Redaktor Nczelny- Executive Editor – Mariusz Fotyma
Sekretarz Redakcji – Secretary – Kazimierz Kęsik

Rada Konsultacyjna – Advisory Board
Pavel Cermak, Havlickuv Brod, Czech Republic
Tadeusz Filipek, Lublin, Poland
Gyorgy Fuleky, Godollo, Hungary
Witold Grzebisz, Poznań, Poland
Janusz Igras, Pulawy, Poland
Stanisław Kalembasa, Siedlce, Poland
Jakab Loch, Debrecen, Hungary
Jan Łabętowicz, Warszawa, Poland
Ewald Schnug, Braunschweig, Germany

Redakcja tomu: Mariusz Fotyma

Copyright by Polish Fertilizer Society - CIEC – 2011-05-31

ISSN 1509-8095

Adres Redakcji – Adress Executive Editor
Zakład Żywnienia i Nawożenia IUNG-PIB
Czartoryskich 8, 24-100 Puławy, Poland
nawfert@iung.pulawy.pl
WWW: nawfert.pl

Printed: IUNG- PIB zam. 2/F/12 Puławy, 200 copies, B-5
Contents

**Division I. Soil fertility and fertilization – Division Editor - Prof. Tadeusz Filipek,**

1. Fotyma M. – New developments in soil testing and plant analysis, Review ...... 5
2. Suwara I., Szulc W. – The effect of long-term fertilization on the soil structure .... 20
3. Szara E., Mercik S., Sosulski T. – The fate of phosphorus in the soil and the balance of this element in long-term field experiments ................................. 29

**Division II. Plant mineral nutrition – Division Editor – Prof. Beata Rutkowska,**

1. Sosulski T., Stępień, W., Mercik S., Szara E. – Crop yields and nitrogen balance in long-term fertilization experiments ................................................................. 41
2. Barłóg P. – Evaluation of plant nutritional status by the CND method: case of sugar beet ............................................................................................................. 51

**Division III. Fertilizers and environment protection – Division Editor – Prof. Alicja Pecio, Reviewer: Prof. Janusz Igras**

1. Pecio A. – Diagnostic of fertilization requirements in a site-specific fertilizer management ........................................................................................................ 78
2. Rutkowska B., Szulc W. – Usefulness of compost from mushrooms substrate for fertilization of Miscantus plantation ................................................................. 91
3. Filipek T., Falkowska K. – Diversity of mineral nitrogen content in soil in the region close to Nitrogen Plant in Puławy ................................................................. 97

**Division IV . General problems**

1. Filipek T., Skowrońska M. – Methodological paradigms in research on agricultural chemistry from the creation of science to the present day ............................. 106
NEW DEVELOPMENTS IN SOIL TESTING AND PLANT ANALYSIS
REVIEW

Mariusz Fotyma, Ewa Fotyma
Institute of Soil Science and Plant Cultivation – National Research Institute,
Pulawy

Abstract

In the review paper, based mainly on the researches carried on at the Department of Plant Nutrition and Fertilization of the Institute in Pulawy, the contemporary approach to plant and soil tests have been presented and discussed. Plant tests are classified as direct, destructive using plant sampling and chemical analysis and indirect, non destructive, using spectral analysis of plants or crop canopy. As the best and most reliable, but cumbersome and destructive, plant test for nitrogen the nitrogen nutrition index NNI is recommended. Soil tests are most commonly based on soil sampling, extraction of samples with different solution and estimation of so called available forms of nutrients. The main and still not fully solved problem lies in the calibration of soil tests, i.e. establishing their threshold values, by which crops show no positive reaction to fertilizer application. The new calibration figures for nitrate nitrogen and available potassium soil test have been proposed.

Key words: soil test, plant test, calibration of soil and plant tests

Introduction

Quantitative fertilizer recommendations are based on the plant and soil tests. The most important parameter of both tests is its critical value. Critical value of the plant test means that the supply of a given nutrient does not hinder the maximal relative growth rate, at particular growth stage. Critical value of the soil test shows that the amount and availability of a given nutrient suffice to secure its absorption rate necessary to cover the nutrient requirements of a plant. The most commonly used direct plant test is the total content of a nutrient in plant biomass and the soil test, the content of so called available form of nutrient in the bulk of soil. From the theory, it all seems to be simple and straightforward. In practice both plant and soil test have, however, to be calibrated against the plant indices. This procedure is based on numerous field experiments and laboratory analysis, hence it is time-consuming.
and expensive. For these reasons once selected and calibrated test is used for a long
time and agrochemical service is very conservative against any changes and even
improvements.

Another problem lays in translation the results of plant and soil test into
fertilizer recommendations, i.e. optimal rates of fertilizers. The below critical values
of both test does not correspond quantitatively to the amount of fertilizers. Besides,
there is a time gap between performing the test and the harvest of the crop. In this
time, the natural plant growth conditions can change dramatically influencing both
availability of the nutrient in soil and its transformation processes in plant. Plant
and soil tests concern most often one nutrient only. However, it is well known that
the critical value of plant test depends on the supply of other nutrients. The critical
value of the soil test depends in turn on other factors influencing the given nutrient
availability to plant roots. Two general approaches for including plant and soil tests
into the fertilizer recommendations are accepted. The first one goes in the direction of
detailing the test by including in its calibration other factors deciding upon utilization
of a given nutrient by crops. In this approach, the weigh is put into such a refined
test and fertilizer recommendations are directly related to the test value. The second
approach is to simplify the test as much as possible and to shift in the direction of
refined recommendation procedure.

Plant tests

The main objective of a plant test is to evaluate the actual nutrient status of
the plant and to extrapolate it into the final crop yield. Plant tests can be split into
straight, concerning one particular nutrient and complex ones, including all vital
nutrients. The straight plant tests are further divided into direct, usually destructive
and indirect, no destructive ones (Fig. 1).

![Diagram of Plant Tests]

*Fig. 1. Division of the plant tests*
The simplest and most commonly used straight plant test is the content of a given nutrient in plant dry mass, or its concentration in plant saps. The critical value, be it also a critical range of this test is estimated in experiments with increasing supply of plant with a given nutrient. The plant should be grown in the possibly best conditions, including supply all other nutrients (Fig. 2).

**Fig. 2. Concentration of nitrogen in plants versus final crop yield**

The theory, critical values (ranges), of the straight plant tests are to be found in several textbooks [Bergmann, Neubert 1976, Bergmann 1992, Reuter and Robinson editors 1997]. The straight tests for single nutrients can be as well used in a semi-complex analysis of plant tissue. It has been done by ranking the relative values of the single nutrient content in descending order (Fig. 3). The relative value is the percent content of the nutrient against its critical value [Stanisławska-Głubiak, Korzeniowska 2007]. On this principle, the computer program for estimating the micronutrient requirements and rates of micronutrient fertilizers has been prepared in IUNG-PIB [Calculator].
For mobile nutrients, like potassium which appears mostly in a cell vacuole it has been argued that its concentration should be measured and expressed rather in terms of tissue water than plant dry mass [Barraclough, Leigh 1993, Danyte, Igras 2008]. Potassium concentration in plant tissue water can be measured directly in the field using hand-held K ionometer (Fig.4). As results from the work of Danyte and Igras [2008] with winter wheat, potassium concentration is a better measure of plant potassium status than the content of this element in plant dry matter. Besides this plant test is less depended on the time of sampling and the plant supply with nitrogen in comparison to the test based on plant dry matter.
The main drawback of straight, direct plant test is its dependence on the plant development stage. To avoid this, the test should be calibrated in the particular stage, early enough to use the result for top-dressed fertilizer application. For nitrogen a very useful concept has been lately presented by Lemaire et al. [1989] and developed by Greenwood et al. [1991]. The authors proved that the nitrogen content decreases during the plant ontogenesis which is explained by plant metabolic processes. What more there is a close relationship between nitrogen content N% and accumulation of dry mass W by plant. This relationship is described by the following universal formulae: N% = a(W)^b, where a and b are the coefficients. It has been argued that these coefficients have the same value for all C_3- type plants and, likewise, for all C_4- type plants. The curve describing this relationship for plants optimally supplied with nitrogen and in a good growing condition is called the N dilution curve (Fig. 5).

![N dilution curve](image)

*Fig. 5. Dilution curve based on own date [Fotyma, Pecio 2009]*

From the curve, the optimal nitrogen concentration corresponding to the known plant biomass can be directly obtained N_{opt}. The relation of the actual nitrogen content (from analysis) N_{act} to the optimal one N_{opt} corresponds to the nitrogen nutrition index NNI which is a plant test for this element. The values of NNI are in the range from close to zero, which show the acute nitrogen deficiency to above one, which show oversupply with this element. The critical, i.e. optimal NNI value is 1. Nitrogen nutrition index seems to be the best destructive contemporary plant test based on the sound ground of metabolic processes during plant growth. The preliminary results of the research carried on in IUNG show that the concept of the dilution curve is applicable to potassium as well [Igras, Danyte 2008].

However good, all described plants straight tests are destructive i.e. plant samples have to be collected and further processed in the laboratory. It is expensive and time consuming procedure, and the result comes not in real time. In the last decade the new, indirect plant tests making use of light reflectance and/or absorption has been developed alongside with the new instruments. The first indirect plant test which has found application in practical agriculture was SPAD (soil Plant Analysis Development) based on the relation between the content of chlorophyll...
and the nitrogen in plant leaves [Pecio, Mikołowicz 2009]. To measure the content of chlorophyll in plant green parts two hand-held instruments are currently used, Minolta Hydro-N-Tester and Opti-Sciences Inc. CCM-200 (Fig. 6).

