Turnover of Soil Organic Matter (SOM) and Long-Term Balances – Tools for Evaluating Sustainable Productivity of Soils

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Accepted 8 May 1998

Summary – Zusammenfassung

Using data from long-term experiments at the Loess-Chernozem site, Bad Lauchstädt und 12 other European sites, the carbon (C) and nitrogen (N) dynamics in soils, the determination of decomposable soil organic matter (SOM), the effect on yield of SOM as well as carbon and nitrogen balances are discussed. Both C and N in SOM have to be divided into an inert and a decomposable fraction. The inert C is strongly correlated with clay content, while most changes in both C and N occur in the readily decomposable fraction. In the experiments considered the latter ranges between 0.2 to 0.6% C and 0.02 to 0.06% N. The annual changes of the C_{org} content amount only to about 0.01% C_{org} corresponding to 500 kg/ha, even under extreme changes of the fertilizing system.

Hot water extractable C (C_{hwe}) has proved to be an appropriate criterion for the calculation of the decomposable C and thus for the N release from soil. Different methods to maintain a SOM balance are compared and first guideline values for an agronomically and ecologically justified SOM content of arable soils are recommended. In arable soils the exceeding of an upper C_{org} value influences neither crop yield nor the C and N balance in a positive way. In terms of ecology and environment, set-aside-programmes or fallows in a crop rotation affect the balances negatively. Atmospheric N deposition can amount to about 50 kg/ha·yr.

Key words: Soil organic matter / carbon and nitrogen balances / yield / decomposable carbon

Die Umsetzung der organischen Bodensubstanz (OBS) und deren Langzeitbilanz – ein Weg zur Bewertung der Produktivität und Nachhaltigkeit von Böden

Auf der Grundlage von Dauerfeldversuchsergebnissen auf dem Löß-Schwarzerdestandort Bad Lauchstädt und 12 weiteren Standorten werden Aussagen zur C- und N-Dynamik im Boden, zur Bestimmung des umsetzbaren Anteils der OBS, zur Ertragswirksamkeit sowie zur Bilanzierung von C und N abgeleitet. Hierbei wird zwischen inertem und umsetzbarem Kohlenstoff bzw. Stickstoff unterschieden. Der inerte C ist sehr eng mit dem Tongehalt korreliert. Veränderungen in der OBS betreffen nahezu ausschließlich den umsetzbaren Anteil. Dieser macht unter den untersuchten Bedingungen 0,2 bis 0,6% C_{org} bzw. 0,02 bis 0,06% N_t aus. Die jährlichen Veränderungen im C_{org}-Gehalt betragen selbst bei extremem Wechsel der Düngung nur etwa 0,01% C_{org} oder 500 kg/ha.

Der heißwasserlösliche Kohlenstoff hat sich als ein geeignetes Kriterium für den umsetzbaren C und damit für die N-Nachlieferung erwiesen. Es werden unterschiedliche Methoden der Bilanzierung der OBS verglichen und erste Orientierungswerte für den Gehalt des Bodens an OBS mitgeteilt. Auf ackerbaulich genutzten Standorten werden bei Überschreiten dieser Orientierungswerte weder die Erträge, noch die C- und N-Bilanzen positiv beeinflußt. Brache und Flächenstillegungen wirken sich ungünstig auf den C- und N-Kreislauf aus. Die atmosphärische N-Deposition kann mit > 50 kg/ha a angesetzt werden.

1 Introduction

Worldwide problems of food supply and environmental pollution, including the increasing concentration of trace gases in the atmosphere and the decreasing resources of clean water, cannot longer be seen within political or geographical borders. The maintenance of soil functions increasingly requires global thinking and these functions are discussed at present from very different points of view. The diversity of soil functions with partly the same or an overlapping meaning complicates their clear definition.

In this paper only the ecological and not the social, soil functions will be considered. They are subdivided in accordance with *Blum* (1997) as:

– the production function (food, energy, raw materials)
– the regulatory function (filter-, buffer- and transformation functions)
– the habitat function (including the gene reserve).

In the last few years situations have emerged, which give reason for serious concern. Every year millions of human beings die of starvation and the nourishment of nearly 1 billion is insufficient. The area of arable land, however, decreases on a global scale by about 10 million ha per year. Thus the production function should definitively have priority in agricultural research (*Diez*, 1995).

With regard to the environment the regulatory function of soils is decisive. It is linked with the production and decay of biomass and with the assimilation and emission of CO_2 on which the CO_2 cycle depends. Whereas uncropped soils (i.e. under fallow) might be a source of CO_2, an optimized crop production could lead to a decrease of CO_2 in the atmosphere. But the soil by its definition as 'the uppermost, inhabited part of the earth's crust in the overlapping area of lithosphere, atmosphere and hydrosphere .... is the site for the plants and habitat for the reducents.... ' (*Autorenkollektiv*, 1991). Regarding its

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pedological state the soil develops inter alia also through the growth of plants and all important soil functions are influenced by the vegetation. A soil permanently free of vegetation is no longer a soil in the sense of this definition.

The definition and determination of soil organic matter (SOM) is still not clear (*Körschens* et al., 1997). According to *Müller* (1980) SOM is defined as 'the living and dead organic matter, which is integrated in soil, where the first represents the edaphone (autochthonous microorganisms) and the latter the humus'.

A direct analytical determination of SOM is impractical, with exception of clay- and carbonate- free soils (*Kuntze* et al., 1988). It is common to calculate SOM by multiplying % organic carbon by the factor 1.724 (*Kononova*, 1958) or 2 (*Blume*, 1990). According to *Kuntze* et al. (1988), *Rasmussen* and *Collins* (1991), *Riek* (1995) the conversion factor ranges between 1.4 and 3.3. Because of this uncertainty it is more precise to use % C_{org} determined by analysis.

The carbon and nitrogen cycles in the soil/plant system are also not fully elucidated and quantified. They, however, are of particular and crucial importance, because:

- both elements are essential for soil functions, but the ranges of favourable and harmful effects are very narrow
- both cycles depend strongly on external influences and are, therefore, difficult to control,
- they are subject to strong site and weather dependent variability which impedes their quantification.
- the diversity and stability of their chemical structures are insufficiently known.

To solve these open questions two approaches were pursued in the past. On the one hand intensive humus research (humus chemistry) attempted to elucidate the chemical structures of SOM by developing fractionation methods (*Tjurin*, 1951; *Kononova*, 1958; *Kögel-Knabner* and *Guggenberger*, 1995). On the other hand empirical approaches were used to quantify the effects of SOM by evaluating field and model experiments, as well as by the simulation of different compartments of SOM. On this basis threshold values for % C were derived (*Heinonen*, 1974; *Franko*, 1997; *Körschens* et al., 1986). There is still a big difference between both approaches.

Up to now the evaluation of field experimental data does not offer sufficient clarity in the cause/effect relations. Nevertheless useful conclusions can be derived from the results for sustainable soil management. In the following long-term experimental data are used to contribute to the solution of these pending questions. Results will be presented about:

- the dynamics of carbon and nitrogen in soil
- the influence of SOM on crop yield
- the interactions between soil and adjacent water and atmospheric ecosystems
- the C and N output on basis of balances

2 Material and methods

Investigations on the topics outlined above require long-term experiments with a corresponding intensive data collection over many years, preferably decades because 'organic carbon' and 'nitrogen' in soil and also crop yields show a high spatial and temporal variability. Significant results can, consequently, only be achieved with an appropriate number of replications in space and time.

The majority of investigations presented in this paper were done at Bad Lauchstädt where the soil is a Loess-Chernozem (Haplic Chernozem) with 21% clay, 110 m above sea level, 484 mm annual precipitation (average 1896–1995) and 8.7°C mean annual temperature (average 1896–1995).

The 'Static Fertilization Experiment Bad Lauchstädt', started in 1902, provides the most important data base. On one part of this field experiment an extension to the experiment was introduced in 1978 to discern the influence of highly different SOM contents on yield and C and N dynamics. Detailed information on this experiment and the site can be found in *Körschens* et al. (1994).

Organic carbon was determined by dry combustion according to STRÖHLEIN. Nitrogen was determined according to KJELDAHL. Hot water extractable carbon (C_{hwe}) was determined to estimate the decomposable part of soil organic matter (*Behm*, 1988; *Körschens* et al., 1990; *Schulz*, 1990 and 1997).

To help verify the conclusions derived from the Bad Lauchstädt experiment results of other long-term experiments are used (Tab. 1).

