The long-term fertilization experiments in Halle (Saale), Germany – Introduction and survey[$ §]

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Dedicated to Prof. Dr. *Günther Schilling* on his 70th birthday

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Summary – Zusammenfassung

Six of originally eight long-term trials in Halle (Saale), Germany, are still continuing. Five are situated at *Julius-Kühn-Feld*, an experimental station launched by *Julius Kühn* in Halle in 1866. Apart from the *Eternal Rye* trial established in 1878, those are phosphorus, potassium, lime, and organic fertilization long-term trials, all being launched by *Karl Schmalfuß* in 1949. Other long-term trials have been terminated, but data are available on the effects of nitrogen fertilization and the physiological reaction of fertilizers. Another long-term trial in Halle (Adam-Kuckhoff-Straße 17b) investigates the influence of fertilization on soil formation from loess. Up to now, the major results are as follows:

1. Changes in soil-ecological properties due to fertilization and rotation were only evident after 30 years, and new steady states sometimes took 70 years to occur.
2. In the long term, the C- and N-contents of the soil largely depend on the amount of hardly decomposable organic matter applied with organic fertilization. High mineral-N doses, with consequent high crop and root residues, increased the humus content of the soil.
3. Mineral fertilization can replace organic fertilization in terms of sustainable yield capacity provided equal nutrient amounts were applied.
4. The high P-supply ability of the soil in Halle could not be explained by traditional soil analysis methods of calculating plant-available P. With some restrictions, the same is valid for K.
5. At the experimental site, soluble salts (nitrate, sulphate) accumulated in the subsoil.
6. A regular lime demand of central German chernozems could be proved, especially in case of low soil organic matter (SOM) and physiologically acid fertilization.

Key words: long-term fertilization experiments / sustainable land use / nutrient availability / soil development / soil organic matter

Die Dauerdüngungsversuche in Halle (Saale) – Einführung und Überblick

Von den ursprünglich acht in Halle angelegten Dauerdüngungsversuchen existieren heute noch sechs. Davon befinden sich fünf auf dem 1866 von *Julius Kühn* angelegten Hallenser Versuchsfeld (*Julius-Kühn-Feld*). Dies sind neben dem 1878 begründeten Versuch *Ewiger Roggenbau* die 1949 von *Karl Schmalfuß* angelegten Dauerversuche zur Phosphor,- Kalium-, Kalk- und organischen Düngung. Daneben werden auch die inzwischen eingestellten Dauerversuche zur Stickstoffdüngung und zur physiologischen Reaktion von Düngemitteln diskutiert. Darüber hinaus gibt es in Halle (Adam-Kuckhoff-Straße 17b) einen Dauerversuch über den Einfluss der Düngung auf die Bodenbildung aus Löss. Die wichtigsten bisher erzielten Ergebnisse lassen sich wie folgt zusammenfassen:

1. Veränderungen in der Düngung oder Fruchtfolge wirken sich nur sehr allmählich auf bodenökologische Eigenschaften aus. Entsprechende Veränderungen werden frühestens nach 30 Jahren messbar, und neue Fließgleichgewichte stellen sich manchmal erst nach 70 Jahren ein.
2. Die C- und N-Gehalte der Böden hängen auf die Dauer vor allem von der mit der organischen Düngung zugesetzten Menge an schwer zersetzbarer Substanz ab. Hohe Mineral-N-Zufuhr wirkt sich über mehr Ernte- und Wurzelrückstände förderlich auf den Bodenhumusgehalt aus.
3. Eine nährstoffäquivalente Mineraldüngung kann die organische Düngung hinsichtlich einer nachhaltigen Ertragsfähigkeit ersetzen.
4. Unter den Hallenser Bodenbedingungen zeigte sich ein hohes P-Nachlieferungsvermögen aus dem Boden, das sich durch die herkömmlichen Methoden zur Ermittlung des pflanzenverfügbaren P nicht hinreichend erfassen lässt. Mit Einschränkungen gilt dies auch für Kalium.
5. Auf dem Versuchsstandort kann es zur Akkumulation leicht löslicher Salze (Nitrat, Sulfat) im Unterboden kommen.
6. Es wurde ein regelmäßiger Kalkbedarf für mitteldeutsche Schwarzerden nachgewiesen, insbesondere bei geringer organischer Bodensubstanz und physiologisch saurer Düngung.

1 Introduction – The importance of long-term trials

The soils of our planet are the basis of human existence because almost 98% of all food originates from terrestrial ecosystems. There is an annual decrease of utilizable land of

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[$] Detailed discussion of single experiments and specific investigations are to be found in this volume (*Beschow* et al., 2000; *Flessa* et al., 2000; *Garz* et al., 2000; *Gransee* and *Merbach*, 2000; *Schmidt* et al., 2000; *Stumpe* et al., 2000a, b) as well as in other publications (*Hütsch*, 1998; *Merbach* et al., 1999b; *Schliephake* et al., 1999; *Springob*, 1995).

[§] This paper is based on a presentation given at the symposium "Dauerdüngungsversuche als Grundlage für nachhaltige Landnutzung und Quantifizierung von Stoffkreisläufen" held on the occasion of 120 years "Ewiger Roggenbau" and 50 years of long-term fertilization trials in Halle (Germany), June 3–5, 1999

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about 10 million ha, due to erosion, desert formation, and soil sealing. At the same time, world population will increase to at least 8.5 billion up to 2020 (*Powlson* et al., 1997). Thus more and more people have to live from less and less soil. A major point in policies therefore is to globally maintain significantly higher agricultural productivity with less ressources and to simultaneously preserve the functioning of the soil as a living space – probably even under changed climatic conditions (*global change*).

Scientific research has to provide results to support decisions in agricultural and ecological policies. This requires thorough understanding of how soils and agricultural ecosystems respond to different forms of land management and fertilization and to climatic factors. Such know-ledge can be gained exclusively by long-term investigations since the effects of human activity and of a change of natural conditions can be seen only gradually due to the buffering of the ecosystems. For this reason, long-term trials offer the great opportunity to study and to document long-term changes of soil and plants of the specific site by means of adjacent variants of fertilization and land use. For example, in such trials the duration and the amount of nutrient supply ability (*Schliephake* et al., 1997), the duration and the level of establishing new steady states (*Körschens* et al., 1998), and the development of soil formation processes (*Beschow* et al., 2000) have been investigated.