**Fig. 6. Hydro – N – Tester**

Hydro-N-tester measures the difference in the absorption of light at the wavelengths 650 and 940 mm giving the reading in SPAD units (0-800). Extensive information concerning the application of SPAD method in Poland is available in the special issue of the journal Fertilizers and Fertilization [ed. Fotyma M., Fotyma E. 2002]. This method has its pros and cons. The main advantage is that SPAD readings are less depended on the plant development stage, i.e. date of sampling, but the disadvantage is differentiation this index among the same crop varieties [Fotyma E., Fotyma M. 2002a, 2002b]. Another indirect plant test for nitrogen, or rather index of plant vegetation is NDVI (normalized difference vegetation index). This index is a ratio of the amount of adsorbed (in the red-light spectrum), by the plant canopy and reflected (in near infra-red spectrum) radiation [Pecio, Mikołowicz 2009]. This index can be measured either by hand-held instrument Green Seeker (Fig. 7) or by remote sensing.

However, the NDVI index is depended on two main factors, i.e. of the plant chlorophyll content and the density of plant canopy and further on the soil surface properties. In fact, in the preliminary investigations carried on by IUNG-PIB with winter wheat, the closer relation has been found between NDVI values and LAI (leaf area index) than between NDVI values and the level of plant supply with nitrogen (Fig. 8).
New developments in soil testing and plant analysis

It has been already stated that the critical value of a particular nutrient depends significantly on plant supply with other elements. Therefore, the complex plant test based on the ratio of two, or more elements content in the plant tissue has been

![Fig. 7. Green Seeker™](image)

![Fig. 8. NDVI index versus LAI index [Fotyma, Pecio 2009]](image)
Mariusz Fotyma, Ewa Fotyma

proposed for some time. The best known in this group of methods are Beaufils nutrient indexes called DRIS (Diagnosis and Recommendation Integrated System) [Black 1993, Barłóg 2009]. The first step in this method is to calculate the DRIS norms, corresponding to critical values of the straight plant test. DRIS norm for two nutrients, e.g. nitrogen and phosphorus is a ratio of these nutrients in the population of high crop yields multiplied by the coefficient of variation of this ratio CV, e.g. n/pCV. The next step is to estimate the DRIS indexes, which are a relative measure of the deficiency or excesses of the nutrients in plant under analysis in relation to the accepted DRIS norm. For three nutrients, nitrogen, phosphorus and potassium usually three norms are available n/p, n/k and k/p. Than the indexes are calculated as follows: \( I_N = \frac{(f(N/P)+f(N/K))-2}{2} \); \( I_P = \frac{(-f(N/P)-f(K/P))+2}{2} \); \( I_K = \frac{(-f(N/K)+f(K/P))+2}{2} \), where \( f(N/P) = \frac{(N/P-n/p)\cdot 1000}{CV} \), if \( N/P > n/p \) and \( f(N/P) = \frac{(1-(n/p-N/P)\cdot 1000)}{CV} \) if \( N/P < n/p \) and so on for phosphorus and potassium. The nutrient indexes may have plus or minus signs. Minus sign means nutrient deficiency and plus nutrient excesses, as serious as the given index value. The sum of indexes without recognition of signs shows the general status of plants with respect to balance all nutrients. The disadvantage of DRIS method is that the norms and indexes as well depend on the plant development stage. To avoid this in the more advanced generation of this method called MDRIS the relation (norms) between the plant dry matter and nutrients content is also recognized. Newly developed CND (compositional nutrient diagnosis) offers another approach for testing the plant nutrient status. This, somewhat complicated statistically approach will be presented in another paper prepared by Barłóg [2009].

**Soil tests**

The main objective of the soil test is to evaluate the amount of available, i.e. accessible to plant roots, nutrient. The most common are chemical soil tests based on solubility of a given nutrient in specific solutions. There is always some theoretical basis for the choice of extractant. From practical point of view, priority is given to universal solutions, which extract several nutrients in one procedure. The amount of soluble nutrients must not be directly related to the nutrient requirements of the plant. Each soil test has therefore, to be calibrated in the direct or indirect way (Fig. 9).

![Fig. 9. Division of soil tests](image_url)
New developments in soil testing and plant analysis

Classical direct calibration procedure, based on-field experiments is time-consuming and very expensive. For these reasons once calibrated soil tests are used for a long time notwithstanding the changing situation in agriculture. There are two other approaches to calibration or refining already made calibration of soil test.

The first approach is based on the numerous analysis of soil samples collected from the whole area of the country, e.g. for monitoring purposes. The set of such analytical results can be recognized as a representative for the general population of all soils in the country. If the distribution of data is normal or very close to normal than it is characterized by average value and standard deviation. Not normal distribution of data is characterized by median value and percentile distribution. The soil test for available (mineral) nitrogen in Poland has been calibrated on this principle. The calibration procedure based on over 50 thousand soils samples had to recognize two characteristics of this sample population. The first was that the content of mineral nitrogen depended significantly on the soil texture and the second one that data distribution within each soil category was far from normal. Taking this into consideration the five classes of mineral nitrogen content in the soil profile 0-90 cm were proposed (Table 1) (Fotyma et al. 2010).

Table 1. Classes of mineral nitrogen $N_{\text{min}}$ content in the soil profile 0-90 cm.

<table>
<thead>
<tr>
<th>Soil texture and the number of soil samples</th>
<th>Very low</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Very high</th>
<th>Median $N_{\text{min}}$ kg/ha$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very light 10924</td>
<td>&lt; 42</td>
<td>42 – 57</td>
<td>58 – 76</td>
<td>77 – 107</td>
<td>&gt; 107</td>
<td>67</td>
</tr>
<tr>
<td>Light 19902</td>
<td>&lt; 52</td>
<td>52 – 71</td>
<td>72 – 94</td>
<td>95 – 131</td>
<td>&gt; 131</td>
<td>83</td>
</tr>
<tr>
<td>Medium 8844</td>
<td>&lt; 59</td>
<td>59 – 79</td>
<td>80 – 104</td>
<td>105 – 145</td>
<td>&gt; 145</td>
<td>92</td>
</tr>
<tr>
<td>Heavy 8024</td>
<td>&lt; 61</td>
<td>61 – 82</td>
<td>83 – 109</td>
<td>110 – 150</td>
<td>&gt;150</td>
<td>96</td>
</tr>
</tbody>
</table>

The second approach relies on calibration the new test or updating the old one against another test better grounded on some theoretical principles. This approach has been applied for validating the soil test for potassium officially used in Poland. The Egner-DL potassium test was validated against the water-soluble potassium. The latter is grounded on the principle of full availability the potassium in soil solution for plants. As a matter of fact, the concentration of potassium in soil solution differs from that in the soils water extract, but there is a close correlation between both forms. Besides it would be practically impossible to isolate a soil solution from numerous soil samples. In the own research almost 27 thousands of soil samples from all over Poland have been analyzed parallel for the content of Egner-DL $K_{\text{DL}}$ and water soluble $K_{\text{H+}}$ potassium. The results are presented in table 2, with recognition of soil texture strongly influencing some date [Fotyma 2010].
Table 2. Summary statistics of the date with recognition of soil structure

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Number of samples</th>
<th>$K_{DL}$ mg·kg$^{-1}$ soil</th>
<th>$K_{H2O}$ mg·kg$^{-1}$ soil</th>
<th>$K_{DL}/K_{H2O} = Q/I$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Median</td>
<td>Average</td>
<td>Median</td>
</tr>
<tr>
<td>Very light</td>
<td>2104</td>
<td>79,8</td>
<td>74,7</td>
<td>24,9</td>
</tr>
<tr>
<td>Light</td>
<td>10476</td>
<td>111</td>
<td>108</td>
<td>30,8</td>
</tr>
<tr>
<td>Medium</td>
<td>10758</td>
<td>123</td>
<td>116</td>
<td>26,7</td>
</tr>
<tr>
<td>Heavy</td>
<td>3610</td>
<td>137</td>
<td>125</td>
<td>27,9</td>
</tr>
<tr>
<td>Total</td>
<td>26948</td>
<td>117</td>
<td>110</td>
<td>28,3</td>
</tr>
</tbody>
</table>

Percentile (pentile) distribution of the date for water soluble potassium $mgK_{H2O}·kg^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>0 – 20 % very low</th>
<th>20 – 40 % low</th>
<th>40 – 60 % medium</th>
<th>60 – 80 % high</th>
<th>80 – 99 % very high</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,5 – 14,4</td>
<td>14,5 – 22,1</td>
<td>22,2 – 30,3</td>
<td>30,4 – 40,9</td>
<td>41,0 – 69,0</td>
<td>26,0</td>
<td></td>
</tr>
</tbody>
</table>