3 Results and discussion

3.1 C and N dynamics

The following observations on the C and N dynamics are based on the fact, that SOM can be divided into at least 2 fractions. One is relatively 'inert'[1)] and hardly involved in C transformations, while the other is mineralizable/decomposable (*Körschens*, 1980a and b). *Jenkinson* and *Rayner* (1977) identified altogether 5 SOM fractions with clearly different half life periods and subdivided the stable part into 'physically stabilized' and 'chemically stabilized' SOM. *Franko* (1997) differentiates in a simulation model the mineralizable part of SOM further in an 'active' and a 'stabilized' fraction.

The inert C and N is, with only few exceptions, closely correlated with the clay content (Fig. 1) and for calculations regarding C and N dynamics this inert C is of little importance. Changes within a foreseeable period can only be detected for the decomposable part of SOM.

Fig. 2 shows results of a small plot experiment on Loess-Tschernozem started in 1956 by *Ansorge* (1966). The plots already had large differences in their % C.

During the 40 years without any fertilizer, C_{org} in the treatment without fertilizer since 1902 decreased only slightly and seems to have reached at 1.5% C_{org}, its final value and a new equilibrium indicating the 'inert' C_{org} content of this site. There were larger decreases in % C in soils

[1)] The term "inert" carbon is used here for that part of carbon, which remains in soil over many decades even under bare fallow and without any fertilization.

Table 1: Overview of long-term fertilizer experiments at selected sites.
Tabelle 1: Übersicht über Dauerdüngungsversuche ausgewählter Standorte.

No	Experimental sites	Initial year	Clay content %	mean temp. °C	precipitation mm	Author
1	Thyrow (Germany)	1937	3	8.6	520	*Schnieder* (1990)
2	Müncheberg (Germany)	1963	5	8.2	521	*Rogasik* (1995)
3	Ascov (Denmark)	1894	12	7.7	790	*Christensen* (1989)
4	Bad Lauchstädt (Germany)	1902	21	8.7	484	*Körschens* et al. (1994)
5	Järna (Sweden)	1958	30	6.0	550	*Pettersson* et al. (1992)
6	Dikopshof (Germany)	1904	10	10.0	637	*Schellberg* and *Körschens* (1996)
7	Skierniewice (Poland)	1923	5	7.9	520	*Mercik* (1993)
8	Seehausen (Germany)	1967	8	9.0	556	*Hülsbergen* (1992)
9	Halle (Germany)	1878	8	9.2	501	*Stumpe* et al. (1990)
10	Ultuna (Sweden)	1956	36	5.5	527	*Kirschmann* et al. (1994)
11	Prag (Czech Republic)	1955	31	7.7	487	*Klir* et al. (1995)
12	Rothamsted (UK) Broadbalk	1843	27	9.0	717	*Powlson* (1996)

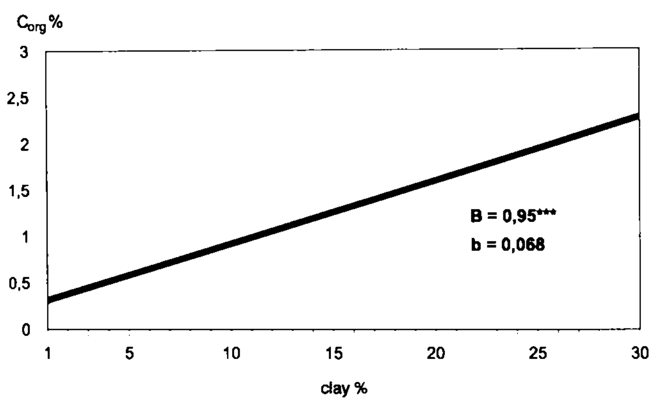

Figure 1: Linear regression between C_{org} content of nil plots (as a criterion for inert C) and the clay content in 21 long-term field experiments.
Abbildung 1: Lineare Regression zwischen dem C_{org}-Gehalt der Nullparzelle (als ein Kriterium für den inerten C) und dem Tongehalt von eigenen und in der Literatur zitierten Dauerfeldversuchen (n = 21).

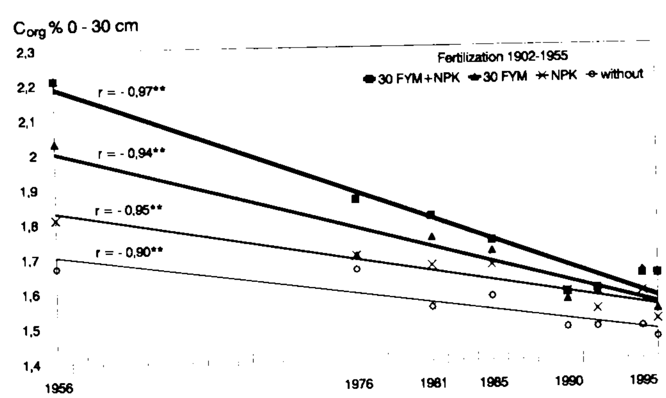

Figure 2: Changes of C_{org} content in dependence of initial level under bare fallow on Loess-Chernozem without any fertilization.
Abbildung 2: Veränderungen des C_{org}-Gehaltes in Abhängigkeit vom Ausgangsniveau unter Schwarzbrache auf Löß-Schwarzerde ohne Düngung.

starting with higher initial C contents. Similar results were found in a long-term experiment in Ultuna (Sweden, see Tab. 1), where after 30 years there was a value of 1.04% C_{org} in the unfertilized bare fallow. In a light sandy soil at Thyrow (Germany) the C_{org} content of the unfertilized 'Nil' plot was 0.34% C_{org} after 50 years and this was comparable to that of a bare fallow because there was no plant growth.

In the following sections the difference between the C_{org} content and the inert C (C_i) is, for practical reasons, considered as the decomposable carbon (C_{dec}). Following our definition (cf section 3.1), the 'inert' carbon could be esti-

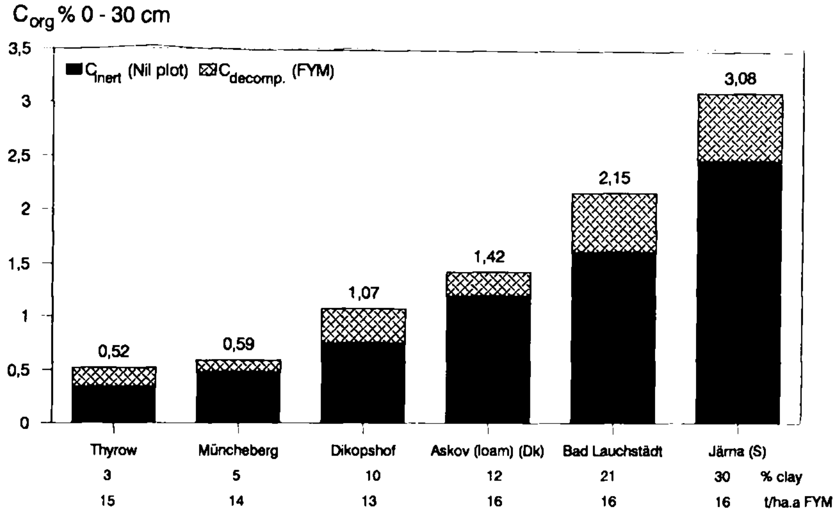

Figure 3: Influence of clay content and farmyard manure application on the inert and decomposable C_{org} content in selected long-term field experiments.

Abbildung 3: Einfluß von Tongehalt und Stalldung auf den C_{org}-Gehalt in ausgewählten Dauerfeldversuchen.

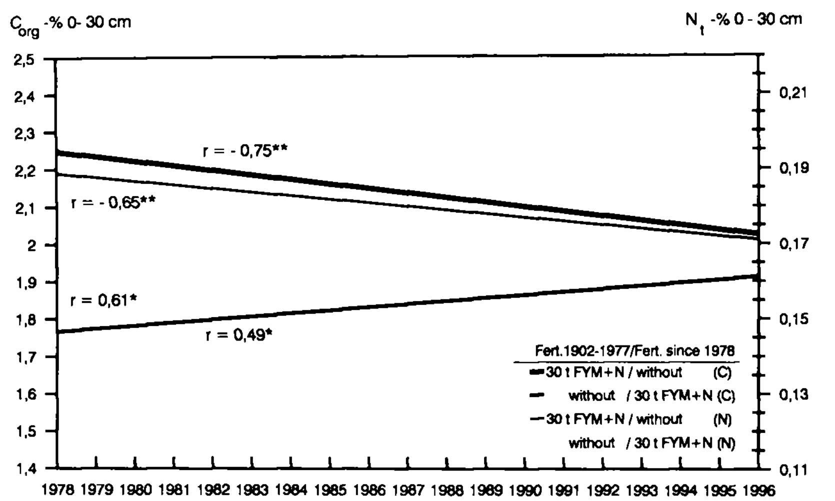

Figure 4: Carbon and nitrogen dynamics in dependence of their initial level and fertilizer application in the 'Static Experiment Bad Lauchstädt' (crop rotation: potato, winter wheat, sugar beet, spring barley).