Since long-term trials contribute to our understanding of current processes, predictions of further development and future effects are made possible.

Furthermore, differences may appear only gradually between forms of land management, and soil and plant material can be investigated to understand the underlying mechanisms. For example, a long-term trial has allowed a check to what extent methods of soil and plant analysis give realistic values of the soil nutrient supply to plants (*Merbach* et al., 1999a). In addition, it can be determined how different fertilizers in the long term affect the formation of organo-mineral complexes in the soil (*Leinweber* and *Reuter*, 1990) and thus the soil structure. Such investigations contribute to the confirmation of scientific predictions.

Concepts of maintaining sustainable land management and long-term fertility of soils depend on the results of long-term trials, which represent major soil, climate, and land use conditions of the world. Unfortunately, in Germany, for example several long-term trials have been terminated in the last decades for technical and financial reasons, among them the then oldest German long-term trial *Göttinger E-Feld*. In general, only 65 trials which have lasted over 50 years remain all over the world (*Körschens*, 1997). For this reason, the International Conference held on the occasion of 60 years long-term trials in Thyrow 1997 in Berlin (see *Peschke*, 1997) issued a memorandum to draw attention to the importance of European long-term trials for sustainable and eco-friendly land management (*Powlson* et al., 1997).

This article is dedicated to the same goal by giving a survey of the long-term trials in Halle. The presented overview will be completed by selected results of the trials discussed in several articles in this volume of the journal (*Beschow* et al., 2000; *Garz* et al., 2000; *Schmidt* et al., 2000; *Stumpe* et al., 2000a,b). The 120 years anniversary of the *Eternal Rye* trial established by *J. Kühn* in 1878 and the 50 years anniversary of the long-term trials launched by *K. Schmalfuß* in 1949 give occasion to this presentation. Besides the wheat trial in Rothamsted (UK) and the *Static Fertilization Experiment* in Bad Lauchstädt (Germany), the trials of Martin-Luther-University Halle – Wittenberg are the most important long-term fertilization trials all over the world (*Merbach* et al., 1999b).

Figure 1: Geographical location of the long-term trials in Halle (adapted from *Merbach* et al., 1999b). Coordinates: N 51° 30.8′, E 11° 59.9′.
Abbildung 1: Geographische Lage der Hallenser Dauerversuche (aus *Merbach* et al., 1999b). Koordinaten: N 51° 30.8′, E 11° 59.9′.

2 Site and natural conditions

2.1 Location

The long-term fertilization experiments have been carried out in the south of the federal state *Sachsen-Anhalt*, at *Julius-Kühn-Feld*, a field named after its founder. This experimental and study site of the Agricultural Faculty of Martin-Luther-University Halle-Wittenberg, is located east of the city of Halle (Figure 1). Geographically, the region belongs to the eastern foreland of the Harz mountains (*Meinen* et al., 1961). The experimental site is situated in a plain (110–115 m above sea level, N 51° 30.8′, E 11° 59.9′), which extends east of the river Saale and Götsche valley (75 m above sea level) over the Petersberg (250 m above sea level) to the Reide lowlands in north-eastern direction.

2.2 Climate and weather

Due to its location in the rain shadow of the Harz mountains, the site belongs to the central German arid region. It is characterized by one of the lowest levels of precipitation in Germany (*Schumann* and *Müller*, 1995).

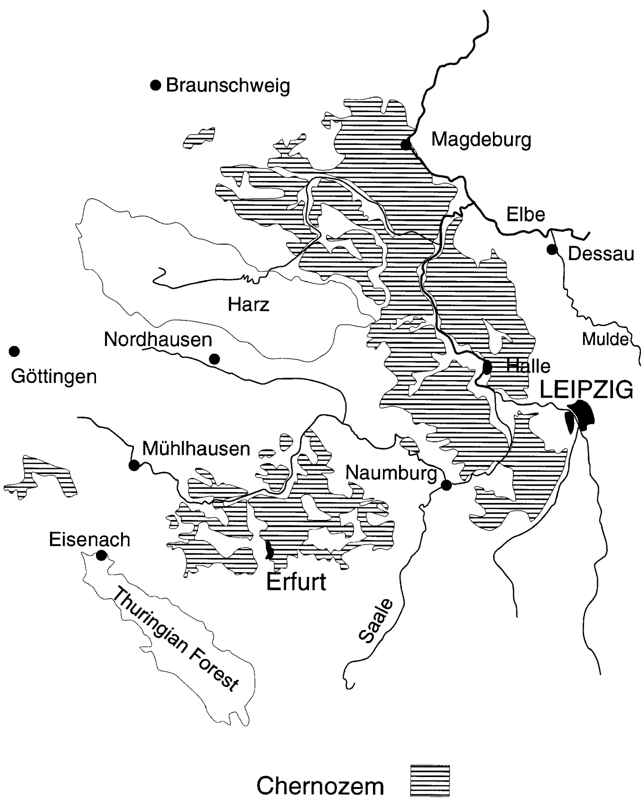

Figure 2: Distribution of central German chernozems (adapted from *Stremme*, 1936).
Abbildung 2: Das Verbreitungsgebiet der mitteldeutschen Schwarzerden (aus *Stremme*, 1936).

The average annual precipitation of 494 mm (1878–1995, Halle-Kröllwitz) is accompanied by a potential evaporation of 450 mm, thus preventing the formation of much groundwater. The average annual precipitation has ranged from 258 mm (1982) to more than 700 mm (1942 and 1944), with a series of dry years with only 414 mm average annual precipitation from 1988 to 1991. Precipitation is summer dominant, with 70% of the rain during the main vegetation months. The mean winter precipitation of 140 mm hardly exceeds the field capacity of the soil which results in almost no water infiltration in dry years.

The average annual air temperature in Halle-Kröllwitz (1878–1995) was 9.2°C; 1956 (with only 7.4°C) and 1934 (with 11.2°C) have been extreme years. The coldest month is January (–0.2°C), the warmest is July (18.0°C). The last spring frost usually occurs mid April, and the first frost end October (*Schumann* and *Müller*, 1995). Average annual sunshine amounts to 1684 hours.