From the table 2, the conclusion can be drawn that the $K_{DL}$ content and soil buffer capacity $Q/I$ value is strongly texture depended, while the content of $K_{H2O}$ is practically the same in soils belonging to different categories, except very light soils. The representation of the very light soils is, however, low which influence the reliability of the date. Another conclusion is that the date is not normally distributed and, hence the better characteristic of average value is median and better characteristic of distribution is percentile distribution. In the bottom row of table 2, the percentile (pentile) distribution of the date for $K_{H2O}$ is included, independently of soil texture. There is a strong, but texture depended correlation between the content of $K_{DL}$ and $K_{H2O}$ potassium. This relation was the best described by multiplicative regression model $K_{DL}=a·K_{H2O}^b$. The parameters of this model for different soil categories can be found in source publication [Fotyma 2010]. Substituting to this model the date from the bottom row of the table 2 the values of $K_{DL}$ have been calculated and presented in table 3 as a new calibration figure for Egner-DL soil potassium.
Table 3. Proposed and officially used classes of available potassium content in soils of Poland

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Classes</th>
<th>Potassium content K_{pot} kg^{-1} soil in availability classes</th>
<th>Median Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Very low</td>
<td>Low</td>
</tr>
<tr>
<td>Very light</td>
<td>Proposed</td>
<td>&lt;46</td>
<td>47–70</td>
</tr>
<tr>
<td></td>
<td>Official</td>
<td>&lt;21</td>
<td>22–62</td>
</tr>
<tr>
<td>Light</td>
<td>Proposed</td>
<td>&lt;56</td>
<td>57–82</td>
</tr>
<tr>
<td></td>
<td>Official</td>
<td>&lt;41</td>
<td>42–83</td>
</tr>
<tr>
<td>Medium</td>
<td>Proposed</td>
<td>&lt;75</td>
<td>76–105</td>
</tr>
<tr>
<td></td>
<td>Official</td>
<td>&lt;62</td>
<td>63–104</td>
</tr>
<tr>
<td>Heavy</td>
<td>Proposed</td>
<td>&lt;82</td>
<td>83–113</td>
</tr>
<tr>
<td></td>
<td>Official</td>
<td>&lt;83</td>
<td>84–125</td>
</tr>
</tbody>
</table>

In the high and very high availability classes proposed calibration figures are lower from the officially used ones. It means the considerable reduction of recommended potassium rates in these ranges of soil availability classes. In the very low and low availability classes, particularly for the very light and light soils the proposed calibration figures are somewhat higher than the official ones. It means increasing recommended potassium rates in these ranges of soil potassium content and texture categories. Generally, introduction the proposed figures into practice would mean a shift in potassium rates from well supplied with potassium and heavier soils into worse supplied, light soils.

Calibration of the soil test can be one-dimensional or two-dimensional and, exceptionally even more complicated. In one-dimensional calibration, the content of the given nutrient is included only. A good example of such calibration is the one for phosphorus in Poland. The five ranges of phosphorus calibration classes are independent of other soil properties and/or kind of crop. A good example of two-dimensional calibration is this for potassium or magnesium. The ranges of calibration classes here are different for four groups of soil texture, which, in fact, gives twenty classes. In Hungary calibration of soil tests for phosphorus and potassium is even more complicated. The ranges of calibration figures depend here on soil type, soil texture, soil pH, organic matter content and the crop grown on the given soil. Such system is very stiff and formal and, practically for each class of available nutrient content the fixed fertilizer rate is attributed.

Using one or two-dimensional calibration figures for recommendation purposes one must remember that the optimal rate of fertilizer, besides the test value depends on several other factors. Kuchenbuch and Buczko [2009] re-examined the results
of several thousands field experiments with phosphorus and potassium fertilization carried on in Austria and Germany. Authors have used a non-parametric date procedure, which consists of a successive segmentation of the date set. In this analysis the dependent variable was relative yield increase and the predictor variables, soil test value, clay and organic matter content, soil pH, crop nutrient use efficiency and fertilizer application rate. The segmentation of the date goes on by introducing one by one the predictor variables and binary splitting the date into two groups differing in the probability of achieving the assumed yield increase. The segmentation process proceeds until the separate segments comprise at least 5% of the total date. The example of this procedure for phosphorus is presented, after Kuchenbuch and Buczko 2009] on figures (Fig. 10, 11). As results from these figures the endpoint segment 9 makes possible to achieve the relative yield increasing of 12%. This segment include the date characterized by P content below 4,4 mg P·100g⁻¹ soil, soil pH below 6,1, for the phosphorus rate above 39,3 kg P·ha⁻¹ and if the crop is sensitive for phosphorus supply.

**Fig. 11.** The content of available phosphorus STP versus yield increase for the endpoint segments (denoted by numbers) [Kuchenbuch, Buczko 2009].
It has been already stated that between numerous soil tests priority is given to universal solutions, which extract several nutrients in one procedure. The main reason is to simplify and make the laboratory procedure cheaper. However, the prerequisites are that this universal solution is grounded on theoretical principles, and the test is well calibrated, the single nutrient test alike. According to the author’s opinion, decisive factor for implementing new, universal soil test is, however, opening the broader horizons in the field of fertilizer recommendations. In Poland, the discussion has started on substituting the three contemporary used soils tests, Egner-DL for P and K, Schachtschabel for Mg and Rinkis for micronutrients, by one universal test based on Mehlich-III extract. This test is already in use in neighboring countries, Czech Republic, Slovak Republic and Latvia. Regardless of benefits in laboratory procedures this test offers the new possibility in refining the fertilizer recommendation for K, Mg, Na and Ca as well as for P fertilization. All listed cations are estimated in one solution. Therefore, the fertilizer recommendation can be based not only on critical values of each of them but on the percent saturation of soil cation exchange capacity as well. What concerns phosphorus is, that the level of soil saturation with this element can be indirectly calculated from the ratio of P to Al. So called active aluminum is one of the elements measurable also in Mehlich-III solution.

Soil’s tests are used not only in fertilizer recommendations but also to characterize the soil fertility on the farm, regional and/or country levels. The most often used score for this characteristic is the percent of soils falling in the particular nutrient’s availability class. It is as a rule done for each nutrient and soil pH separately. Lately, Filipiak (2010) has proposed a synthetic factor of soil fertility including soil texture, soil pH and the content of available forms of phosphorus, potassium and magnesium. The values of this index were calculated by factor analysis, using date from soil monitoring in Poland and have been split into five groups of soil fertility. Verification of the new factor has been made by analysis of variance against the crop yields and the individual soil characteristics. Both approaches prove the validity and usability of this factor (Table 4). The results of these investigations pose a novelty in the literature concerning soil agrochemical properties.

**Table 4. The average values of soil parameters in the classes of the index of soil fertility**

<table>
<thead>
<tr>
<th>fertility class</th>
<th>crop yield, t·ha⁻¹</th>
<th>pH</th>
<th>SOM</th>
<th>% silt</th>
<th>P₂O₅</th>
<th>K₂O</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>39,8 a</td>
<td>4,3 a</td>
<td>1,19 a</td>
<td>14,1 a</td>
<td>1,0 a</td>
<td>0,8 a</td>
<td>0,4 a</td>
</tr>
<tr>
<td>4</td>
<td>48,2 b</td>
<td>5,7 b</td>
<td>2,08 b</td>
<td>25,3 b</td>
<td>4,0 b</td>
<td>3,6 b</td>
<td>2,1 b</td>
</tr>
<tr>
<td>3</td>
<td>50,2 c</td>
<td>5,8 c</td>
<td>2,21 c</td>
<td>25,2 b</td>
<td>14,7 c</td>
<td>14,1 c</td>
<td>6,8 c</td>
</tr>
<tr>
<td>2</td>
<td>55,9 d</td>
<td>6,5 d</td>
<td>2,51 d</td>
<td>25,4 b</td>
<td>26,7 d</td>
<td>23,0 d</td>
<td>8,0 d</td>
</tr>
<tr>
<td>1</td>
<td>60,1 e</td>
<td>6,8 e</td>
<td>2,71 e</td>
<td>24,8 b</td>
<td>53,2 e</td>
<td>39,6 e</td>
<td>10,0 e</td>
</tr>
</tbody>
</table>

The same letter means no significant difference.
Summary

1. Plant test estimates the plant nutritional status, related to the plant growth rate. Soil test measures the content of available nutrient in the soil, deciding upon absorption of this nutrient by plant roots.

2. Plant tests can be split into straight and complex ones. The former can be further split into direct (destructive) and indirect (non destructive). Plant tests are not directly related to plant’s fertilizer requirements.

3. The best direct plant test is NNI index and indirect one the greenness index SPAD. Both tests are relatively insensitive to plant growth stage, but SPAD index must be calibrated for a specific crop variety.

4. NDVI index needs further developments, because it depends simultaneously on canopy density and chlorophyll content in the plants.

5. Chemical soil tests are so good, as good is their calibration. Calibration procedure can be split into direct based on plant indices and indirect against another already calibrated test.

6. The new developments in calibration of $N_{\text{min}}$ and $K_{\text{DL}}$ soil tests are presented.

7. Soil test must not be handled quantitatively, and it only predicts the probability of getting some yield increases under the influence of fertilization with the particular nutrient.

8. Soil fertility can be characterized by one synthetic factor, including all soil parameters measured by agrochemical laboratories.