Abbildung 4: Kohlenstoff- und Stickstoffdynamik in Abhängigkeit von Ausgangsniveau und Düngung im Statischen Düngungsversuch Bad Lauchstädt nach Erweiterung der Versuchsfrage (Fruchtfolge: Kartoffeln, Winterweizen, Zuckerrüben, Sommergerste).

mated from the C_{org} content in the 'Nil' plots of long-term experiments provided, that the soil has reached its equilibrium % C_{org} value.

For selected long-term experiments with soils with different clay content but with nearly the same farmyard manure (FYM) application, the 'inert' and decomposable carbon (C_{dec}) is presented in Fig. 3.

C_i increases with increasing clay content from 0.34% to 2.45%, the C_{dec} from 0.11% to 0.63%. This increase in both fractions is caused by the fact that C_i increases with clay content, as discussed previously, and C_{dec} increases because the mineralization rate decreases.

In sandy soils the absolute content of C_{dec} is consequently lower, but as a proportion of the total carbon it is higher.

From these and previous results (*Körschens*, et al. 1997), it is clear that the optimum C_{dec} content in loam and loess soils under European temperate climate conditions is below 0.6%. On sandy soils it is difficult to achieve > 0.4% C_{dec} which, for other reasons, would be considered too low, for example soil physical properties are closely correlated with the carbon content and could be improved by an increase of C_{org} in soil (*Körschens* and *Waldschmidt*, 1995).

The C_{org} and N_t content of soil changes very slowly. At a farm scale alterations in soil management are generally not detectable until after 10 years. To investigate the dynamics of C_{org} and N_t in soil it is, therefore, advisable to collect and analyze soil samples taken each year from each plot to discern any trends.

On one part of the 'Static Fertilization Experiment Bad Lauchstädt' the fertilization was reversed after 75 years of constant treatment. In part of the former FYM + N treatments, with soils containing 2.3% C_{org} this treatment was stopped, whereas from 1978 the highest organic-mineral fertilization has been applied on part of the former 'Nil' plot. This made it possible, to quantify changes in C_{org} and N_t during 18 years after extreme changes in fertilizer use (Fig. 4).

In 1978 the FYM + N treated soil had 2.25% C_{org} and after this treatment was stopped, % C_{org} declined by 0.013% annually, corresponding to a loss of 520 kg C/ha, and % N by 0.0011% N annually, amounting to 44 kg N/ha. This calculated quantity of N is in very good agreement with the difference in N uptake between the previous FYM + N plot and the continuous 'Nil' plot.

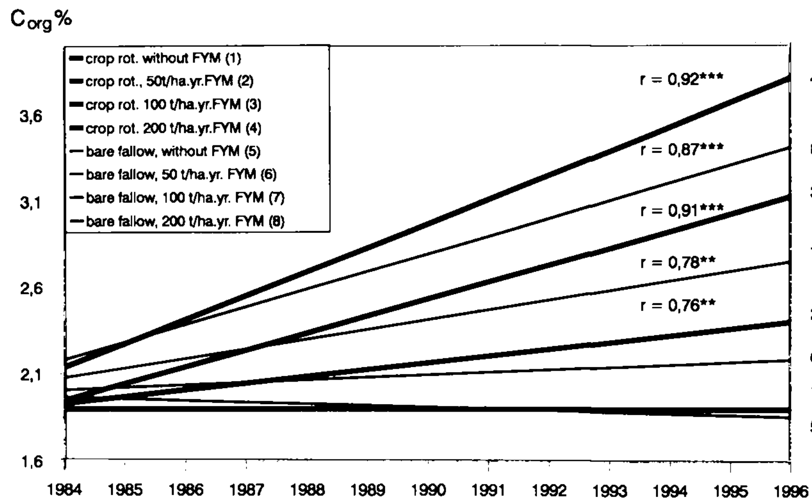

Figure 5: Development of C_{org} content in a crop rotation and a bare fallow respectively in a long-term field experiment with extremely high application of farmyard manure on Loess-Chernozem at Bad Lauchstädt (0–30 cm).
Abbildung 5: Entwicklung der C_{org}-Gehalte in einem Dauerfeldversuch mit extrem hohen Stalldunggaben in der Fruchtfolge und unter Schwarzbrache auf Löß-Schwarzerde in Bad Lauchstädt (0–30 cm).

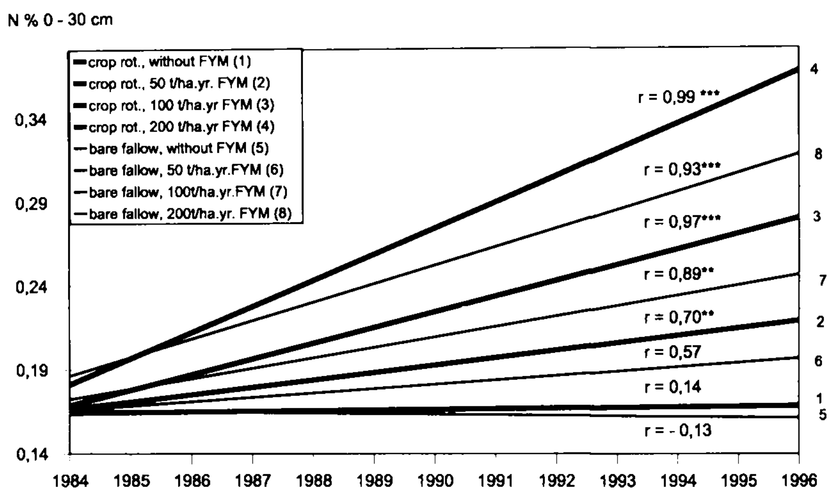

Figure 6: Development of N_t content in a crop rotation and a bare fallow respectively in a long-term field experiment with extremely high application of farmyard manure on Loess-Chernozem at Bad Lauchstädt (0–30 cm).
Abbildung 6: Entwicklung der N_t-Gehalte im Boden in einem Dauerfeldversuch mit extrem hohen Stalldunggaben in der Fruchtfolge und unter Schwarzbrache auf Löß-Schwarzerde in Bad Lauchstädt (0–30 cm).

Following the application of FYM to the previously unfertilized plot the increase in C_{org} was 0.0081% annually and for nitrogen it was 0.0012% N annually. It is obvious, that it will be many decades before a new equilibrium is reached.

The rate of increase in C_{org} and N can also be seen in another long-term experiment started in 1984 on the Loess-Chernozem in Bad Lauchstädt. The plots received extremly large amounts of FYM (0, 50, 100 and 200 t/ha per year) with a crop rotation[1] and a bare fallow. (Fig. 5 and 6)

All FYM treated soils show a significant increase in both C_{org} and N in the plough layer. With 200 t/ha · yr FYM there was an increase of 1.8% C_{org} by 1996, which corresponds to an accumulation of 35% of the carbon applied with the FYM. The relatively small increase of C_{org} in the subsoil is not considered in the following calculation.

Averaged over all treatments and years, there is about 0.28% less C and 0.027% less N in bare fallow soils than in those growing the crop rotation. However the differences between fallow and rotation increase from 'Nil' to high FYM treatments:

- without fertilization 0.06% C_{org} and 0.011% N_t
- 50 t/ha·yr FYM 0.20% C_{org} and 0.022% N_t
- 100 t/ha·yr FYM 0.38% C_{org} and 0.025% N_t
- 200 t/ha·yr FYM 0.48% C_{org} and 0.048% N_t

One reason for this increasing differentiation between crop rotation and bare fallow is probably the amount of crop and root residues returned to the soil increasing with increasing rates of FYM. Another explanation could be, that as the vegetation density increases with increasing rates of FYM then there may have been less soil aeration which decreased mineralization intensity.

In summary it can be concluded that in considering C, N dynamics for agronomic and ecological purposes a knowledge of C_{dec} changes is more informative than those of total C_{org}.

In the following chapter the possibilities for estimating the decomposable C by means of simple determinable chemical parameters will be discussed.

[1] sugar beet, maize, winter wheat, potato, maize, winter wheat, sugar beet, potato, maize, sugar beet, potato, maize, sugar beet

Table 2: Relationship between the decomposable fraction of SOM, soil respiration and net N mineralization under incubation conditions in selected long-term experiments in Europe.