2.3 Geology and landscape

Julius-Kühn-Field is located on the edge of the loess-chernozem region that connects the chernozems of the *Thüringer Becken* (near by Erfurt) with those of the *Magdeburger Börde* (Fig. 2). The loess layer contains relatively much sand (45–80%) and has a depth of only 0.8 to 1.2 m (*Altermann* and *Mautschke*, 1972). During the Weichsel Ice Age, the so called sandy loess drifted over glacial till from the Saale Ice Age (*Laatsch*, 1938). Glacial till and merged sands form the basement of the plain. There is a salient stone floor between the sandy loess layer and the glacial till.

Due to human activities, the region has almost no forests and belongs to the landscape of *Halle Croplands* (*Diemann*, 1995). According to *Weinert* (1995), the potential, natural vegetation of the central German arid region consists of clear oak – hornbeam forests and subcontinental and submediterranean grass floors (dry and half-dry grass).

Table 1: Texture and characteristics of the topsoil of the long-term trials in Halle.
Tabelle 1: Textur und Eigenschaften des Oberbodens der Dauerversuche auf dem Versuchsfeld Halle.

	Eternal Rye trial	*Fields A* to *F* (*Schmalfuß* trials)
Fractions (%)		
– clay: < 2 µm	8	12
– fine silt: 2.0–6.3 µm	5	5
– medium silt: 6.3–20 µm	5	6
– coarse silt: 20–63 µm	13	22
– fine sand: 63–200 µm	47	28
– medium sand: 200–630 µm	19	24
– coarse sand: 630–2000 µm	3	3
Particle density (g cm^{-3})	2.6	2.6
Bulk density (g cm^{-3})	1.5	1.5
Hygroscopicity (mass %)	2.3	2.6
Water capacity (mass %)	25	28
Field capacity (mass %)	13	15
C_t (%)	1.3	1.5
N_t (%)	0.10	0.12
C/N	13.0	12.5
pH ($CaCl_2$)	6.3	6.5
P (DL) (mg (100 g)$^{-1}$)	6	6
K (DL) (mg (100 g)$^{-1}$)	15	15
Mg ($CaCl_2$) (mg (100 g)$^{-1}$)	8	8
Cation exchange capacity (me. (100 g)$^{-1}$)	11	13

The site is characterized by its nearness to cities and industrial plants, mainly concentrated chemical industry (*Chemical Triangle Leipzig – Halle – Bitterfeld*) with its miscellaneous impacts on the environment. For instance, during the peak times of brown coal industries deposits of 70 cm ash were found in the vicinity of power plants (*Enders*, 1995).

2.4 Soil conditions

Julius-Kühn-Feld has a plane surface, sometimes slightly inclined southwards. The soil is a *Haplic Phaeozem* with an A-horizon of about 60 cm.

The texture depends on the location of the plot (southwest or northeast of the region) and varies from 48 to 75% sand, 16 to 37% silt, and 7 to 15% clay. According to *Merker* (1956), the soil of the *Eternal Rye* trial can be characterized as loamy sand in 0–80 cm depth and as somewhat loamy sand to sand in 80–100 cm depth. The sandy loess contains average 11% fine soil (< 6 µm) (*Stumpe*, 1979). Vertically, the sandy loess layer has a relatively homogeneous texture.

The soil of the *Schmalfuß* trials is a sandy loam. Differences in the texture of both sites (*Eternal Rye* and the *Schmalfuß* trials) are restricted to the fine sand fraction which decreases in favor of silt and clay. This is the reason for the different values of the relevant physical and chemical soil characteristics (Table 1).

The humus contents of the A_p-horizon amount to 2.1 to 2.6% depending on the soil type. In the root space (up to 100 cm depth), there is a deposit of about 8 to 10 t ha^{-1} total N which is hardly plant-available, due to the low mineralization ability of the soil organic matter. This causes significant yield decreases in the absence of N fertilization.

The effective field capacity of the soil depends on the size of particles and the amount of humus. In 0–100 cm depth, it amounts to 110 to 180 l m^{-2}.

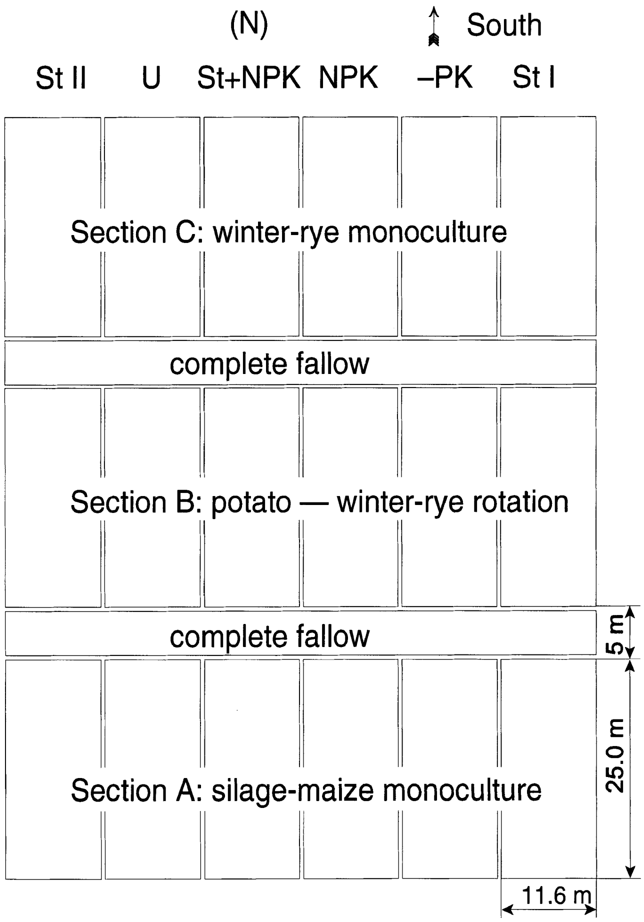

Figure 3: Lay out of the *Eternal Rye* trial since 1961: Fertilization variants, different rotations, and fallow paths between them (adapted from *Merbach* et al., 1999b). ***StII:*** Annual FYM (8 t ha^{-1}) 1893–1952, then unmanured; ***U:*** No fertilization; ***N:*** Exclusively N fertilization (40 kg ha^{-1} N), in 1990 replaced by St and NPK (see text); ***NPK:*** Mineral fertilization (40 kg ha^{-1} N, 24 kg ha^{-1} P, 75 kg ha^{-1} K); ***–PK:*** Exclusively P and K fertilization (24 kg ha^{-1} P, 75 kg ha^{-1} K); ***StI:*** Annual farmyard manuring (FYM) (12 t ha^{-1}).