Literature


Bergmann, W., Neubert P. 1976. Pflazendiagnose und Pflazenanalyse. VEB Fischer Verlag, Jena


New developments in soil testing and plant analysis


Fotyma, M., Kęsik, K., Pietruch Cz. 2010. Mineral nitrogen in soils of Poland as and indicator of plant nitrogen requirements and soils water cleanness (in Polish). Nawozy i Nawożenie – Fertilizers and Fertilization. 38: 5-83


Prof. Mariusz Fotyma  
Department of Plant Nutrition and Fertilization  
Institute of Soil Science and Plant Cultivation – State Research Institute  
Czartoryskich 8, 24-100 Pulawy, Poland  
fot@iung.pulawy.pl
THE EFFECT OF LONG-TERM FERTILIZATION ON THE SOIL STRUCTURE

Irena Suwara, Wiesław Szulc
University of Life Sciences, Warsaw

Abstract

In the paper, the results concerning the influence of different fertilization systems on the soil structure, based on two long-term experiments, carried on in the years 1990 and 1993 at Experimental Station Łyczyn are presented. The fertilization systems significantly influenced soil structure. Manure and lime application increased index of soil structure, the mean weight diameter of crumb and water aggregate stability. High rate of mineral fertilizers decreased the index of soil structure and the water resistance of soil aggregates in comparison to control treatment. The most favourable effect on soil structure exerted farmyard manure supplemented by limestone and mineral fertilizers.

Key words: long-term experiment, fertilization systems, soil structure, water resistance of soil aggregates.

Introduction

Soil structure is one of the most significant factors affecting soil fertility and counteracting its degradation. The soil characterized by good aggregate stability is less prone to erosion, less susceptible to compaction and has better water-air conditions [Domżał and Pranagal 1994, Kędziora 2007, Lenart et al. 2005, Pagliai et al. 2004, Piechota 2005, Suwara 2010]. The uses of heavy machines, intensification of mineral fertilization and limiting the number of crops in rotation, have negative environmental consequences and endanger the basic functions of agricultural areas. The main threats for arable land are deterioration of soil structure, decrease of soil water retention and intensification of water and wind erosion. Good indicator of soil quality is the durable soil structure.

The effect of long-term fertilization on the soil structure

on soil productivity by increasing organic carbon inputs into the soil and improving soil structure [Christensen 1997, Gawrońska-Kulesza and Suwara 1989, Lenart and Gawrońska-Kulesza 1992, Lenart 2002, Piechota 2005, Suwara and Gawrońska-Kulesza 1994, Suwara et al. 2005, Suwara 2010, Weill et al. 1988]. In these studies application of farmyard manure improved the soil structure against the control treatment and solely mineral fertilizers. However, the opinions concerning the role of mineral fertilizers are somewhat contradictory. Many researches have not confirmed the negative impact of mineral fertilizers (NPK) on the soil structure [Lenart 2002, Piechota 2005, Suwara and Gawrońska-Kulesza 1994]. Some other authors [Suwara et al. 2005, Suwara 2010] claim that mineral fertilizers applied without liming decreased water resistance of soil aggregates in comparison to control treatment and treatment with farmyard manure application. These differences most probably result from different weather and soil conditions in which experiments have been carried on.

The aim of the own research was to determine the influence of different fertilization systems on selected parameters of soil structure.

Materials and methods

Long-term fertilization experiments were established at Łyczyn near Warsaw (52°05′ N, 21°09′ E) on loess derived soil, with light loamy sand texture, belonging to rye good complex. According to FAO, this soil is Albie Luvisols characterized by Ap–Eet–Bt–C horizons. The first experiment A has been carried on since 1960 in four-course crop rotation, including potatoes, spring barley, winter oilseed rape, winter rye. The second experiment B was established in 1968 with the same crop rotation, but winter wheat was grown instead of winter rye. The treatments in one factorial, in four replication experiments are listed below:

– experiment A: 0-control without fertilization, NPK-mineral fertilization, Ca-liming, CaNPK-mineral fertilization with liming, FYM-farmyard manure, FYM+NPK-farmyard manure with mineral fertilization, FYM+Ca-farmyard manure with liming, FYM+Ca+NPK -farmyard manure with liming and mineral fertilization;

– experiment B: Ca-control with liming, CaNPKm-middle level of mineral fertilization with liming, CaNPK-high level of mineral fertilization with liming, FYM+Ca-farmyard manure with liming, FYM+CaNPKm-farmyard manure with liming and middle level of mineral fertilization, FYM+CaNPK-farmyard manure with liming and high level of mineral fertilization.

In both experiments, the rate of 1.6 t CaO·ha⁻¹ was applied every 4th years, and farmyard manure was applied at the rate 30 t·ha⁻¹ under potatoes and 20 t·ha⁻¹ under winter oilseed rape. In experiment A, the average yearly dose of mineral fertilizers in crop rotation is 334 kg NPK per hectare and in experiment B, at the middle level
of mineral fertilization, the dose is 144 kg NPK per hectare and at the high level -288 kg NPK per hectare. In experiment A, the pH of the arable soil layer was between 4,1 and 7,2 and in experiment B, pH was 6,3.

Soil samples (about 2,5 kg) from the plough layer (0-25) were collected in 1990 in experiment B, after winter wheat and in 1993 in experiment A, after winter rye. Soil moisture at the time of sampling was between 5,9 and 6,5%. Soil samples were air-dried and sifted by 10 mm mesh sieve. Further on the fraction below 10 meshes (500g-samples) has been sifted for 2 minutes on a set of sieves 7, 5, 3, 1, 0,5 and 0,25 mesh. The aggregates remaining on each sieve were weighed and the percentage of each fraction has been calculated.

On this base the mean weight diameter of aggregates (MWDa), index of misting of soil aggregates (Wr) and of soil structure (K) were calculated [Rewut 1980]:

\[
K = \frac{\% \text{ share of aggregates in diameter } 0.25-7 \ mm}{\% \text{ share of aggregates in diameter } <0.25 \ mm \text{ and in diameter } >7 \ mm}
\]

\[
Wr = \frac{\% \text{ share of aggregates in diameter } <0.25 \ mm}{\% \text{ share of aggregates in diameter } >0.25 \ mm}
\]

To obtain a representative soil sample for water resistance of soil aggregates analysis, after dry sifting, 10% from each fraction of aggregates was taken, joined and gave an average 50g soil sample. This sample was used to determine the water resistance of soil aggregates by the method of wet sifting according to Baksheev [Roszak i in. 1997].

In the analysis of water resistance a separator for soil aggregates was used with a set of sieves with 7; 5; 3; 1; 0,5 and 0,25 mm meshes, constructed in the Institute of Agrophysics of the Polish Academy of Sciences, Lublin [Roszak i in. 1997]. The analysis was conducted for 12 minutes. The aggregates from each sieve were air-dried, weighed and the results were calculated in per cents in relation to the initial sample weight.

The stability of the granular structure was expressed by the mean weight diameter of crumb (MWDg) and index of water resistance (Ww):

\[
Ww = \frac{MWDg}{MWDa} \cdot 100 \ [%]
\]

The obtained results concerning K, Wr, MWDa, MWDg and Ww were calculated statistically by analysis of variance and tested by Tukey’s test.
The effect of long-term fertilization on the soil structure

Results

The fertilization system significantly affected the index of soil structure (K) in both experiments (fig. 1). In experiment A, application of farmyard manure and liming increased the percentage of desirable soil aggregates in diameter between 0.25 and 7 mm (index K) in comparison to control (0) and mineral fertilization (NPK) treatments. Application of high doses of mineral fertilizers decreased by 9.4% the index of soil structure against a control. The positive influence of farmyard manure on the index of soil structure was also observed in experiment B. The highest value of this soil parameter has been found in treatment with lime, farmyard manure and mean doses of NPK (FYM+CaNPKm).

Figure 1. Index of soil structure (K) depending on fertilization.

a) experiment A – 1993,

b) experiment B – 1990.

Index of soil misting (Wr) (fig. 2) was significantly depended on the fertilization system as well. In both experiments, the lowest percentage of an aggregates’ fraction <0.25 mm in soil was observed in the treatment with farmyard manure application. The results of experiment A showed that liming application decreased the amount of undesirable microaggregates (<0.25 mm).
The fertilization system differentiated not only the aggregate composition of soil but also the mean weight diameter of aggregate (MWDa) and crumb (MWDg) and index of soil water resistance (Ww) (Tab. 1 and 2). The mean weight diameter of aggregate (MWDa) in the soil from experiment A fluctuated between 0,62 and 0,95 mm. The highest MWDa characterized soil in treatments with lime and manure application (0,90-0,95 mm), and the lowest was obtained in treatments with mineral fertilization (NPK) and in control (0,62-0,63 mm). Application of lime increased MWDa at about 36,5% and applying farmyard manure at about 26,5% relative to not fertilized soils. In experiment B under the influence of manure, an increase of mean weight diameter of aggregate (MWDa) was also observed.
Table 1. Parameters characterizing the soil structure in experiment A (1993).

<table>
<thead>
<tr>
<th>Fertilization</th>
<th>without FYM</th>
<th></th>
<th>with FYM</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MWDa</td>
<td>MWDg</td>
<td>Ww (%)</td>
<td>MWDa</td>
<td>MWDg</td>
</tr>
<tr>
<td>0</td>
<td>0.63</td>
<td>0.50</td>
<td>79.4</td>
<td>0.70</td>
<td>0.63</td>
</tr>
<tr>
<td>NPK</td>
<td>0.62</td>
<td>0.42</td>
<td>67.7</td>
<td>0.68</td>
<td>0.56</td>
</tr>
<tr>
<td>Ca</td>
<td>0.75</td>
<td>0.58</td>
<td>77.3</td>
<td>0.90</td>
<td>0.80</td>
</tr>
<tr>
<td>CaNPK</td>
<td>0.83</td>
<td>0.60</td>
<td>72.1</td>
<td>0.95</td>
<td>0.84</td>
</tr>
<tr>
<td>LSD$_{0.05}$</td>
<td></td>
<td></td>
<td></td>
<td>MWDa 0.08; MWDg 0.07; Ww 8.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Parameters characterizing the soil structure in experiment B (1990).