Tabelle 2: Beziehungen zwischen der umsetzbaren Fraktion der OBS, der Bodenatmung und der Netto-N-Mineralisierung unter Inkubationsbedingungen in ausgewählten Dauerversuchen Europas.

	C_{org} (%)	C_{hwe} (mg/100 g dm)	cumulated respiration after 35 d (mgC/100 g dm)	Net N mineralis. after 35 d (mg/kg)
Bad Lauchstädt				
without	1.49	21.4	19.9	9.2
NPK	1.72	26.8	18.6	9.3
FYM[1)]	1.90	45.6	24.8	16.5
FYM[1)] + NPK	2.10	47.7	24.9	14.3
FYM[2)]	2.19	38.6	23.7	15.3
FYM[2)] + NPK	2.29	43.2	30.3	23.2
Prague				
without	1.24	30.8	21.7	4.7
NPK	1.37	28.9	16.2	8.9
FYM[3)]	1.55	28.0	20.0	13.0
FYM[3)] + NPK	1.67	43.3	22.3	11.6
Rothamsted				
M1 without	1.08	24.5	21.2	4.0
M1 NPK	1.04	22.3	24.0	7.7
M1 FYM	3.24	96.3	59.8	16.9
R1 without	0.77	16.5	18.5	4.3
R1 NPK	0.80	16.7	22.8	4.6
R1 FYM	2.83	59.9	34.1	25.0

1) 20 t/ha every second year
2) 30 t/ha every second year
3) 21 t/ha every second year

3.2 Determination of the decomposable carbon (C_{dec}) and N release

There is still an urgent need to be able to define the optimum SOM content for various sites and management systems.

A simple and reliable method for an approximate determination of C_{dec} is the hot water extraction (*Schulz*, 1997). As water is used as solvent this fractionation nearly corresponds to natural conditions (*Körschens* et al., 1990; *Schulz*, 1990) and provides realistic results. *Beck* (1984) and *Insam* and *Domsch* (1988) have shown that the earliest detectable effects of changes in the supply of organic matter to soils are in the most readily mineralizable fraction.

The hot water extractable fraction is not a well defined fraction of the SOM. It contains parts of the soil microbial biomass, simple organic compounds and compounds which are hydrolyzable or depolymerizable under the given extraction conditions by water (*Schulz*, 1997). Thus C_{hwe} can be considered as part of the active SOM (*Franko*, 1997).

The close relation between the hot water extractable fraction (C_{hwe}) and microbial biomass is seen in the highly significant correlation between C_{hwe} and soil respiration ($r^2 = 0.97$ $n = 15$) and with the nitrate release during incubation ($r^2 = 0.91$, $n = 15$) respectively (*Schulz*, 1990).

The results for C_{hwe}, cumulated respiration over a 35 day period and N mineralization for 3 European long-term experiments (analyzed as part of an EU project) showed significant correlations between C_{hwe}/microbial biomass $r = 0.92$, C_{hwe}/respiration $r = 0.88$ and C_{hwe}/N mineralization $r = 0.77$ (Tab. 2).

From the results of previous extensive investigations on potentially mineralizable carbon and nitrogen by *Stanford* and *Smith* (1972) and by *Freytag* (1987) with the long-term experimental data given here, the following mathematical relation could be derived:

$$C_{dec} = 15 \cdot C_{hwe}$$

A similar factor for the conversion of C_{hwe} to C_{dec} was found by *Manzke* (1995).

The relationship between the 'inert' C and the content of clay and fine silt was quantified using data from a large number of long-term experiments as follows (*Körschens*, 1980):

$$C_{inert} = 0.04 \cdot (\text{\% clay+fine silt}), \text{ (particles} < 6.3\ \mu\text{m)}$$

Thus if C_{org} equals $C_{dec} + C_{inert}$ then:

$$C_{org} = 15 \cdot C_{hwe} + 0.04\ (\text{\% clay+fine silt})$$

To validate this formula the experimental data from 2 sites Bad Lauchstädt (Haplic Chernozem) and Thyrow (Albic Luvisol) were used (Fig. 7). The scatter and the fitted lines suggest that, as a first approximation, C_{hwe} could be used to estimate C_{dec}.

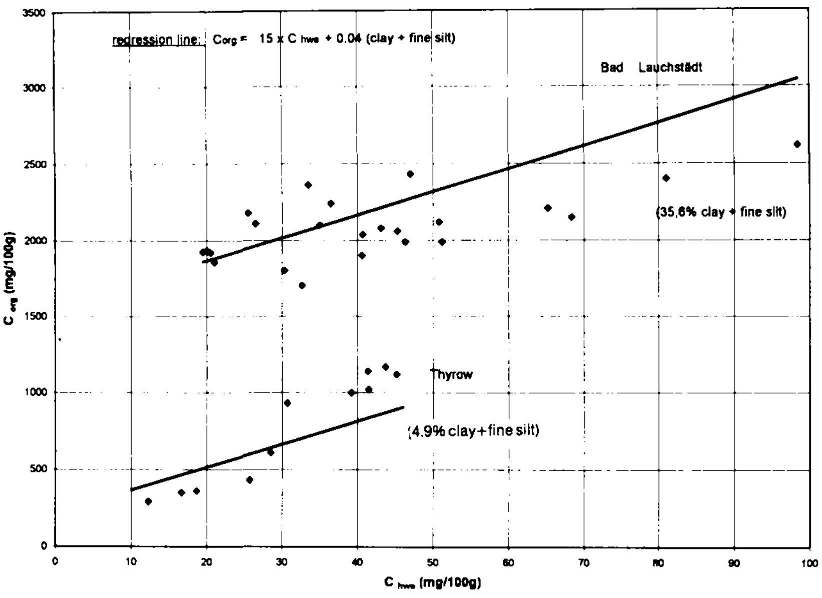

Figure 7: Correlation between hot water extractable and decomposable carbon as a comparison of calculated (lines) and experimental (points) data of a Loess-Chernozem at Bad Lauchstädt and a sandy soil at Thyrow.

Abbildung 7: Korrelation zwischen heißwasserextrahierbarem und umsetzbarem Kohlenstoff als Vergleich von berechneten (Linien) und experimentellen Daten (Punkte) einer Löß-Schwarzerde (Bad Lauchstädt) und eines Sandbodens in Thyrow.

Table 3: Influence of organic and mineral fertilizers on total organic carbon content and the hot water extractable fraction of SOM in soil.
Tabelle 3: Einfluß organischer und mineralischer Düngung auf den Gesamtgehalt an organischem Kohlenstoff und die heißwasserlösliche Fraktion der OBS im Boden.

Fertilizer	C_{org} (%)	C_{hwe} (mg/100 g)
IOSDV Experim. Dahlem		
(*Köhn* et al., 1997)		
without	0.63	17.3
mineral	0.65	20.8
FYM	0.83	22.8
mineral + FYM	0.77	21.3
straw/GM/L	0.70	19.9
mineral+FYM/GM/L	0.91	26.0
Nutrient Deficiency Experiment		
Thyrow (*Schulz*, 1997)		
without	0.29	12.3
NPK	0.36	18.7
NPK + Ca	0.35	16.7
FYM	0.43	25.7
NPK + Ca + FYM	0.61	28.5
Static Soil Fertility Experiment Thyrow		
(*Ellmer* et al., 1997)		
PK	0.30	18.7
NPK	0.34	19.2
FYM 1	0.53	34.1
FYM 2	0.72	37.3
straw	0.50	34.3
FYM 1 + clay	0.79	40.5

FYM... farm yard manure; GM... green manure; L... leaves

The influence of organic and mineral fertilization on the content of C_{dec}, estimated by the C_{hwe}, can be seen from the data in Tab. 2 and 3. The decomposable part of SOM is increased only a little by mineral fertilization, much more by the application of FYM.

Table 4: Contents total organic carbon (C_{org}) and hot water extractable carbon (C_{hwe}) in the unfertilized treatments of selected long term experiments.
Tabelle 4: C_{org}-Gehalte und C-Gehalte der Heißwasserfraktion von ungedüngten Varianten ausgewählter Dauerversuche.

Experimental site	C_{org} (%)	C_{hwe} [mg · 100g^{-1}]
Static Fertil.Exp.Lauchstädt	1.69	16.8
Model Exp.Lauchstädt (loam)	1.48	16.1
Groß Kreutz (loamy sand)	0.34	19.6
Sülten (sand)	0.42	17.5
Thyrow (sand)	0.29	12.3
Timirjazev-Akademie (bare fallow, with lime) (loamy sand)	0.34	9.6

Independent of soil type and content of C_{org}, the C_{hwe} results for unfertilized treatments in six long-term experiments show remarkable similarity. This suggests that for these soils there is a limit for SOM depletion below C_{hwe} values < 20 mg/100 g soil dry matter (Tab. 4).