Abbildung 3: Lageplan der Düngungsvarianten und Abteilungen mit unterschiedlichen Nutzungsweisen sowie der Schwarzbrachestreifen im Versuch *Ewiger Roggenbau* seit 1961 (aus *Merbach* et al., 1999b).

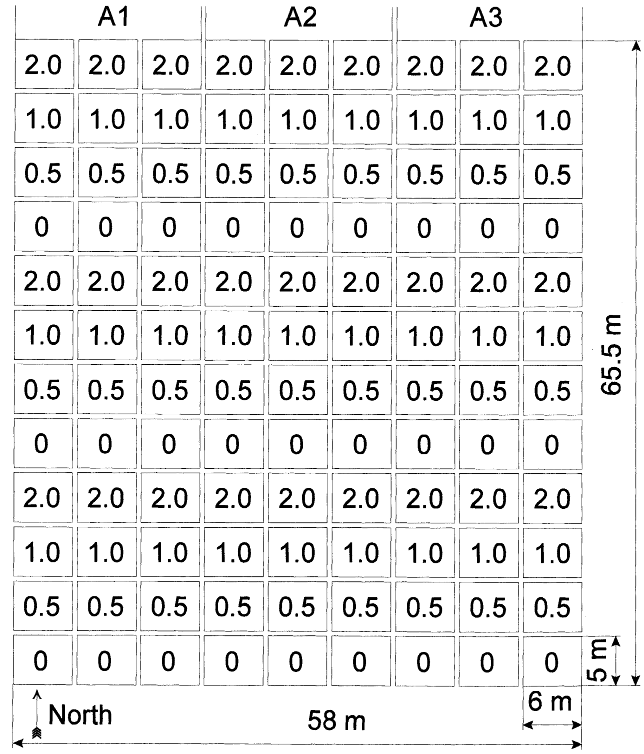

Figure 4: Lay out of *Field A* (lime trial): 0, 0.5; 1.0; 2.0 t CaO ha^{-1} after grain. *A1, A2, A3*: Identical subdivisions.

Abbildung 4: Lageplan des Kalkdüngungsversuches, *Feld A*: 0, 0,5; 1,0; 2,0 t CaO ha^{-1} nach Getreide. *A1, A2, A3*: Identische Versuchsabteilungen.

The ground water level varies between 1.5 m (early spring) and 2.5 m (late summer). In sequential humid years (1987 and 1988), groundwater can rise up to less than 1 m; in dry years (1991 and 1992) it can be at 3 m in spring.

The loess cover does not contain any compacted layer, except for a moderate plough-pan. The bank of glacial till, which is several meters thick and in greater depths relatively dense, contains locally very clayey layers. In general, it has a low water permeability. Ice wedges and stray sand formed by fluviatile sedimentation in the upper layers of the glacial till cause a heterogeneous water balance, which becomes apparent under extreme weather conditions. The eastern, somewhat deeper part of the experimental site has been drained at 1.3 m depth.

The soil has a slightly acid (mostly at the surface) to neutral reaction. The subsoil has a sufficient calcium storage consisting mainly of $CaCO_3$ and some gypsum, which might be explained by SO_2 immissions (*Garz* et al., 2000).

3 The long-term trials at *Julius-Kühn-Feld* in Halle – their goals and important results

3.1 Introductory survey

The long-term trials in Halle include:

a) the ***Eternal Rye* trial established in 1878 by *J. Kühn***. It has a size of 0.6 ha and is the world's second oldest long-term fertilization trial after the wheat trial in Rothamsted (England) (*Schmidt* et al., 2000).

b) the **long-term fertilization trials established by *K. Schmalfuß* in 1949**. Originally, they covered 4.8 ha (1116 plots) divided into the following trials:

Field A: lime fertilization	252 plots
Field B: physiological reaction of fertilizers	72 plots
Field C: potassium fertilization	240 plots
Field D: phosphate fertilization	144 plots
Field E: nitrate fertilization	192 plots
Field F: organic fertilization	216 plots

The trials in *Field B* and *Field E* have been terminated. In case of *Field A*, *Field C*, and *Field D*, the size of the trials has been limited to 108, 120, or 72 plots, respectively. Currently, there exist 364 plots. The originally extensive vegetable growing was ceased in 1970.

c) The **soil formation long-term trial established in 1948 by *K. Schmalfuß*** on the campus of the chair of *Physiology and Nutrition of Plants* in Halle, Adam-Kuckhoff-Straße 17b (*Beschow* et al., 2000).

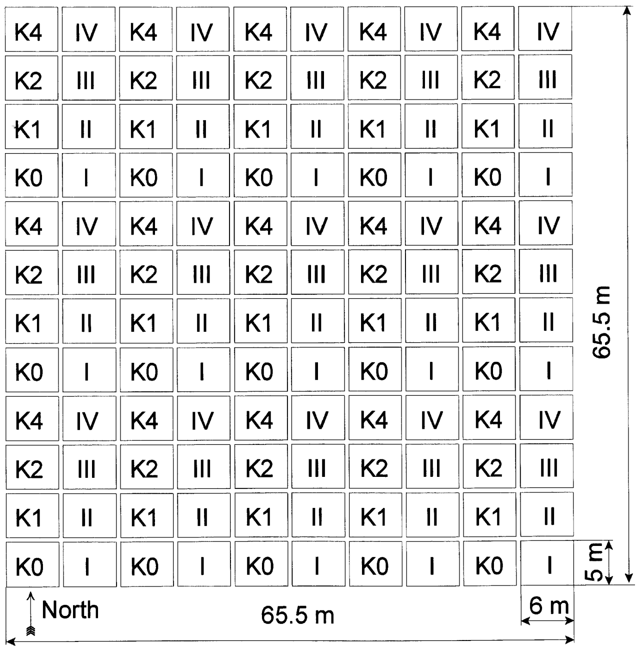

Figure 5: Lay out of *Field C* (potassium fertilization trial) since 1970. K0, K1, K2, and K4 correspond to the following amounts: 0; 40; 80; and 160 kg K ha^{-1} with grain crops, or 0; 80; 160; 320 kg K ha^{-1} with root crops (as muriate of potash with 50% K_2O = 41.5% K). All plots with Roman numbers received K2 as: I = *Kainite*, II = muriate of potash (50% K_2O = 41.5% K), III = potassium sulphate, IV = *Kamex*.