<table>
<thead>
<tr>
<th>Fertilization</th>
<th>without FYM</th>
<th></th>
<th>with FYM</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MWDa</td>
<td>MWDg</td>
<td>Ww (%)</td>
<td>MWDa</td>
<td>MWDg</td>
</tr>
<tr>
<td>Ca</td>
<td>0.45</td>
<td>0.40</td>
<td>88.9</td>
<td>0.56</td>
<td>0.50</td>
</tr>
<tr>
<td>CaNPK$_m$</td>
<td>0.54</td>
<td>0.42</td>
<td>77.8</td>
<td>0.75</td>
<td>0.69</td>
</tr>
<tr>
<td>CaNPK</td>
<td>0.44</td>
<td>0.35</td>
<td>79.5</td>
<td>0.74</td>
<td>0.65</td>
</tr>
<tr>
<td>LSD$_{0.05}$</td>
<td></td>
<td></td>
<td></td>
<td>MWDa 0.10; MWDg 0.08; Ww 10.1</td>
<td></td>
</tr>
<tr>
<td>NIR$_{0.05}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MWDa– mean weight diameter of aggregate, MWDg– mean weight diameter of crumb, Ww– index of water resistance

The mean weight diameter of crumb (MWDg) in both experiments was the highest in the treatments with lime, manure and mineral fertilizers application (Tab. 1 and 2). In experiment A mineral fertilization (NPK) applied without liming decreased the MWDg at about 16% compared to control (Tab. 1). In experiment B at high level of mineral fertilizers the smallest MWDg was recorded in spite of liming (Tab. 2). It can be concluded that the influence of mineral fertilizers on soil structure largely depends on their doses.

The water resistance analysis showed differences between the compared treatments in both experiments (Tab. 1 and 2). The highest water resistance of aggregates was recorded in the soil with manure application. The smallest stability of aggregates was observed in the soil where mineral fertilizers (NPK, CaNPK) were applied only.
From these studies it can be found that changes occurring in the soil structure are caused by the influence of fertilizers and manures. Systematic applying of farmyard manure every 2 years and liming every 4 years with mineral fertilizers assured the most favourable aggregate composition of the soil. This has been confirmed by many authors [Gawrońska-Kulesza and Suwara 1989, Lenart 2002, Suwara et al. 2005, Suwara 2010]. Obtained results confirm a very strong favourable action of farmyard manure including liming on soil structure, particularly on aggregate stability. This seems to be associated with a continuous supply of organic substance to the soil which created appropriate conditions of the formation of aggregates more resistant to the disintegrating action of water. This role of farmyard manure in the formation of soil structure has been established in numerous papers [Grzebisz 1988, Kłosowski and Mercik 1980, Lenart 2002, Lenart and Gawrońska-Kulesza 1992, Suwara 1999, Suwara et al. 2005, Suwara 2010]. It has been proved that liming together with farmyard manure and mineral fertilization had the most favourable influence on soil structure. To sum up, the greatest improvement of the soil structure was caused by liming applied together with FYM and NPK.


Conclusions

1. The long-term differentiated fertilization is a factor modifying significantly soil structure.
2. Regular application of farmyard manure and limestone are the prerequisites of good soil structure.
3. Mineral fertilizers applied in high doses influence negatively soil structure, even against the treatment without fertilization.

References


The effect of long-term fertilization on the soil structure


Dr hab. Irena Suwara
Warsaw University of Life Sciences (SGGW), Department of Agronomy
Nowoursynowska 159,
02–776 Warsaw, Poland
E-mail: irena_suwara@sggw.pl
Abstract

The phosphorus balance sheet for the years 1996–2009 was calculated, based on the results obtained in permanent field experiments carried on at the Experimental Station Skierniewice belonging to Life University. Field A with free crop rotation without manure and without leguminous crops, field D with rye monoculture without manure, and field E with a five-course crop rotation and manure application have been selected for these investigations. In each field two treatments, without phosphorus and with phosphorus was taken into consideration. Balance sheet included the input of phosphorus in fertilizers, output in harvested plant products and changes in the total and/or available phosphorus in the soils.

In the fertilized treatment, the phosphorus surplus was recorded, which has been reflected in changes of the total and to a smaller extent in available phosphorus content. In the light soils showing low sorption capacity, about half of the phosphorus surplus migrated down the soil profile. In the control treatment, crops have taken up significant amounts of phosphorus from the not-readily-available forms, depleting both the topsoil and the deeper layers of the soil profile. Anyhow, the rates of total and available forms of phosphorus increases in the fertilized treatments were higher than the rates of its depletion in the control treatment. The migration of phosphorus surplus down the soil profile was the greatest in the rye monoculture, smaller in free crop rotation and the smallest in five-course crop rotation.

Key words: phosphorus balance sheet, total phosphorus, available phosphorus, long term experiments

Introduction

It is commonly believed that about 20 % phosphorus from mineral fertilizers only is utilized in the first year after its application. The unused phosphorus remaining
in the soil undergoes various transformations leading to the creation of forms with different degrees of availability to plants [Sądej 2000, Zhang et al. 2004]. Increasing the pool of available phosphorus contributes to a better supply of this element to plants. However, systematic accumulation of phosphorus in the soil can lead to exceed its sorption capacity and to an uncontrolled loss of this element beyond the soil-plant system. The extent of these processes depends on many factors such as soil type, soil pH, climatic conditions, fertilizer rate, and the crop rotation [Black et al. 2003, Bunemann et al. 2006, Ekholm et al. 2005]. Due to soil variability and a relatively slow rate of transformation processes, an assessment of the quantitative changes undergone by phosphorus in the soil can be made most accurately in long-term experiments. Such experiments are carried out in many European countries [Benbih et al. 1999, Black et al. 2000, Colomb et al. 2007, Ellmer et al. 2000, Gransee et al. 2000, Saarela et al. 2004].

In the own research, the advantage of the long-term fertilization experiments which has started in Skierniewice in 1923, was taken. On the base of this experiment, the balance sheet for phosphorus in the years 1996–2009 was calculated. For this purpose, the quantitative changes in the content of total and available phosphorus in the soil profile were evaluated against the differences in phosphorus inputs in fertilizers and outputs with crop yields, in three crop rotations.

**Materials and methods**

Field permanent experiments are carried on since 1923 in Exp. Station Skierniewice on a typical podzolic soil classified by FAO as Haplic Luvisols. The clay content (ř <0.002 mm) is 7–8% in the Ap horizon (0–25cm), 4-5% in the Bt horizon (25–45 cm) and 13–15% in the Bt and C horizons (>45 cm). A detailed description of these experiments, including soil and climatic conditions, for a period of many years can be found in the paper produced by Moskal et al [1999]. Three crop rotation systems, A, free rotation without FYM and without leguminous crops, D, rye monoculture, and E, five-course rotations are maintained. In the last rotation potatoes on FYM, spring barley, leguminous crops (mostly clover), winter wheat and rye are grown. From several fertilizer treatments, the ones with phosphorus (CaNPK) and without phosphorus (CaNK) were selected. The fertilizer rates 90 kg N ha⁻¹ as ammonium nitrate, 26 kg P ha⁻¹ as superphosphate and 91 kg K ha⁻¹ as potassium chloride have been applied since 1976. Limestone was applied every fourth- fifth year at a rate of 1600-2000 kg CaO ha⁻¹.

Soil samples were collected in the year 1996 and then in 2009 from the soil layers Ap, Eet and Bt and stored in the laboratory in air-dry condition. In samples, the available phosphorus according to Egner- DL method and total phosphorus after digestion in aqua regia (only in Ap layer) have been determined colorimetrically by the vanadium-molybdenum method. Plant samples, collected in all years have been
analyzed for the phosphorus content by the same method after mineralization in the mixture of HNO₃ and HClO₄. Phosphorus balance sheet was calculated for each treatment according to the formulae:

\[ P_{\text{balance}} = P_{\text{input}} - P_{\text{output}} +/\ - P_{\text{difference}} \]

where: \( P_{\text{input}} \) – amount of phosphorus in manure and superphosphate, \( P_{\text{output}} \) – amount of phosphorus removed with crop yield, \( P_{\text{difference}} \) – difference in the amounts of total P in Ap soil layer (soil density 1.5 g cm\(^{-1}\)).

Results

Phosphorus uptake by plants

The yield of the main crop products for the years 1996–2009, has been presented in the paper of Sosulski et al. (this issue) and are not discussed here. The average phosphorus content in the crop products and phosphorus uptake by crops are included in table 1.