Differences in the proportion of C_{hwe} in C_{org} are due to the different amounts of C_i in the total soil carbon.

From the analysis of more than 1000 soil samples from different long-term experiments, model experiments and farms of the former GDR five groups of C_{hwe} were proposed to rate the SOM content of soils using hot water extractable carbon as a parameter (Tab. 5):

3.3 The effects of SOM on yield

SOM is important for sustaining the production function of a soil. SOM effects can come from (1) nutrients and (2) improvements in soil structure including physical properties, like water holding capacity, bulk density and sorption capacity.

Improvements in yield due to SOM have been demonstrated (*Asmus*, 1995; *Körschens* et al., 1997), but the

Table 5: Ranges of C_{hwe} for a classification of soils according to their supply with organic matter derived for sandy and loamy soils without groundwater influence, an average annual temperature of 6–10°C and an average annual precipitation of 400–800 mm.

Tabelle 5: C_{hwl}-Bereiche für eine Klassifizierung von Böden nach ihrem OBS-Versorgungsgrad für sandige und lehmige Böden ohne Grundwassereinfluß, einer Jahresmitteltemperatur von 6–10°C und einer mittleren Jahresniederschlagssumme von 400–800 mm.

C_{hwe} – range [$mg \cdot 100g^{-1}$]	SOM content	
> 40	1	(very high)
30 ... 40	2	(high)
25 ... 30	3	(medium; recommended)
20 ... 25	4	(low)
< 20	5	(very low)

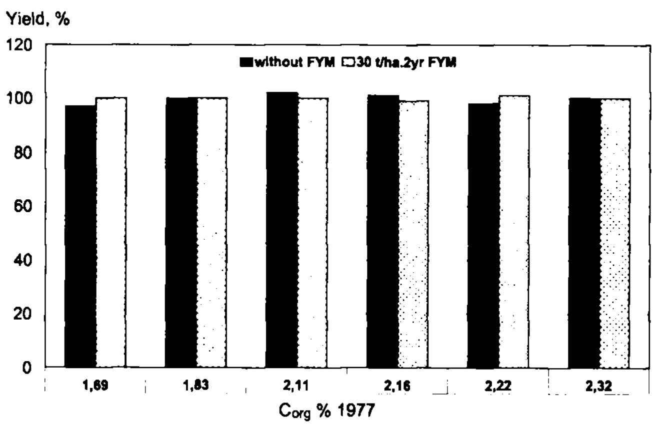

Figure 8: Relative crop yield in dependence of C_{org} content in the soil (at start of the experiment in 1977) and farmyard manure at optimal mineral N fertilization. Average of the crop rotation 1979–1996 in the Static Fertilization Experiment Bad Lauchstädt.

Abbildung 8: Relativerträge in Abhängigkeit vom C_{org}-Gehalt im Boden (zu Versuchsbeginn 1977) und von der organischen Düngung bei jeweils optimaler Mineral-N-Düngung im Durchschnitt der Fruchtfolge 1979 bis 1996 im Statischen Düngungsversuch Bad Lauchstädt.

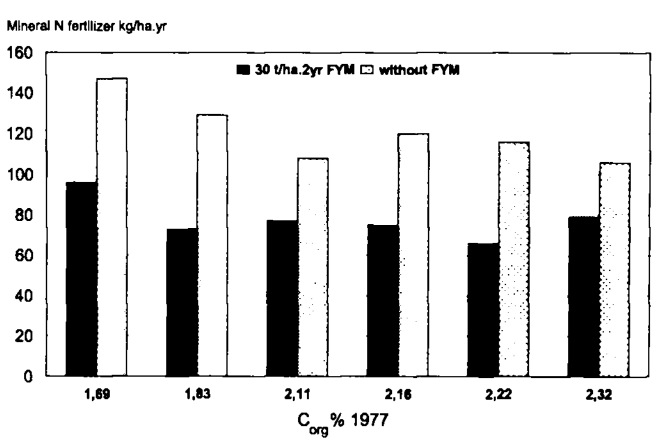

Figure 9: Mineral N fertilizer required for achieving maximum yield in dependence of C_{org} content in the soil and organic manuring (see legend to Fig. 8).

Abbildung 9: Mineral-N-Aufwand für den jeweiligen Höchstertrag in Abhängigkeit vom C_{org}-Gehalt im Boden und von der organischen Düngung (vgl. Legende Abb. 8).

effects are often small, yield increases up to 10% on sandy soils and up to 6% on loamy soils. In these investigations, however, the nutrient effect could not be separated from the soil quality improving effect. Some effects of different SOM levels in combination with farmyard manure and different mineral N levels on yields are now available from the extension to the Static Fertilization Experiment Bad Lauchstädt (Fig. 8).

In average of all crops and years for the Loess-Chernozem site no positive yield response neither by a higher SOM level in soil nor by FYM application was found when mineral fertilization was at optimum. Relative yields varied between 97 and 101%. As far as nutrient effects of SOM are concerned the application of mineral N fertilizer increased yields at all levels of SOM (Fig. 9).

In the treatments without FYM, on average, 43 kg/ha · yr more mineral N fertilizer was necessary to reach the highest yield but optimal N declined from 147 kg N/ha at low SOM (1.69% C_{org}) to 108 kg N/a at highest SOM. In the FYM plots optimal mineral N ranged from 96 at low SOM to 67 kg N/ha at 2.22% C_{org}. This result supports the conclusion that on this site the soil improving effect of SOM on crop yield (Fig. 8) was less important than the nitrogen effect of decomposable SOM. Thus the decomposable SOM and its N release as well as the N supply by FYM and by mineral fertilizer are decisive for growth and yield.

3.4 Nitrogen and carbon balances

For the evaluation of sustainability of various land use systems nutrient balances and organic matter fluxes are an indispensable tool. Nitrogen balances are of special importance, because the effects on yield and the risk of pollution are closely related. Improper, excessive use of nitrogen has led in recent decades to high N losses. Carbon balances, on the one hand, are of growing interest for the estimation of the sink potential of soils for atmospheric CO_2, and the role of agricultural systems in the global carbon cycle.

Long-term experiments allow a relatively simple calculation of balances by comparing the input in form of fertilizer with the output in form of harvested products. Further balance factors, like C and N input via seeds and indirect C inputs (fuel C consumed in the manufacturing of pesticides, fertilizer, fuel) can be neglected as constant factors.

In almost all of the long-term experiments reported here (Tab. 1) the C and N contents in soil have reached an equilibrium. For experiments of shorter duration and with extreme fertilization treatments the changes are well documented by measurements during many years and can thus be quantified and used for balances.

3.4.1 *Nitrogen balances*

Tab. 6 presents the nitrogen balances for 8 long-term experiments at 6 sites. The balance was quantified as follows:

Table 6: N balance of different European long-term experiments.
Tabelle 6: Stickstoffbilanzen in verschiedenen europäischen Dauerversuchen.

Site/Experiment	Evaluated period	Years	Treatment	Input per year (N kg/ha·yr)	Changes soil-N (N kg/ha·yr)	Uptake by plants (N kg/ha·yr)	Balance (N kg/ha·yr)	N loss % of input
Bad Lauchstädt								
Static Experiment	1965–	32	Nil	0		50**		
stripe 2	1996		NPK	111		152	− 9	8
			15 FYM	93		114	− 29	31
			15[1)] FYM+NPK	174		185	− 39	22
Static experiment								
(extension part)	1978–	19	Nil (N1)	0		56**	—	
1902–1977 without	1996		NPK (N3)	83	24	117	+ 2	–
fertilization = 1.7% C			NPK (N5)	166	24	179	− 19	11
in soil			15 FYM (N1)	95	23	102	− 26	27
			15 FYM+NPK (N3)	178	47	164	− 23	13
			15 FYM+NPK (N5)	261	47	206	− 64	25
1902–1977 15 FYM	1978–	19	Nil (N1)	0	− 39	97 (58**)		
+NPK = 2.3% C in soil	1996		NPK (N3)	83	− 39	162	+ 18	–
			NPK (N5)	166	− 39	210	− 53	32
			15 FYM (N1)	95		130	− 23	26
			15 FYM+NPK (N3)	178	12	170	− 54	30
			15 FYM+NPK (N5)	261	12	198	−109	42
Model experiment								
with high	1984–	13	Nil	0	− 50	173 (123**)		
FYM application	1996		50 FYM	340	111	250	−102	30
			100 FYM	680	345	271	−187	28
			200 FYM	1360	555	276	−652	48
Skierniewice								
Field D	1968–	27	Nil	0		31**		
	1994		NPK	81		83	− 29	36
			20 FYM	100	29	57	− 45	45
Rothamsted								
Broadbalk	1968–	27	Nil	0		24**		
monoculture	1994		NPK	144		119	− 49	34
			35 FYM	246	34	109	−127	52
			35 FYM+N	342	61	159	−146	43
Broadbalk			Nil	0		43**		
crop rotation			NPK	144		121	− 66	46
			35 FYM	246	34	122	−133	54
			35 FYM+N	327	61	144	−165	50
Prague								
Ruzyne Field B	1968–	27	Nil	0		61**		
	1994		NPK	104		116	− 49	47
			10 FYM	59		92	− 28	47
			10 FYM+NPK	163		142	− 82	50
Thyrow								
Nutrient-deficiency	1977–	12	Nil	0		17**		
experiment	1988		NPK	75		70	− 22	29
(*Schnieder* 1990)			15 FYM	102		42	− 77	75
			15 FYM+NPK	177		92	−102	58
Halle								
Permanent rye	1971–	20	Nil	0		25**		
(*Garz* et al., 1994)	1990		NPK	40		48	− 17	42
			12 FYM	60		59	− 26	43

