out (for details on litter decomposition refer to Schaefer et al., Chap. 6, this Volume).

4. *The site receives high N inputs which interact with litter components to make them less decomposable*. Nitrogen concentration in the litter may affect its decomposition. From a literature review, Berg and Matzner (1997) came to the conclusion that during initial decomposition phases high levels of N in the leaf

litter increased the weight loss, but in the later phases the decomposition rate decreased as the easily mineraliseable cellulose and other components were consumed and the residues were enriched with lignin and N. The decrease in decomposition was more in N-rich substrates. Berg and McClaugerthy (2003) postulated that this decrease in decomposition was related to the formation of less degradable lignin compounds which were formed under high initial N levels in the litter. This could result from two reaction mechanisms: (1) There may be a reduction in the formation of lignolytic enzymes, and (2) chemical changes may occur where lignin incorporates N and undergoes condensation reactions. Berg (2000) reported that a positive relationship existed between retardation in the decomposition of litter and its N concentration. An increase in N concentration from 4 to 13 mg g^{-1} increased the fraction of non-degradable litter component from about 10% to 50%. N concentration of freshly fallen leaves of beech at the Solling site was 13.3 ($\pm$1.8) mg g^{-1} sampled in 13 out of 30 years between 1968 and 1997, which lies in the range given by Berg (2000) where a significant decrease in litter decomposition would be expected. In samples collected on a transect from Sweden to Italy, Persson et al. (2000) showed that the rate of CO_2 development decreased with an increase in N content or with narrowing of C:N ratios of the litter. Yanai et al. (2001) and Hyvönen et al (2007) conclude in their literature reviews that in northern coniferous forests N fertilisation results in higher surface organic layer contents due to lower litter decomposition rates. This is in accordance with the observations of Olson et al. (2005), that fertilisation of Norway Spruce in boreal forests reduced heterotrophic soil respiration and increased the thickness of the mor layer. In northern temperate forests of Michigan, the annual addition of 30 kg ha^{-1} of NO_3–N for 10 years led to increased carbon content of the organic layer and the upper mineral soil (0–10 cm) (Pregitzer et al. 2007) as well as to reduced CO_2 respiration rates (Burton et al. 2004) and lignolytic activity (DeForest et al. 2004).

From the available data on the beech site at Solling, it is not easy to decide which of the four hypotheses described above can be accepted, including the factors considered individually or in combination which are involved in reducing litter decomposition. This study, being primarily a field-based one, was not designed to include the individual factors described above. But if the observation made on this site is a commonly occurring phenomenon on all German forests where acidity plays a major role in causing this reduction in litter decomposition, then one-third of the total forest area will show a similar type of reduction in litter decomposition. On the remaining areas, the top organic layers are expected to be less acid either due to base-rich soil parent material (BMVELF 2002) or due to recent application of lime materials (27% of the forest area in Germany have been limed). The effects of heavy metals will depend on a number of factors. For example, the possibility of Cd and Zn affecting decomposition processes may be small due to their low concentration in most forest soils (98% of sites showed low values according to the data summarised by BMELF 1997) when related to the critical values provided by Tyler (1992). Forest sites which may show values higher than the critical values given by

Tyler (1992) for Cu would lie around 40% of all sites. The effect of Pb in decreasing faunal activity may occur on 40% of the sites, but only 2% of the forest sites may show the effects of Pb on microbial activity. The effect of high levels of N can be evaluated by considering N values in the leaf litter. In Lower Saxony, Germany, on 12 monitoring sites measured during 1994–2004, N levels in the leaf litter were 14 ± 2 mg N g^{-1} indicating a non-degradable litter fraction of about 30–40% on these sites (Berg 2000). As the N inputs through atmospheric depositions are commonly high in forests of Germany, the hypothesis relating litter N concentration to litter decomposition has major significance and would need additional research efforts.

During litter accumulation, N and a number of other elements such as Ca and P would be retained in the surface organic layer. Retention of these elements may impact on the nutrition of forests in a number of ways. For example, the amount of N retained increases the nutrient potential of the site, which would require special attention at the time of harvesting. Management of such sites would require special efforts to keep the N losses by leaching and denitrification at a low level. Special management practices would still be required on forest sites, despite the high atmospheric N depositions. The amount of P and Ca removed from the cycling fraction by litter retention would remain unavailable for further uptake by plants decreasing their concentrations in leaves. For example, the P concentration of beech leaves at the Solling site has decreased to almost half the values observed 30 years ago. There may be other reasons for this decrease in foliar levels of P in this stand, but its retention in the surface organic layer also seems to be an important factor.

4.5   Summary

Comparison of C and N contents in the 80 cm soil depth of the three mature beech stands indicated that the Solling, Zierenberg and the Göttinger Wald sites differed in the total amount and the depthwise distribution. The important factors which differed on these sites were: the intensity of faunal activity for depthwise distribution of organic matter, clay content (for providing physical protection to decomposition of organic matter in Göttinger Wald soil) and high soil Al (for providing chemical protection to decomposition in Solling soil). In the highly acid Solling soil where faunal activity was low, an accumulation of C occurred in the organic layer accounting for 20% of the total C in the surface 80 cm soil depth. In high faunal activity soils at the Göttinger Wald and Zierenberg sites, only about 4% of the total C in the 80 cm depth was present in the organic layer.

Long-term data on soil C and N and other nutrients measured periodically over 35 years at the Solling site indicated a continual increase of organic layer expressed as C content from 20 to 32 Mg ha^{-1} showing a positive linear trend in time. During the same period, the amount of N in the organic layer of the beech stand increased from 860 to 1,600 kg ha^{-1}. This change in soil C, N and other nutrients was

probably related to high atmospheric inputs of acidity, N and heavy metals causing a change in litter quality and decomposing conditions. This accumulation of organic matter in the surface organic layers may have significant effects on ecosystem functioning and on future management practices by affecting the cycling of nutrients, especially that of P.

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