The content of phosphorus in crop products and the uptake of this element with the crops depended on crop rotation and phosphorus fertilization. The highest values of both characteristics have been found in rotation E, with farmyard manure application. Phosphorus fertilizers (CaNPK) increased considerably the content and uptake of phosphorus in comparison to the control treatment (CaNK). The content and uptake of phosphorus by rye grown in monoculture (D) was lower than by rye in free rotation (E) do not mention the rye grown in five-course rotation with manure (E).
**Table 1.** Phosphorus content [g P kg\(^{-1}\) d.w.] in crop plants and phosphorus uptake [kg P ha\(^{-1}\) year\(^{-1}\)] by crops, depending on fertilization and crop rotation, average for the years 1996–2009

<table>
<thead>
<tr>
<th>Field</th>
<th>Crop</th>
<th>P content [g kg(^{-1}) d.w.]</th>
<th>P uptake [kg ha(^{-1}) year(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CaNK</td>
<td>CaNPK</td>
</tr>
<tr>
<td>D</td>
<td>Rye</td>
<td>2,53</td>
<td>2,98</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>0,49</td>
<td>0,62</td>
</tr>
<tr>
<td></td>
<td>Wheat</td>
<td>3,12</td>
<td>3,60</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>0,63</td>
<td>0,90</td>
</tr>
<tr>
<td></td>
<td>Rye</td>
<td>3,14</td>
<td>3,20</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>1,02</td>
<td>0,51</td>
</tr>
<tr>
<td></td>
<td>Clover</td>
<td>2,05</td>
<td>2,60</td>
</tr>
<tr>
<td></td>
<td>Barley</td>
<td>3,44</td>
<td>3,88</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>1,05</td>
<td>1,23</td>
</tr>
<tr>
<td></td>
<td>Potato</td>
<td>2,14</td>
<td>2,23</td>
</tr>
<tr>
<td></td>
<td>Triticale</td>
<td>3,26</td>
<td>3,86</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>0,76</td>
<td>0,87</td>
</tr>
<tr>
<td></td>
<td>Rye</td>
<td>3,10</td>
<td>2,97</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>0,49</td>
<td>0,68</td>
</tr>
<tr>
<td></td>
<td>Barley</td>
<td>3,28</td>
<td>3,64</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>0,98</td>
<td>1,12</td>
</tr>
<tr>
<td></td>
<td>Potato</td>
<td>2,20</td>
<td>2,01</td>
</tr>
<tr>
<td></td>
<td>Wheat</td>
<td>2,91</td>
<td>3,12</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>0,64</td>
<td>0,76</td>
</tr>
<tr>
<td></td>
<td>Mustard</td>
<td>3,98</td>
<td>4,4</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>1,10</td>
<td>1,2</td>
</tr>
<tr>
<td></td>
<td>Green maize</td>
<td>2,04</td>
<td>2,7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

D-rye monoculture without FYM, E-five-field rotation with FYM, A - free rotation without FYM
The fate of phosphorus in the soil and the balance of this element in long-term field experiments

Total and available phosphorus content in the soil

The total and available phosphorus content in soil samples collected at the beginning (1996), and the end (2009) of the period covered by this research is presented in table 2. By interpreting these data it should be kept in mind that the research period was 14 years only, while the period from the beginning of this experiment counted 73 years. Already at the beginning of the research period (1996) the average for a rotation’s differences in the total topsoil phosphorus content between CaNPK and CaNK treatments was 140 mg P kg\(^{-1}\) soil, while during this period until 2009 has increased to 190 mg P kg\(^{-1}\) soil, i.e. by about 35%. It can be therefore concluded that the rate of increasing the difference in the total P content in topsoil between treatments in comparison was much faster in the last 13 years, than in the 73 years which went by from the beginning of this experiment. It results from the fact that in the research period (1996–2009) the content of total phosphorus in CaNPK treatment increased on average by 37 mg P kg\(^{-1}\) soil, while in CaNK treatment decreased by 12 mg P kg\(^{-1}\) soil, only. One can therefore conclude that the soil phosphorus reserves in the treatment without fertilization are seriously depleted. The same regularities, even stronger manifested concern the content of available phosphorus in the topsoil. During the research period, the content of available phosphorus increased on average by 7.2 mg P kg\(^{-1}\) soil in CaNPK treatment and decreased by marginal value of 1.4 mg P kg\(^{-1}\) soil in the CaNK treatment. It means that in this treatment, crops are forced to exploit the non-available forms of phosphorus. The above-described differences in increasing and/or decreasing total and available phosphorus content in the topsoil were, to some extent, counteracted by manure application in E rotation and manifested the most in rye monoculture D.

Table 2. Amounts of total phosphorus in the topsoil in the years 1996 and 2009, and of available phosphorus in three layers of soil in 2009, depending on fertilization and crop rotation (mg P kg\(^{-1}\) soil)

<table>
<thead>
<tr>
<th>mg P kg(^{-1}) soil</th>
<th>A</th>
<th>E</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CaNPK</td>
<td>CaNK</td>
<td>CaNPK</td>
</tr>
<tr>
<td>Total P</td>
<td>344</td>
<td>379</td>
<td>198</td>
</tr>
<tr>
<td>Available P 0–25 cm</td>
<td>51.6</td>
<td>62.4</td>
<td>10.6</td>
</tr>
<tr>
<td>25–45 cm</td>
<td>26.2</td>
<td>4.0</td>
<td>23.3</td>
</tr>
<tr>
<td>45–65 cm</td>
<td>13.3</td>
<td>4.2</td>
<td>15.3</td>
</tr>
</tbody>
</table>

D-rye monoculture without FYM, E-five-field rotation with FYM, A - free rotation without FYM
The processes of enriching the soil in available phosphorus in CaNPK treatment and depleting in CaNK treatment concern deeper soil layers as well. The average difference of P-DL content between these treatments was 13.2 mg P kg\(^{-1}\) soil in the soil layer 25–45 cm and 6.9 in the soil layer 45–65 cm. It means that the surplus of phosphorus from fertilizers is partly moved down the soil profile while crops not fertilized with this element absorb it also from the subsoil.

**Phosphorus balance sheet**

The phosphorus balance sheet was drawn up for three crop rotations that can be associated with three types of farms, combined plant production without livestock (A), mixed agricultural production with livestock (E), simplified plant production without livestock (D). Balance calculations for phosphorus include rates of mineral fertilizers and manure, uptake by plants and changes in the total phosphorus content in the arable soil layer, over 14 years (1996–2009) (Tab. 3).

**Table 3.** Balance sheet for superphosphate phosphorus in the topsoil, depending on crop rotation and fertilization in the years 1996–2009

<table>
<thead>
<tr>
<th>Components [kg P·ha(^{-1}) year(^{-1})]</th>
<th>Crop rotation and fertilization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>CaNPK</td>
</tr>
<tr>
<td>P input in fertilizers superphosphate</td>
<td>26</td>
</tr>
<tr>
<td>manure</td>
<td>0</td>
</tr>
<tr>
<td>P uptake by plants total from superphosphate</td>
<td>14.2</td>
</tr>
<tr>
<td></td>
<td>3.6</td>
</tr>
<tr>
<td>% utilization of P from superphosphate</td>
<td>13.8</td>
</tr>
<tr>
<td>input – uptake from superphosphate</td>
<td>22.4</td>
</tr>
<tr>
<td>gain (+) or loss (-) in topsoil(^*)</td>
<td>9.4</td>
</tr>
<tr>
<td>uptake from deeper soil layers</td>
<td></td>
</tr>
<tr>
<td>loss from arable layer</td>
<td>13.0</td>
</tr>
<tr>
<td>% of loss relative to rate</td>
<td>50.0</td>
</tr>
</tbody>
</table>

\(^*\) total P, recalculated from the table 2 for the soil layer 25 cm thick and soil density 1.5 g cm\(^{-3}\)
The fate of phosphorus in the soil and the balance of this element in long-term field experiments

Considering that superphosphate stimulates neither the phosphorus uptake from the soil (all rotations) nor from manure (rotation E), phosphorus utilization from this fertilizer ranges between 13.6 and 16.5%. The surplus of phosphorus in CaNPK treatment accumulates partly in the topsoil (38–53%) and partly moved down the soil profile. The deficiencies of phosphorus in CaNK treatment were balanced partly by the phosphorus uptake from the topsoil (37–48%) and partly from the subsoil. It is worth noting that the highest share of phosphorus uptake from the subsoil was found in rotation E with manure application.

Discussion

The effect of fertilization with phosphorus on the increase in yield and uptake of this component by plants was not always clear. Many studies show that depending on the initial status of phosphorus in the soil for the first few or even more than a dozen years of experiments, there was no significant effect of the size of the dose of phosphorus on the crop yield and uptake of this component by plants [Colomb et al. 2007, Gallet et al. 2003]. In the experiments in Skierniewice, in which varied fertilization regimes have been applied since 1923, the effect of superphosphate fertilization on yield, chemical composition of plants and phosphorus uptake by crops became apparent already in earlier years [Mercik et al. 2000, Stępien and Mercik 1999]. In the years 1996–2009, which are the subject of this analysis, irrespective of the crop rotation scheme used (A or E), the absence of “fresh fertilizer strength” over many years was responsible for significantly lower phosphorus levels in plants, both in the primary and secondary crops (CaNK), compared with the plants fertilized every year with superphosphate (CaNPK) (Table 1). Both the grain and straw of the rye grown in monoculture (D) contained less of this component compared with the rye grown in rotation (A and E). The highest P content in the plant was obtained in rotation with a leguminous plant and an additional dose of phosphorus in the form of manure (Field E). Barley, wheat and potatoes responded to fertilization with manure in a similar way. The consequence of lower yields and lower phosphorus levels in the crops grown on the plots not fertilized with superphosphate was a lower uptake of this component in relation to the plots with full mineral fertilization (CaNPK). The results of P uptake by plants indicate that the reduction in this uptake in the case of CaNK fertilization in relation to full CaNPK fertilization ranged from 9% (barley, field E) to 40% (clover, field E). Rye grown in rotation coped better with the lack of phosphorus fertilization, where the fall in P uptake in the case of CaNK fertilization was 11–20%, while in the cultivation of rye in monoculture this decrease was 35%. Application of FYM once every five years eliminated the decrease in phosphorus uptake by plants on CaNK plots relative to CaNPK (field E) compared with the corresponding combinations in the field A. However, it should be emphasized that the extent of phosphorus uptake by plants grown in the experiments in Skierniewice...
in the period under consideration, here was slightly lower than the average uptake calculated for the period 1967–1997 [Stepień and Mercik 1999].