1) FYM t/ha · yr, **) considered as atmospheric N deposition
Balance = output (N uptake by plants + increasing soil N) minus input (fertilizer+atmospheric N deposition + decreasing soil N)

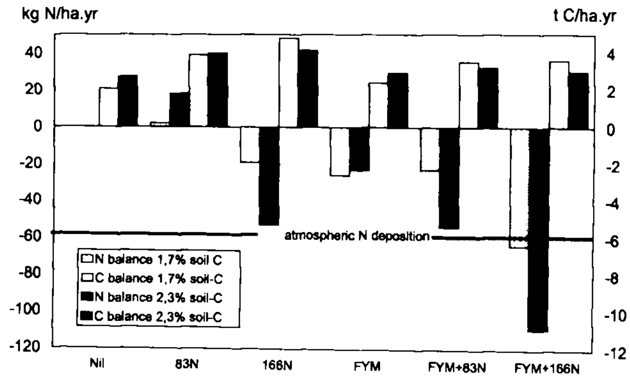

Figure 10: N and C balances in different fertilization treatments in dependence of the initial C_{org} content in soil (Static Fertilization Experiment Bad Lauchstädt, average of 1978–1996).

Abbildung 10: N- und C-Bilanzen unterschiedlicher Düngungsvarianten in Abhängigkeit vom Ausgangsgehalt des Bodens an organischem Kohlenstoff (Statischer Düngungsversuch Bad Lauchstädt, Durchschnitt 1978–1996).

Balance = Output (N uptake by plants + increasing soil N) minus Input (Fertilizer + atmospheric N deposition + decreasing soil N)

The changes in N content of soil were quantified via linear regressions of measured values during the evaluation period.

The N inputs from unknown sources but probably atmospheric deposition were incorporated in the calculation based on the N removal by the crops harvested on each unfertilized plot during the respective period. At the different sites values range from 17 to 123 kg N/ha. In the two Bad Lauchstädt experiments 50–58 kg N/ha·yr were calculated as the average of 32 and 19 experimental years respectively. The amount was confirmed by direct measurements of the N deposition into a soil/plant system by *Mehlert* (1996). Data from the model experiment with extremely high FYM applications where 123 kg N/ha uptake were measured for the unfertilized plot are excluded.

The N uptake of 61 kg/ha·yr from the unfertilized plot of the Czech experiment corresponds quite well with the value at Bad Lauchstädt (Tab. 6).

At all other sites N uptakes in the nil plots were lower (17–43 kg/ha·yr). On the sandy soils at Skierniewice (Poland) and Thyrow (Germany) a part of the N deposition was probably lost by leaching, in the Broadbalk experiment (Rothamsted, Great Britain) and in the Permanent Rye Experiment (Halle, Germany) the low N uptakes from the unfertilized plots (34 and 25 kg N/ha·yr respectively) are possibly related to the fact that the crops were grown in monoculture. This is supported for Broadbalk by the great N uptake by the grown crop in rotation and by direct deposition measurements at Rothamsted which amount to more than 50 kg/ha·yr (*Goulding*, 1990).

A comparison of the sites with regard to nitrogen losses (as expressed by negative N balances), shows the lowest N losses for the Loess-Chernozem at Bad Lauchstädt, excluding the model experiment with its very large FYM applications. A rooting depth down to 2 m and low annual precipitation favour a high N efficiency at this site. The lowest N utilization or in other words the greatest loss of input N was recorded in the sandy soil in Thyrow, followed by the treatment with FYM at Rothamsted, where for more than 150 years with 35 t FYM/ha·yr annually enormous N quantities have been applied and where the maritime climate with 725 mm rainfall per year favours N leaching.

Conclusions with regard to the influence of different C levels in soil and different fertilizers on the N and C balance can be drawn from the extension part of the 'Static Fertilization Experiment Bad Lauchstädt'.

The plots at the start point of this experiment (Fig. 10) had either 1.7 or 2.3 % C_{org} respectively as a result of 75 years of different fertilization, i.e. without fertilizer or with 15 t FYM/ha·yr+NPK.

Comparing the N balances at both C levels the losses increase with increasing fertilization more rapidly on the C rich soils. The optimum rate of N fertilizer is distinctly lower due to the greater N release from the soil (see also section 3.3). Accordingly higher losses are to expected, because the N release from the soil cannot be controlled.

The comparison of different forms of fertilization is of special interest (Tab. 6). Contrary to the common opinion of advocates of organic farming, mineral fertilization has resulted in the lowest N losses. Results on other sites confirm, that this is not only due to the favourable conditions of the Loess-Chernozem in Bad Lauchstädt. At the sandy sites in Thyrow and Skierniewice small losses (22–29 kg) and a high N utilization (64–71 %) were also reported for those treatments which had received mineral fertilizer only. Higher losses of 25–77 kg at usual farm levels of FYM application and of 127–167 kg N where 35 t FYM/ha·yr were applied were measured for the exclusively organic fertilization. Thus the N utilization was 25–74 %.

The model experiment with large FYM applications gave some specific results. Treatments with 100 and 200 t FYM/ha·yr do not correspond with the conditions in practical farming, but provide valuable information for the potential accumulation of C and N in soil. At the highest FYM level 48 % of the FYM N got lost and 40 % had been stored in the soil, on average, during 13 years. Results of older long-term experiments show that with increasing experimental duration the annual increase of N in soil becomes smaller as SOM increases towards a new equilibrium value. This, however, also means that in the future an increase of the N losses is to be expected.

3.4.2 *Carbon balance*

Carbon balances are of growing interest for the estimation of the source/sink potential of soils for atmospheric CO_2. However, the sink potential of arable soils is very low.

Table 7: C balance of different European long-term experiments.
Tabelle 7: C-Bilanz unterschiedlicher europäischer Dauerversuche.

Site/Experiment	Evaluated period	Years	Treatment	Input Fertilizer (C t/ha · yr)	Changes soil-C (C t/ha · yr)	Output (harvested crops) (C t/ha · yr)	Difference (C t/ha · yr)
Bad Lauchstädt							
Static experiment	1965–	32	Nil	0		1.8	+1.80
stripe 2	1996		NPK	0.17		4.55	+4.38
			15 FYM	1.31		4.09	+2.78
			15[1] FYM+NPK	1.48		4.88	+3.40
Static experiment							
(extension part)	1979–	18	Nil (N1)	0	0	2.06	+2.06
1902–1977 without	1996		NPK (N3)	0.13	0.11	3.92	+3.90
fertilization = 1.7% C			NPK (N5)	0.25	0.11	4.95	+4.81
in soil			15 FYM (N1)	1.31	0.21	3.5	+2.4
			15 FYM+NPK (N3)	1.44	0.32	4.65	+3.53
			15 FYM+NPK (N5)	1.56	0.32	4.84	+3.60
1902–1977 15 FYM	1979–	18	Nil (N1)	0	–0.48	3.21	+2.73
+NPK = 2.3% C in soil	1996		NPK (N3)	0.13	–0.48	4.66	+4.0
			NPK (N5)	0.25	–0.48	4.88	+4.15
			15 FYM (N1)	1.31		4.24	+2.93
			15 FYM+NPK (N3)	1.44		4.67	+3.23
			15 FYM+NPK (N5)	1.56		4.55	+2.99
Model experiment							
with high	1984–	13	Nil	0		5.44	+5.44
FYM application	1996		50 FYM	4.38	1.51	6.57	+3.70
			100 FYM	8.75	3.74	6.5	+1.49
			200 FYM	17.5	5.28	6.49	–5.73
Skierniewice							
Field D	1968–	27	Nil	0		1.18	+1.18
	1994		NPK	0.12		2.13	+2.01
			20 FYM	2	0.20	2.89	+1.09
Rothamsted							
Broadbalk	1968–	27	Nil	0		0.80	+0.80
monoculture	1994		NPK	0.22		3.30	+3.08
			35 FYM	3.5	0.24	3.60	+0.34
			35 FYM+N	3.64	0.47	4.56	+1.39
Broadbalk			Nil	0		1.05	+1.05
crop rotation			NPK	0.22		3.13	+2.91
			35 FYM	3.5	0.24	3.23	–0.03
			35 FYM+N	3.64	0.47	3.62	+0.45
Prague							
Ruzyne Field B	1968–	27	Nil	0		2.65	+2.65
	1994		NPK	0.16		3.94	+3.78
			10 FYM	1		3.71	+2.71
			10 FYM+NPK	1.16		4.44	+3.28
Thyrow							
Nutrient deficiency	1977–	12	Nil	0		0.70	+0.7
experiment	1988		NPK	0.11		1.84	+1.73
(*Schnieder*, 1990)			15 FYM	1.5		1.31	–0.19
			15 FYM+NPK	1.61		2.15	+0.54
Halle							
Eternal rye	1971–	20	Nil	0		1.20	+1.2
(*Garz* et al., 1994)	1990		NPK	0.06		2.47	+2.41
			12 FYM	1.2		2.58	+1.38