Abbildung 5: Lageplan des Kaliumdüngungsversuches, *Feld C* (seit 1970). K0, K1, K2 und K4 entsprechen folgenden Mengen: 0; 40; 80 und 160 kg K ha^{-1} bei Getreide bzw. 0; 80; 160; 320 kg K ha^{-1} bei Hackfrüchten (als 50er Kali). Formen: I = *Kainit*, II = 50er Kali, III = Schwefelsaures Kali, IV = *Kamex*.

3.2 The *Eternal Rye* trial

The *Eternal Rye* trial, established as a monoculture, investigates the long-term effects of different mineral and organic fertilizers on yield and soil. It originally consisted of five, later six, plots of 1000 m^2 each. Figure 3 shows the fertilization variants tested up to 1989/90 (without replications). The following changes have taken place after harvesting in 1990:

– The mineral-N application was increased from 40 to 60 kg ha^{-1} thus aligning it with the N supply by farmyard manure (FYM) (*St I*).

– At *St I*, FYM has been changed to doses containing exactly 60 kg ha^{-1} N (approximately 12 t ha^{-1} FYM).

– After a single very high PK application, *N treatment* has been replaced by a combined FYM and mineral fertilization in the amounts of the variants *St I* and *NPK* (120 kg ha^{-1} N).

In all plots, the pH value is kept slightly acid by occasionally applying different doses of lime.

Figure 3 demonstrates how, after the harvesting in 1961, the trial had been divided into three parts. In the southern part (Division C), rye monoculture has been continued, in the central part it had been changed to a potato – rye – rotation (Division B), and in the northern part to maize monoculture (Division A). Fertilization remained unaltered. As a consequence, the trial program has been enriched by an additional factor since different yields and root residues, different vegetation periods and crop husbandry were likely to affect the humus content of the soil. First results concerning the altered soil-C dynamics are discussed by *Schmidt* et al. (2000) and *Flessa* et al. (2000).

In the course of its history, much has been reported about the *Eternal Rye* trial (*Kühn*, 1901; *Scheffer*, 1931; *Schmalfuß*, 1950; *Stumpe* et al., 1984; *Garz* and *Hagedorn*, 1990; *Merbach* et al., 1999b). A more detailed evaluation after 120 years is given by *Schmidt* et al. (2000).

In summary, the *Eternal Rye* trial has shown that the nutrient demands of plants can be met by mineral fertilization (*NPK*) without any yield deficits. FYM has resulted in a limited increase of humus but in only a small yield increase compared with mineral fertilization. Due to increasing crop residues, mineral fertilization (*NPK*) also contributed to a stable amount of humus. N deficiency (*U, –PK*) resulted in a rapid yield reduction whereas PK deficiency could be identified only after 30 years of the trial due to the supply of these nutrients by the soil. Steady states of nutrient and C content of the soil characteristic for each fertilization treatment appeared only after 30 to 40 years. The change of the *N* variant into a *NPK+FYM* (*NPK+St*) fertilization in fall 1990, combined with a single high PK application, quickly restored the complete crop production capacity. The continuous rye growing demonstrates the important influence of weather, especially rain, on yield – directly by water supply to the plants, and indirectly by turnover processes in the soil. During rainy years, leaching causes N losses even in unfertilized areas. The transition to the potato – rye rotation increased the yield of rye. A decrease of the humus content, caused by less crop residues, took place in this rotation as well as in the case of continuous silage maize. This occured at the same rate as in the second FYM plot (*St II*) where fertilization was stopped in 1952. More detailed data concerning balances and turnover of the nutrients N, P, and K can be found in *Einicke* et al. (1976), *Springob* (1995), *Schliephake* et al. (1997; 1999), and *Garz* et al. (1998).

3.3 The long-term trials established in 1949

The six long-term fertilization trials at *Fields A* to *F* originally belonged to a large, closed, and unified area. Due to the termination and the changes of some trials, the unity is not maintained any longer but the standardization has remained. The plots cover 30 m^2 each (6 m at right angles, and 5 m parallel to the direction of tilling) and are separated by stripes of 0.5 m width (for details see *Stumpe* et al., 1990).

The lime fertilization trial (*Field A*)

The effects of a differentiated lime application on plants and soil are investigated in *Field A*. Every three years after harvesting, 0, 0.5, 1.0, and 2.0 t CaO ha^{-1} were applied as $CaCO_3$ with three replications in a legume – root crops – grain rotation (see Fig. 4). The existence of three identical subdivisions allows the simultaneous cultivation of all three crops each year. The nutrient demand of the plants determines the amount of applied NPK, which is given as