It is generally believed that phosphorus does not move much along the soil profile, which means that the impact of fertilization on the quantitative changes in this component in the soil should be seen mainly in the topsoil and depend on the P dose and the positive balance of P [Colomb et al. 2007, Sądej 2000]. From the point of view of plant nutrition, of significance is the available phosphorus content in the soil, especially in the arable layer. On the plots fertilized with CaNPK, only slightly higher levels of available phosphorus were found in field A in comparison with field D. In spite of the additional application of P with manure, the lowest levels of this component were obtained in the topsoil of field E. This may be due to a higher phosphorus uptake by plants in this field than in the other two fields, as well as to the possibility of increased migration of phosphorus derived from organic fertilizers [Gosek 2002]. The systematic use of phosphorus at the rate of 26 kg P ha\(^{-1}\), i.e. in excess of the rate of uptake by plants (average 4.0–4.4 kg P ha\(^{-1}\) year\(^{-1}\)) caused only a slight increase in the available phosphorus content (4.5 to 10.8 mg P kg\(^{-1}\) soil). Much greater changes during the studied period occurred in the levels of total phosphorus (32–43 mg P kg\(^{-1}\) soil) in the topsoil. A similar relationship as to the rate of accumulation of excess phosphorus fertilizers in the soil has also been observed in other long-term fertilization experiments [Black et al. 2003, Carlgren and Mattsson 2001, Saarela et al. 2004, Ellmer et al. 2000]. As research by Colomb et al. [2007] has shown, the rate of accumulation of phosphorus in the soil depends on the initial status and the dose of phosphorus, but only the initial increase in P in the soil is rapid, after which it begins to decline steadily. More uniform, however, is the decrease in the total phosphorus content over time due to the negative phosphorus balance. The available phosphorus content determined in 2009 in the three layers of the soil profile, regardless of the crop rotation and fertilization regimes, was the highest in the arable humus layer (9.8–62.4 mg P kg\(^{-1}\) soil) and decreased with the depth of the soil profile. Much smaller variation in this component can be seen in the profile of those plots on which fertilization with superphosphate is not carried out. In the Bt horizon, mostly the smallest amounts of available phosphorus were found, and the differences between the various fertilization combinations are the smallest there. The highest amounts of available phosphorus in the deepest layer of the soil can be found on those plots where fertilization with FYM is applied (field E). This confirms the more rapid migration of phosphorus from organic fertilizers than from superphosphate, as reported by Black et al. [2000] and Gosek [2002].

Previously, on the same fields, for a period of 30 years, this utilization was significantly higher and amounted to 28–30% [Moskal et al. 1999]. However, one should take into account the increase in the phosphorus application rate that occurred in 1976, from 22.6 to 26 kg ha\(^{-1}\) year\(^{-1}\), which usually translates into lower utilization of the component from the fertilizer. A decrease in the uptake of phosphorus by maize during the experiment was reported by Benbi and Biswas [1999], where
at the beginning it was more than 31% and after 20 years, it fell to 11%. In our study, the highest utilization of phosphorus from superphosphate was 16.5%. This level of utilization was obtained in the system of cultivation with manure and a papilionaceous plant (E). On the fields under free crop rotation without manure and with rye monoculture, where only mineral fertilization is applied, this utilization was slightly lower and amounted to 13.8% (A) and 14.6% (D).

Taking into account the amount of phosphorus introduced in mineral fertilizers and manure, and the extent of P uptake by plants, it was calculated by how much, theoretically, the total P content should have changed in the topsoil over the examined 14-year period of experiments. Low utilization of phosphorus from superphosphate should have caused accumulation of P in the arable layer of soil in the amount of over 22 kg P each year, regardless of the system of crop rotation. Taking into account the density of the soil and the changes in the total phosphorus content, the actual increase in this component in the topsoil was calculated. Depending on the field, these increments ranged from 8.6 to 11.5 kg P per year. These amounts were thus clearly smaller than those based on the P doses and P uptake by plants. So there was significant migration of P to deeper layers. The largest migration to deeper soil layers occurred in the field with rye monoculture (52.3%), slightly smaller in the system without manure, under free crop rotation in field A (48%), and the smallest in field E (39%). Similar results for rye monoculture (field D) were obtained by Szczurek [1973]. Low levels, particularly in the arable layer, of clayey components in the soils in Skierniewice may be one of the reasons for the low sorption capacity towards phosphorus, which are crucial to retaining phosphorus in the soil [Black et al. 2003].

The changes in available phosphorus that occurred at the same time indicate that only small amounts of the balance surplus remain in the arable layer of the soil in the forms available to plants. Migration of significant quantities of fertilizer-derived phosphorus unused by plants from the arable layer of the soil deeper into the soil profile, with a considerable balance surplus of fertilizer phosphorus, have also been recorded in other long-term experiments [Bunemann et al. 2006, Ellmer et al. 2000, Gransee and Merbach 2000, Mercik and Stepien 2000]. The steady increase in the amount of phosphorus migrating from the topsoil deeper into the soil profile can, however, after exhausting the sorption capacity of the soil, lead over time to the leaching of phosphorus into the groundwater, making it vulnerable to eutrophication [McDowell et al. 2001, Pautler and Sims 2000].

On the plots not fertilized with superphosphate or manure, the crop plants took up from 7.7 to 10.6 kg P per hectare annually. This phosphorus came largely from the forms not readily available, more of which were depleted during the examined period than of those of available phosphorus. More than half of the phosphorus taken up on those plots came from the deeper soil layers. Similar observations have also been made in other experiments, in which a prolonged lack of fertilization or fertilization with insufficient quantities of phosphorus, with a negative P balance on the balance sheet, indicates the possibility of this component being taken up from the forms
which are not readily available and which come not only from the topsoil but also the deeper layers of the soil profile. It remains to be explained which phosphorus fractions are the easiest for plants to use. However, it can be supposed that of crucial importance in this process are organic acids exuded by the roots, which, apart from releasing phosphorus from the forms that are not readily available, contribute to the development of many microorganisms. In the rhizosphere of many crop plants there exist mycorrhizal fungi, which show the greatest activity in the release of phosphorus from the forms not readily available to plants into the environment [Gransee and Merbach 2000].

Conclusions

1. In the conditions of the experiments a balance-sheet equilibrium for phosphorus can be achieved by applying about 15 kg P ha\(^{-1}\)·year\(^{-1}\) in mineral fertilizers.

2. The positive phosphorus balance lasting for dozens of years caused an increase in the amount of total phosphorus in the soil, and to a lesser extent in the amount of available phosphorus. The rate of increase in the amounts of both forms of phosphorus under the influence of the balance surplus was greater than the rate of depletion of phosphorus from the soil by crop plants in the absence of fertilization with this component.

3. In light soils with a low sorption capacity for phosphorus more than half of the balance surplus of phosphorus applied as superphosphate migrated from the topsoil deeper into the soil profile, increasing there mainly the levels of the not-readily-available forms, and only slightly the amount of available phosphorus.

4. Abandoning fertilization with phosphorus over many years led to a significant uptake of this component (7,7–13,2 kg ha\(^{-1}\) year\(^{-1}\)) from the not-readily-available forms, which came not only from the topsoil but also from the deeper layers of the soil profile.

5. In the cultivation of rye in monoculture without manure there is greater migration of the phosphorus balance surplus (52%) into the soil profile than in the cultivation of rye under five-field rotation with manure and a papilionaceous plant (39%).

References


Sosulski, T., Mercik, S., Stępień, W., Szara, E. 2011. Crop fields, nitrogen content in the soil and nitrogen balance in long-term fertilization experiments. [this issue].


Ewa Szara
Warsaw University of Life Sciences-SGGW
Department of Soil Environment Sciences
Nowoursynowska 159, 02-776 Warszawa
ewa_szara@sggw.pl
CROP YIELDS AND NITROGEN BALANCE IN LONG-TERM FERTILIZATION EXPERIMENTS

Tomasz Sosulski, Wojciech Stępień, Stanisław Mercik, Ewa Szara

University of Life Sciences-SGGW, Warsaw

Abstract

The permanent field experiments have been carried on since 1923 at Experimental Station Skierniewice, belonging to Warsaw University of Life Sciences. In these fertilization experiments, the crop response to the withdrawal of nitrogen and/or phosphorus and potassium in relation to complete mineral fertilization (CaNPK, NPK) is investigated. Crops are grown in three rotations: arbitrary rotation without a leguminous plant and without manure, five-course rotation with a leguminous plant and with manure, and rye, or potato monoculture. Crop yields and changes in the soil chemical properties are published every 10-15 years. The paper concerns crop yields and nitrogen balance, in the last 15 years.