1) FYM t/ha · yr

On the basis of the data from the long-term experiments discussed here there is only a very narrow range of decomposable carbon in arable soils, namely 0.2 to 0.6%. Lower values lead to a lower fertility and thus productivity. The application of large amounts of organic matter increases the microbial transformation processes, which leads to a high CO_2 and nutrient release. The latter is supported by the results of the N balances, where it was obvious that the risk of N losses increased with increasing supply of organic manure. So to have any positive influence on the global CO_2 balance arable soils should be used to produce biomass as a source for obtaining energy and raw materials.

The C balances of the long-term experiments included in Tab. 7 are calculated as follows:

C balance = C output (harvested plant + increase soil C) minus C input (fertilizer − decrease soil C)

- harvested plant C = dry matter yield · factor 0.4
- FYM C = applied amount · factor 0.1[1]
- 1 kg mineral N = 1.5 kg C (*Vernon Cole* et al., 1993)

The C input in form of mineral P and K per ha was according to the fuel requirement/kg P or K fertilizer given by *Van Dasselar* and *Pothoven* (1994) irrelevant for the C balance and therefore neglectable.

Other balance factors, as seeds, plant protection products[2], etc. are constant factors in these fertilization experiments and can be disregarded like the C input for P and K.

A comparison of the C balances for the different fertilization treatments shows for all sites a positive balance for the exclusively mineral fertilizer treatments. Negative balances, i.e. C losses, were calculated for the highest FYM treatment in the model experiment Bad Lauchstädt, for the 35 t/ha · yr FYM treatment where crops were grown in rotation on Broadbalk at Rothamsted and for the FYM treatment in Thyrow. The additional use of mineral N in the combined organic-mineral treatments improved the C balances compared to the organic fertilization alone.

Results from the extension part of the Static Fertilization Experiment show that a higher C level in soil has no modifying effect on the C balance (Tab. 7, Fig. 10). The C balance for both plots, 1.7 and 2.3% C_{org} respectively are similar. But the results for the N balances have shown, that a higher C level represents a higher potential for N losses and is altogether more difficult to control.

3.5 Calculation of the humus demand

In agricultural advisory work the humus balance is a tool to calculate the necessary supplementation of organic matter. Different approaches can be followed.

Welte (1963) presupposed a knowledge about the humus content of soil and calculates the essential annual supply by means of the equation:

$$A = k_m \, (H_o + A)$$

where H_o = humus content under equilibrium conditions, A = annual input of organic matter (organic fertilizers, crop and root residues) and k_m = is a decay coefficient. *Kortleven* (1963) assumed the humus content to correspond to approximately twenty times the annual input and calculates humus substitution using the equation

$$y_m = K_1 \,/\, K_2 \cdot x$$

where y_m is humus content in steady state, which is reached after many years constant fertilization, K_1 is the humification coefficient, K_2 the decay coefficient and x the input of organic matter.

Rauhe (1965) took on the one hand N in the soil and on the other hand N in the primary organic matter (POM) as the reference value for the calculation of the amount of organic materials needed to maintain the humus balance. He estimated that for the compensation of the annual SOM loss, 20 times as much organic material as the annual N uptake by the crops is required. This then depends on the species and yield. For example:

One hectar cereals with a yield of 3.5 t/ha decomposes 1 t/ha humus, corresponding to 1 humus unit (HU) with 50 kg N. For compensation 10 t FYM are necessary.

The humus balance methods as used above were applied for more than 30 years in Germany. During this time conditions have changed considerably, the application of N fertilizer has about doubled just as the yields have done. Also fertilizer management has become more sophisticated and plant protection as well as husbandry techniques have improved. Under the present conditions therefore the calculation of a humus balance must now start from the following premises:

- The quantity of crop and root residues remaining in the field has increased in the last decades, thus there is a better supply of organic matter to the soils.
- A SOM balance must be based on C, not N, as N can be applied at any time, for example together with the incorporation of straw or with other organic fertilizers of wide C/N ratio.
- Only the decomposable part of SOM should be considered. The guideline value corresponds to 0.2–0.6% C_{org} (see section 3.6). A sandy soil with only 3% clay and 0.7% C_{org} is well supplied with SOM, while a Loess-Chernozem with 21% clay only reaches the same level of C_{dec} at approximately 2% C_{org}. In both cases the decomposable C amounts 0.4 to 0.5%.
- The yield effectiveness of the SOM only amounts up to 10%. With exclusive mineral fertilization at least 90% of the potential yield can be achieved and this on a most efficient and ecological basis.
- For arable soils there is an upper limit to SOM on ecological consideration if exceeding the limit has no positive

[1] for Bad Lauchstädt the analyzed C values of the FYM were available: 1 fresh matter t FYM = 0.0875 t C

[2] the C expenditure for seeds, plant protection, fuel etc. was calculated for the experiments in Bad Lauchstädt to be equivalent to 0.2 t/ha · yr (*Van Dasselar* and *Pothoven*, 1994)

Table 8: Factors for the calculation of the 'substitution effective organic matter' (ROM) (t/ha · yr) (*Autorenkollektiv*, 1977).
Tabelle 8: Faktoren für die Berechnung des Bedarfes an 'Reproduktionswirksamer Organischer Substanz' (ROS) (t/ha · a) (*Autorenkollektiv*, 1977).

Crop	Sand	Loamy sand, sandy loam	Loam, clay	Chernozem
sugar beet, potato, vegetables	–3.6	–4.0	–4.4	–2.9
corn	–2.7	–3.0	–3.3	–2.2
cereals, oilseeds	–1.4	–1.5	–1.6	–1.1
fodder rye	–0.9	–1.0	–1.1	–0.7
stubble crops	+0.5	+0.5	+0.6	+0.6
seed legumes	+0.9	+1.0	+1.1	+1.1
underseed, (well developed)	+1.8	+2.0	+2.2	+2.2
perennial crops[1] (alfalfa, ley, gras	+2.7	+3.0	+3.3	+3.3

1) annually

Table 9: Substitution effectiveness of different organic manures in comparison to farmyard manure dry matter (*Autorenkollektiv*, 1977).
Tabelle 9: Reproduktionswirksamkeit unterschiedlicher organischer Dünger, relativ zur Stalldungtrockenmasse (*Autorenkollektiv*, 1977).

organic manure	fresh matter as equivalent to FYM dm
FYM, slurry solid material	5
slurry, 8% dm	25
slurry, 4% dm	50
straw	1.5
green manure (above ground matter)	25
refuse compost	5.5
sludge	10
peat, peat compost	4.5

yield effect, and there is the risk of environmental pollution due to N and CO_2 losses.

A simple method for the calculation of the demand for 'replacement effective organic matter' (ROM) by different soil types or cropping systems was suggested by *Autorenkollektiv* (1977). On the basis of numerous long-term experiments so-called 'coverage' factors for meeting the ROM requirement were derived. They demonstrate the difference between crops drawing on and accumulating humus respectively (Tab. 8).