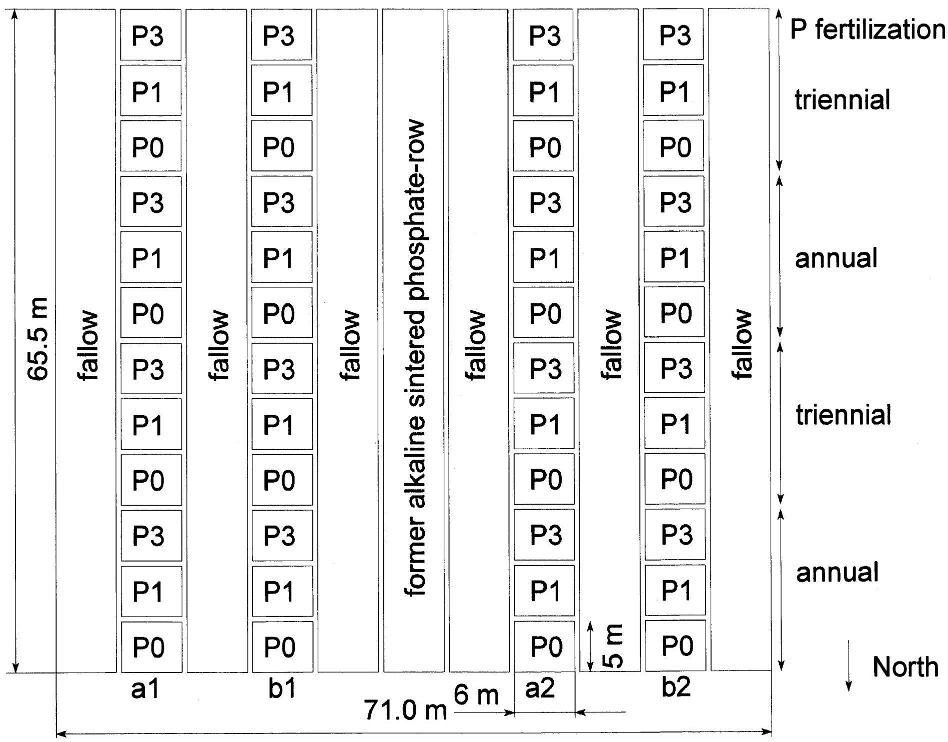

Figure 6: Lay out of *Field D* (P fertilization trial) since 1970. P forms: a) basic slag, b) superphosphate. P levels: P0 = without P, P1 = 45 kg P ha^{-1}, P3 = 135 kg P ha^{-1}.
Abbildung 6: Lageplan des P-Düngungsversuches *Feld D* seit 1970. P-Formen: a) Thomasphosphat, b) Superphosphat. P-Mengenstufen: P0 = ohne P, P1 = 45 kg P ha^{-1}, P3 = 135 kg P ha^{-1}.

ammonium sulphate, superphosphate, and muriate of potash (60% K_2O = 49.8% K). No organic fertilization is applied.

Detailed results have been presented by *Garz* et al. (1969); *Schliephake* and *Otto* (1990), and *Merbach* et al. (1999b). In summary, the omission of lime to this slightly acid soil has resulted in a decreasing pH in the surface soil up to 4.8 after the 50 years of the trial. Apart from calcium uptake by the plants, the input of acid and alkaline materials from the atmosphere has played an important but not quantifiable role. The presence of a considerable amount of gypsum probably reflects those inputs and suggests a moderate moisturing of the soil (*Garz* et al., 2000). To sustain the original pH, an annual supply of about 250 kg ha^{-1} CaO is necessary. Higher amounts have resulted in complete neutralization and accumulation of small amounts of $CaCO_3$. The supposed masking of free Al^{3+} by the abundant humic materials, as well as the fact that there is enough Ca^{2+} in the soil solution, has probably caused the strikingly low response of the crops to the slowly increasing acidification (*Merbach* et al., 1999b). Within the last years, changes in the subsoil which has not been directly affected by cultivation have been detected (*Garz* et al., 2000).

Trial on the physiological action of fertilizers (*Field B*)

From 1949 to 1969, the effects of the continuous use of physiologically acid and physiologically alkaline mineral fertilizers have been investigated in *Field B*. Ammonium sulphate in combination with superphosphate has been compared to the application of sodium nitrate in combination with basic slag. K has been applied as muriate of potash (40% K_2O = 33.2% K). Both treatments have been replicated 12 times in two subdivisions. A third subdivision, located between these two, has been fertilized with urea and calcium hydrogen phosphate and served as the standard treatment. Liming has been another test factor: The northern half of the subdivisions has been treated with 2 t ha^{-1} CaO (as $CaCO_3$) every four years (after spring wheat or onion) whereas the other half remained without liming (with six replications altogether). One agricultural rotation (potato – spring wheat – sugar beet – oats) has been examined as well as one field vegetables rotation (tomatoes (since 1954 carrots)-savoy cabbage – celery). After harvesting in 1968, the trial was terminated. Up to now, two evaluations of the trial have been presented (*Hagemann* and *Kolbe*, 1968; *Merbach* et al., 1999b). The main results showed that physiologically acid, neutral, and alkaline fertilizers (i.e. N applied as ammonium, amide, or nitrate) in this order have a declining effect on the acid – base balance of the soil. Additional lime fertilization nearly compensated the resulting differences in the soil-pH. pH-values of 5.5 to 6.0 (with only slight modifications) have been accompanied by the highest yields.

The potassium fertilization trial (*Field C*)

Several K fertilizers have been compared, and increasing K supply has been examined in *Field C*. The experimental design consists of several subdivisions. The effects of four K levels (K0, K1, K2, K4, as muriate of potash with 50% K_2O = 41.5% K), and four K fertilizers (all at K2) were investigated (Fig. 5). With 12 subdivisions per row, the four variants amount to three replications. Since 1970 there is a simultaneous cultivation of all five crops each year.

Apart from an agricultural rotation pea (since 1970 maize) – winter wheat (since 1970 spring wheat) – spring barley – sugar beets – potato), a vegetable rotation (*Phaseolus* beans – carrots – celery – onion – tomatoes) has been investigated (the latter from 1949 to 1969 only). Present evaluations demonstrate that the sandy loess soil has a remarkable K supply power due to its illite clay minerals (*Stumpe* et al., 1989). Even after 40 years without K fertilization, the soil still delivers about 65 kg ha^{-1} a^{-1} K, which is almost sufficient for highest yields of spring wheat. At the K2 level, the K supplied by the soil is reduced to 15 kg ha^{-1}. With increasing exhaustion of slow-release ("specifically bound") K, measurable changes in the clay fraction take place (*Leinweber* and *Reuter*, 1989). Furthermore, the soil develops a selective fixation ability for K^+ ions and NH_4^+ ions. The opposite is the case if the K supply exceeds the K need. On the other hand, the high K^+ fixation ability of the subsoil prevents considerable leaching (*Garz* et al., 1993). The same is valid for ammonium N. The minor constituents of the potassium fertilizers, magnesium and especially sodium are less adsorbed and are, therefore, subject to a downward movement. The chloride being not absorbed moves with about the same speed as the soil water (*Herbst* et al., 1980). If there is no deep seeping in dry years, chloride temporarily concentrates in the subsoil. This is even more the case with sulfate, which is converted to less soluble gypsum under decreasing soil moisture (*Garz* et al., 1993). Details of subsoil changes are discussed by *Garz* et al. (2000).

The phosphate fertilization trial (*Field D*)

An examination of three P amounts (P0, P1, P3) has been combined with that of three P fertilizer forms (superphosphate, basic slag, and alkali sinter phosphate, the last terminated in 1995) in *Field D*. Each fertilizer has been investigated on a field consisting of two subdivisions. Figure 6 demonstrates the principle of the trial as well as the P levels and the fertilization intervals.

There has been a rotation of lucerne – lucerne – winter rye – sugar beet – spring barley, with the P storage fertilization applied to lucerne and winter rye. Up to 1969, an additional field vegetable rotation was grown. Current results show that after more than 40 years without any P supply the yield has hardly been lower than that with P fertilizer (Stumpe et al. 1994). This suggests a remarkably high availability of P at the beginning of the trial. One reason is the long lasting effect of P, which may have been accumulated in the A horizon during the former utilization of the field. The availability of phosphate in the subsoil seems to play an important role also (*Garz* et al., 2000; *Gransee* and *Merbach*, 2000). This might be due to high root density, rooting depth, and root exudation of the plants (*Schilling* et al., 1998; *Merbach* et al., 1999a,c). Under these circumstances fertilization according to crop requirement is obviously sufficient to maintain a satisfactory P level for average yields (for details see *Gransee* and *Merbach*, 2000).

The nitrogen fertilization trial (*Field E*)

From 1949 to 1980, different amounts of N (e.g. spring barley: 0, 10, 20, 40, 80, 160 kg ha^{-1} N; sugar beet: 0, 20, 40, 80, 160, 320 kg ha^{-1} N as calcium ammonium nitrate) have been applied in *Field E*. In addition, from 1949 to 1969 different forms of mineral-N fertilizers (calcium ammonium nitrate, sodium nitrate, ammonium sulphate, urea) have been compared both in an agricultural rotation (early potato – winter rape – winter wheat – sugar beets – spring barley) and a vegetable rotation (onion – carrots – poppy – tomatoes – savoy cabbage). Results from this trial have shown that N has a considerable influence on crop quality (e.g. sucrose and starch content, malting quality) in case of both deficiency and excess (*Merbach* et al., 1999b, p. 73). All N-fertilizer forms used in this trial have shown slight differences in yield in the course of the years. However, during the first three rotations, average crop yields differed less than 1% from the trial average. Spring barley responded negatively to the acidification of the soil in case of fertilization with ammonium sulphate (*Kolbe* and *Scharf*, 1967). Inorganic N fertilization influenced the content of soil organic matter slightly positively, which can be attributed to the higher amount of root and crop residues as a result of higher yields (*Scharf*, 1967). This emphasizes the importance crop residues have for the maintenance of humus content, apart from FYM and slurry.

Organic fertilizer trials (*Field F*)

The effects of mineral and organic fertilizers, separately and in combination, on yield and on C and N contents in the soil have been investigated in *Field F*. The trial consists of three subdivisions (*Stumpe* et al. 2000a, b). *F1* examines the combination of both fertilizer forms at different nutrient levels; *F2* the combination of FYM and differentiated mineral-N applications; *F3* the application of differently stored farmyard manures (until 1971). Later, the residual-effects of the changes in the soil humus content, which had been caused by the FYM, were investigated. From 1950 to 1961 a potato – spring barley – sugar beet – spring wheat rotation had been cultivated; in 1962 it was changed to a potato – oat (since 1981: winter wheat) – silage maize – spring barley – sugar beet – spring wheat rotation. Details of the experimental design and evaluations can be found in *Merbach* et al. (1999b).

In summary, yield decreases in the nutrient lacking trial (*F1a*) compared to complete inorganic fertilization have been observed only in case of the variants *U* (*Unfertilized*), *PK* (omission of N fertilization (yield reduction 30 to 60%)), and *NP* (omission of K fertilization) (10 to 30%). Omission of P fertilization has not resulted in yield depressions indicating the higher P than K supply ability of the soil (as in *Field D*).

A comparison of the effects of FYM treatment (*F1b*) and inorganic fertilization on the yield shows that the combination of FYM and moderate inorganic N fertilization allows higher yields (about 10%). Increasing inorganic N supply has led to a decrease or even complete lack of FYM effects. Yield was not directly influenced by straw manuring if optimal inorganic fertilizers had been applied (*F2a*). Both FYM and straw have had beneficial residual effects probably caused by the increasing humus content (*Kolbe* and *Stumpe*, 1968; *Stumpe* et al., 1976). With optimal inorganic fertilization, differences in humus content (*F3*) of 0.1% to 0.2% C have not significantly influenced the yields (*Stumpe* et al. 2000a, b). On the other hand, high levels of FYM fertilizers (40 t ha^{-1} – biennially before root crop) have led to significant responses, especially on the low inorganic-N fertilized plots. Obviously, the regular supply of organic substances is much more important than a slightly higher C content of the soil. *Stumpe* et al. (2000a, b) provide a more detailed discussion of experimental findings.

4 The soil development trial (Halle, Adam-Kuckhoff-Str. 17b)

This trial aims at the quantification of i) yield development, ii) the accumulation of soil organic matter (SOM) and its fractions, and iii) nutrient dynamics in the developing soil, and determines the role of mineral fertilization for those processes (*Schmalfuß*, 1965). The trial is located at an arid loess site which contains almost no humus. Such investigations can be of some relevance for the evaluation of recultivation measures of loess layers leveled down as a result of intensive brown coal mining in the region. Detailed information about the used loess substrate and the experimental design is provided by *Beschow* et al. (2000).

Current results show that the original loess substrate has developed into a soil rich of humus in the course of several decades. This formation has been influenced by plant residues, their microbial metabolites, and fertilization. The enrichment of SOM still continues and goes along with increasing humification and a narrowing C/N ratio. On the other hand, the dry matter yields did not increase any more after 30 years, and they do not correlate to the C_{org} content of the top soil. The upper 10 cm of the soil have been enriched by plant-available nitrogen, phosphorus, and potassium. At the same time, the cation exchange capacity has increased to values that correspond with those in black earth soils in central Germany. During the soil developing process, a progressive decalcification has been detected, which is still going on. A possible further change of black earth to leached brown soil by continous lime losses might be observed in the future.