As a standard the dry matter of FYM was used, 1 t FYM dry matter corresponds to 1 t ROM. To meet the SOM demand by different organic fertilizers 'coverage' factors were calculated to be equivalent to 1 t FYM dry matter (Tab. 9). These factors account for the different substitution effectiveness of the various organic fertilizers.

For example: After sugar beet on Chernozem 2.9 t ROM/ha are necessary to meet the losses of SOM in the soil (Tab. 8, line 1, column 4). 2.9 t ROM are equal to 2.9 t FYM dry matter or 14.5 t FYM fresh matter (Tab. 11, line 1) or 4.35 t straw (Tab. 9, line 4).

This method of calculating ROM requirement is used in several provinces of Germany and is the most appropriate method because it was derived following extensive investigations to quantify and verify the factors. However, the method does not consider differences in C_{org} content of soils, but assumes that there is already a sufficient level of SOM.

Leithold et al. (1996) modified the factors of the 'simple method for calculation of demand for organic matter', given in Tab. 8 and 9, and combined these data with the HU according to *Rauhe* and *Schönmeier* (1966). The demand of ROM using this modified method is a little more than 100% higher than that of the simple method. However, site differences are no longer considered. Unfortunately there is not sufficient experimental proof for the increased coverage factors.

For 'organic farming' the ROM demand is assumed by *Leithold* et al. (1996) to be 50% higher to compensate for the nutrients which cannot be applied in mineral fertilizers.

Another simple humus balance method has been proposed by *Diez* and *Krauss* (1992). They balance the yearly humus loss due to mineralization against the C input by crop and root residues and organic fertilizers taking into consideration different humus reproduction coefficients.

Tab. 10 presents the results by different balance methods for three contrasting sites and compares them with the experimentally determined optimum. The results show a good agreement between optimum values and the first method. The method of *Diez* and *Krauss* (1992) shows quite a good agreement, except that the lower the total SOM content the greater the discrepancy between the calculated demand and the optimum. This is due to the fact that in this method the decay is related to the total SOM content. Consequently the demand increases as the clay content increases and thus with the 'inert' C content. This means that on the sandy soil at Thyrow the calculated demand is the lowest.

The estimated demand for organic manures using method III is in all cases much higher than the experimentally determined optimum, in some cases nearly 100% higher. For organic farming, as mentioned above, even 30 t FYM/ha each year would be required to balance the humus. This amount of FYM would apply 180 kg N/ha · yr, and some mineralization will occur in periods, when there is no N uptake by plants, inevitably leading to high leaching and gaseous N losses. The situation would not be much better if organic fertilizers other than FYM, i.e. straw, were used because for humus formation nitrogen is necessary. This N may be supplied as legume N or as atmospheric deposition, or as inorganic N residues in soil. This immobilized N will later be released again during the decomposition of SOM. Accordingly a large humus supply can make the N release from a soil unpredictable and leads, therefore, to larger N losses (*Diez*, 1995).

Table 10: Requirement for FYM (fresh matter, t/ha · yr) to maintain the humus balance, calculated according to different methods for different sites.
Tabelle 10: Bedarf an Stalldung (t/ha · a) zum Ausgleich der Humusbilanz, berechnet für verschiedene Standorte nach verschiedenen Methoden.

Sites		Balance methods		
		I	II	III
	Optimum	*Autorenkollektiv* (1977)	*Diez* and *Krauss* (1992)	*Leithold* et al. (1996)
Haplic Chernozem Bad Lauchstädt	10[1)]	10	12.5	19.6
Gleyic Luvisol Seehausen	9–15[2)]	12.5	12.0	17.7
Albic Luvisol Thyrow	10[3)]	12.5	7	20

1) *Körschens* et al. (1994)
2) *Leithold* et al. (1996)
3) *Lettau* et al. (1997)

3.6 Guideline values for the SOM content of soils

Guideline values for the SOM content of loamy and sandy soils without ground water influence were derived from the results of numerous long-term experiments, from evaluations of about 12000 soil analyses from farmers fields (*Körschens*, 1980a) and from various laboratory and field experiments on the meliorative value of organic fertilizers (*Körschens* et al., 1986). As Tab. 11 shows these values increase from 1–1.5% SOM ($C_{org} \times 1.724$)[1)] in sandy soils to 3.5–4.4% SOM in clay soils, the increase being due to the proportion of C_i increasing with clay content. The ranges for the optimum SOM content are relatively small when the lower value of the range is set as equivalent to 0.5% of decomposable SOM (For example: for a soil with 4% clay + fine silt, (first line in Tab. 11), 0.5% is inert SOM, this plus 0.5% decomposable SOM gives 1% total SOM.

The difference between lower and upper limit of the recommended ranges amounts to well 0.5% decomposable SOM, so that with 1% the highest recommendable supply is reached, which corresponds to 35 to 45 t/ha decomposable SOM in the plough layer.

Table 11: Guideline ranges for the SOM content of sandy and loamy soils without groundwater influence (% SOM in ploughing layer) depending on fine silt and clay (< 6.3 μm).
Tabelle 11: Orientierungswerte für die Einstufung grundwasserferner S- und Lö-Standorte nach dem Grad ihrer Versorgung mit organischer Substanz (% OS im Bearbeitungshorizont) in Abhängigkeit vom Feinanteilgehalt (Korngrößen < 6,3 μm).

Clay + fine silt %	Sandy soils		Loamy soils	
	upper value	lower value	upper value	lower value
4	1.5	1.0		
5	1.5	1.0		
6	1.5	1.0		
7	1.5	1.0		
8	1.6	1.1		
9	1.7	1.2		
10	1.7	1.2	2.0	1.3
11	1.8	1.3	2.1	1.4
12	1.9	1.4	2.2	1.4
13	1.9	1.4	2.2	1.5
14	2.0	1.5	2.3	1.6
15	2.1	1.6	2.4	1.7
16	2.1	1.6	2.5	1.8
17	2.2	1.7	2.6	1.8
18	2.3	1.8	2.7	1.9
19	2.3	1.8	2.8	2.0
20	2.4	1.9	2.8	2.1
21	2.5	2.0	2.9	2.1
22	2.5	2.0	3.0	2.2
23	2.6	2.1	3.1	2.3
24	2.7	2.2	3.2	2.4
25	2.8	2.2	3.3	2.5
26			3.4	2.5
27			3.4	2.6
28			3.5	2.7
29			3.6	2.8
30			3.7	2.8
31			3.8	2.9
32			3.9	3.0
33			4.0	3.1
34			4.1	3.2
35			4.1	3.2
36			4.2	3.3
37			4.3	3.4
38			4.4	3.5

4 Conclusions

Following conclusions can be reached from this presentation and previous work:

1. Discussions about SOM require that at least two fractions are considered, one being relatively inert (hardly involved in mineralization processes), the other being decomposable and thus dependent on soil and crop management.

2. Changes of the C_{org} content in soil are almost exclusively the decomposable part of the carbon which changes very slowly.

3. The soil improving effect of SOM contributes to crop yield on sandy soils up to 10%, on loamy soils up to 5%. This could be shown by comparing treatments with exclusively mineral fertilization with those of optimal organic+ mineral fertilization.

4. The ranges for the optimal quantities of C and N in soil are only small. At comparable sites in Germany they are between 0.2 and 0.6% C_{dec} and 0.02 and 0.06% N respectively. Below these values soil fertility, yield and CO_2 absorp-

[1)] Despite our recommendations to calculate only on the basis of C_{org} (see section 1) in practice it is still common to use SOM.

tion by the plant biomass are insufficient, above these values there are losses which could lead to the risk of pollution.

5. The hot water extractable carbon has proved to be an appropriate criterion for the characterization of the decomposable carbon.

6. Raising the C level above the upper recommended limit influences neither C nor N balances in a positive way on arable soils. The potential of soil as a sink for carbon is only small and could result in large losses of N and C. Organic manure should only be applied in relation to the C balance on a farm and will be site specific. The optimum C content should not be exceeded. Surplus organic materials would be better used as substitutes for fossil energy.

7. The results of the Broadbalk Experiment at Rothamsted show, that on soils highly supplied with SOM a bare fallow in the crop rotation (no plant production and thus no nitrogen uptake from the soil), will distinctly aggravate N leaching and is therefore not recommendable. Crop production for food or for energy and raw material is, in ecological terms, to be preferred to set-aside-programmes.

8. The deposition of atmospheric N is an important factor in the N balance and in the calculation of optimum amount of N to be applied either as mineral or organic fertilizer. Its exact quantification via direct measurements and its consideration in fertilizer strategies is important. Indirect evidence from N uptake in unfertilized plots of long-term experiments indicates an atmospheric input, which can amount to about 50 kg N/ha·yr.

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