5 Conclusion and prospects

5.1 Major results

Up to now, the long-term trials in Halle brought about several important results. They have confirmed the long-term reactions of agro-ecological systems to changes in fertilization and land use practices. It has been shown that the effects of changes in cropping systems (*Eternal Rye*, 1961) or the termination of fertilization (*St II* variant of *Eternal Rye*, 1953) are quantifiable only after 30 years. In many cases, new steady states have been established only after 70 years (variants *U* and *St I* of *Eternal Rye*). This refers to the soil-C and -N contents (especially to the quality of humus) as well as to available P and K after omitted mineral fertilization (*Schliephake* et al., 1997). For example, residual effects of the annually applied FYM from 1893 to 1953 (*St II* of *Eternal Rye*) can be observed still today by the N supply ability of the soil. Such results are of major relevance when evaluating set-aside programs.

In the second place, it has been shown that N- and C-contents of the soil depend on the amount of hardly decomposable matter applied with organic fertilization. In reality, the ways of enhancing the humus content are limited (*Stumpe* et al., 2000a, b). High mineral-N application increases the humus content by more crop and root residues (*Scharf*, 1967).

Furthermore, it has been confirmed especially by the *Eternal Rye* trial that nutrient-equivalent mineral fertilization can replace organic fertilization with regard to yield (for details see *Schmidt* et al., 2000; *Stumpe* et al., 2000a, b).

The high P supply ability that has been observed in the long-term trials in Halle (*Eternal Rye*, P fertilization trial) cannot be explained by the currently used methods of determining plant-available P (*Schliephake* et al., 1997; *Merbach* et al., 1999a). In general, K (potassium fertilization trial) behaved similarly although, in case of omitted K fertilization, changes of clay minerals have been observed due to K losses of illite (*Stumpe* et al., 1989; *Leinweber* and *Reuter*, 1989). Therefore, delayed fertilization effects of N due to NH_4^+ fixation cannot be excluded. At the same time, easily-soluble salts have accumulated in the subsoil where they have been subject to leaching in years with high precipitation (*Garz* et al., 1993; *Herbst* et al., 1980).

Next, the trials have demonstrated the regular liming requirement of central German chernozems (lime fertilization trial), particularly in case of soils low in organic matter and with physiologically acid fertilization (*Merbach* et al., 1999b).

Moreover, the nitrogen fertilizer recommendations evolved by *LUFA Sachsen-Anhalt* is chiefly based on material and data from the long-term trials at *Julius-Kühn-Feld* (*Holz*, 1999).

Last but not least, the long-term trials in Halle have contributed to the elucidation of some fundamental principles such as the way of fertilizer-N in agricultural ecosystems by means of ^{15}N (*Schliephake* et al., 1999). They enable also a better understanding of the K-dynamics in the soil (*Springob*, 1995) or of the fate of climate-relevant methane (*Hütsch*, 1998).

These selected examples already illustrate the broad applicability of the various results of the long-term trials in Halle. Thanks to their long duration and, therefore, to the revealed differentiation between the treatments, the trials can help solving current questions of agricultural and environmental policies.

5.2 Validity of the long-term trials in Halle

As with all field experiments, the validity of results of the Halle trials is restricted principally to specific sites. In general, the results can be transfered to other sites with similar soil, climate, and weather conditions. For this reason, the experimental site determines the level of universality of the results in question. The site of the Halle trials is characterized by low precipitation and high radiation. The loess and sandy loess soil is typical for the eastern and southern forelands of the Harz mountains. The site is therefore representative for similar areas in the region between the rivers Saale, Elbe, and Mulde. There is no significant deviation to other arid sites in central and eastern Europe which are characterized by low movement and leaching of nutrients and harmful substances. Thus the Halle trials can give valuable advice for agricultural practices for both the central German arid regions and also for central and eastern European regions. The Halle trials are therefore particularly valuable. They should be continued and, if necessary, carefully modified to meet changing conditions.

5.3 Approaches to continue the Halle trials of long-term fertilization

The basic target of the long-term fertilization trials in Halle remains the scientific evaluation of fertilization and land use strategies by gaining knowledge about the processes in soil-plant systems. Apart from the recording of long-term effects of different fertilization, long-term experiments are needed to better characterize the annual variability of yields and the dynamics of turnover processes in the soil (*Schmidt* et al., 2000).

Further documentation is needed of the long-term effects of organic and mineral fertilization on the amount and quality of SOM. In particular, this refers to the slow leveling of C and N steady states, and the quality and stability of SOM. To provide this information, more physical, chemical, and microbiological methods need to be included. Investigations of this type have already begun (*Flessa* et al., 2000; *Schmidt* et al., 2000).

Investigations of long-term balances and movements of nutrients in the soil are needed. Above all, the movement and plant-availability of nutrients and harmful substances need to be recorded more precisely, including inputs from the atmosphere (*Weigel* et al. 2000) as well as including subsoil effects (*Garz* et al., 2000). Furthermore, the extent to which usual methods of calculating the nutrient status of plants or the plant-availability of nutrients in the soil must be examined by measurements (*Schilling* et al., 1998; *Merbach* et al., 1999b). Besides the nutrients already studied, magnesium and sulphur need to be included into the long-term fertilization trials.

Further examination is needed of long-term effects of different fertilization on soil structure and soil formation processes. These studies should include clay mineral modification due to K removal (*Leinweber* and *Reuter*, 1989), the development of stable organo-mineral complexes, and the effects of continued decalcification on soil development (*Beschow* et al., 2000).

Continuous research is also needed on the long-term effects of different fertilization on yield, root growth, and root function. These investigations should focus on nutrient mobilization by roots including exudates (*Merbach* et al., 1999a, c; *Schilling* et al., 1998), N uptake under conditions of K deficiency or straw application, and the influence of pH on root growth.

There should be intensified interdisciplinary use of selected treatments for specific investigations of fundamental principles. Examples are the projects on the ^{13}C enrichment of SOM after maize cultivation (*Flessa* et al., 2000) and on release of climate-relevant trace gases (*Hütsch*, 1998).

Last but not least, there should be an increased use of the long-term trials as public demonstrations to illustrate the complex nature of agricultural soil management.

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