Key words: long –term field experiments, crop rotation, nitrogen balance

Introduction

Permanent field experiments are invaluable for assessing the long-term consequences of different fertilization practices. They concern the agronomic and economic effects of fertilizers, influence of fertilizers on soil properties as well as environmental threats resulting from improper fertilizer use. Soil samples collected regularly in time-intervals and stored in the bank of samples are used for testing and calibrating the new methods of soil analysis and fertilizer recommendations. Such experiments constituting a part of nation’s cultural inheritance are being carried on in England (Rothamstedt since 1843), France (Grignon Triveral, since 1875), Germany (Halle, since 1878, Bad Lauchstadt since 1902 and Dikopshof since 1904), Denmark Ascov 1894) and Skierniewice (Poland since 1922-1924) to mention the most famous ones.

The fertilization experiments in Skierniewice are still carried on, without major changes or interruptions. The key results covering crop yields and soil fertility parameters have been published in 10-15-year intervals, lately in 1999 [Mercik et
The climatic conditions in Skierniewice are typical for central Poland. The long-term, since 1921 average annual temperature is 7.9°C, and for the period covered by this paper raised to 8.4°C. The rise in temperature should be explained rather by a different method of calculating the daily averages than by the global warming. The average annual precipitation is 529 mm (the lowest in January, the highest in July). The soil is stagnic luvisol (pseudogley podzolic) soil characterized by the clay content (ř <0.002 mm) 7–8% in the Ap horizon (0–25 cm), 4–5% in the Bt horizon (25–45 cm) and 13–15% in the Bt and C horizons (> 45 cm). Soil belongs to quality class IIIb or IVa, and to the very good rye complex.

The scheme of experiments from which the reported results originate includes only the treatments with limestone application (Table 1). Therefore, the effect of nutrients has been assessed under the conditions of optimal soil pH.

**Table 1. The scheme of crop rotations and selected fertilization treatments**

<table>
<thead>
<tr>
<th>Fields</th>
<th>Crop rotation</th>
<th>Fertilizer treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Arbitrary rotation without legumes and without farmyard manure</td>
<td>Ca, CaNPK, NPK, CaPK, CaPN, CaKN</td>
</tr>
<tr>
<td>E</td>
<td>Five-course crop rotation: potato (30 t FYM · ha⁻¹), spring barley, red clover or lupine, winter wheat, rye</td>
<td>FYM (only in D)</td>
</tr>
<tr>
<td>D</td>
<td>Monocultures: potato, rye and/or triticale (since 1976)</td>
<td></td>
</tr>
</tbody>
</table>

The doses of mineral fertilizers have increased from 30 kg N, 13 kg P and 25 kg K · ha⁻¹ in the years 1922 - 1975 to 90 kg N, 26 kg P and 91 kg K · ha⁻¹ since 1976 r. Lime is applied every five years in the amount of 2.0 t Ca · ha⁻¹.
Results

Rye

The average yields of rye for both experimental periods were the highest in rotation E with leguminous crop and manure application, and the lowest in monoculture (Table 2).

Table 2. Average yield of rye depending on crop rotation and fertilization

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CaNPK</td>
<td>4.32</td>
<td>4.53</td>
<td>3.65</td>
</tr>
<tr>
<td>NPK</td>
<td>4.33</td>
<td>4.36</td>
<td>3.62</td>
</tr>
<tr>
<td>CaPK</td>
<td>1.80</td>
<td>3.02</td>
<td>1.55</td>
</tr>
<tr>
<td>CaPN</td>
<td>3.62</td>
<td>4.20</td>
<td>2.99</td>
</tr>
<tr>
<td>CaKN</td>
<td>2.97</td>
<td>3.77</td>
<td>2.54</td>
</tr>
<tr>
<td>Ca</td>
<td>1.54</td>
<td>2.70</td>
<td>1.49</td>
</tr>
<tr>
<td>FYM</td>
<td>-</td>
<td>-</td>
<td>2.52</td>
</tr>
<tr>
<td>Average</td>
<td>3.10</td>
<td>3.76</td>
<td>2.62</td>
</tr>
</tbody>
</table>

In the rotation A and in monoculture, the long-term (1976-2009) average rye yield does not differ substantially from this harvested in the period of the last 13 years. Therefore, it can be concluded that rye tolerates well cultivation in monoculture. In rotation E, yield of rye in the period 1996-2009 significantly increased in comparison to long-term averages (1976-2009). It can be explained by beneficial effect of leguminous crop and regular manure application, which both have increased the content of soil organic matter. Thereby, the difference in yield on behalf of this rotation against rotation A and D, rose considerably. It is worth noting that rye yields in rotation E, in the treatments without nitrogen (Ca and/or CaPK) were equal or even higher than recorded in monoculture with full fertilization (CaNPK).

The most limiting nutrient in rye production is nitrogen, followed by phosphorus and potassium. The data in table 2 confirm well known insusceptibility of rye on soil’s acidity. The very low difference in yields between CaNPK and NPK treatments is on behalf of this fact. Farmyard manure, applied in a yearly rate 20 t·ha⁻¹ seems to be quite good sources of nutrients for rye grown in monoculture. However, the yield in the treatments with full fertilization NPK surpassed considerably the one on farmyard manure solely.
Winter wheat

The average yield of wheat in the period 1996-2009 was higher in rotation E, then in rotation A, while the reverse was true for a long-term period of investigations (1976-2009). Winter wheat proved to be more susceptible, as the rye to the deficiencies of phosphorus and particularly to soil acidity. Consequently, the highest yield of winter wheat has been recorded in the treatment with full fertilization, CaNPK.

Table 3. Yields of winter wheat and spring barley in t·ha⁻¹ depending on crop rotation and fertilization.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Fertilization</th>
<th>Rotation A</th>
<th>Rotation E</th>
</tr>
</thead>
<tbody>
<tr>
<td>winter wheat</td>
<td>CaNPK</td>
<td>4.86</td>
<td>4.30</td>
</tr>
<tr>
<td></td>
<td>NPK</td>
<td>4.53</td>
<td>3.77</td>
</tr>
<tr>
<td></td>
<td>CaPK</td>
<td>3.73</td>
<td>2.53</td>
</tr>
<tr>
<td></td>
<td>CaPN</td>
<td>4.53</td>
<td>3.74</td>
</tr>
<tr>
<td></td>
<td>CaKN</td>
<td>4.36</td>
<td>3.59</td>
</tr>
<tr>
<td></td>
<td>Ca</td>
<td>3.46</td>
<td>2.10</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>4.25</td>
<td>3.34</td>
</tr>
<tr>
<td>spring barley</td>
<td>CaNPK</td>
<td>3.41</td>
<td>3.32</td>
</tr>
<tr>
<td></td>
<td>NPK</td>
<td>2.00</td>
<td>2.17</td>
</tr>
<tr>
<td></td>
<td>CaPK</td>
<td>1.73</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td>CaPN</td>
<td>2.71</td>
<td>2.73</td>
</tr>
<tr>
<td></td>
<td>CaKN</td>
<td>2.86</td>
<td>2.78</td>
</tr>
<tr>
<td></td>
<td>Ca</td>
<td>1.36</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>2.35</td>
<td>2.33</td>
</tr>
</tbody>
</table>

Spring barley

In both scrutinized experimental periods the yield of spring barley was considerably higher in rotation E, then in rotation A. In almost all fertilization treatments the yield difference was well above 1 t grain·ha⁻¹ on behalf of rotation E, i.e. much higher than the corresponding difference in the yield of winter wheat. The most pronounced difference in the barley yields between these two rotations
Crop yields and nitrogen balance in long-term fertilization experiments

Crop yields and nitrogen balance in long-term fertilization experiments

was revealed in the treatment CaPK. Barley, particularly grown in rotation A is more susceptible to soil acidity in comparison to wheat. It results from comparison of the treatments NPK and CaNPK. The negative effect of soil acidity was partly alleviated by application of manure and cultivating the leguminous crops in rotation E.

Potato

The rye alike, the highest yield of potato was recorded in rotation E, followed by rotation A and the lowest in potato monoculture (Table 4). The yield of tubers in rotation E, particularly in the long-term experimental period was almost doubled in comparison to this in rotation A. The yield difference between rotation A, do not speak about rotation E, and monoculture is significant and much higher than in case of rye.

Table 4. Yield of potato tubers in t · ha⁻¹ depending on crop rotation and fertilization.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CaNPK</td>
<td>23.02</td>
<td>20.75</td>
<td>31.86</td>
<td>25.84</td>
<td>15.10</td>
<td>15.86</td>
</tr>
<tr>
<td>NPK</td>
<td>20.01</td>
<td>18.48</td>
<td>32.05</td>
<td>25.90</td>
<td>13.77</td>
<td>15.08</td>
</tr>
<tr>
<td>CaPN</td>
<td>15.16</td>
<td>14.64</td>
<td>28.59</td>
<td>23.14</td>
<td>11.96</td>
<td>13.05</td>
</tr>
<tr>
<td>CaKN</td>
<td>15.64</td>
<td>15.07</td>
<td>29.03</td>
<td>23.84</td>
<td>12.14</td>
<td>13.70</td>
</tr>
<tr>
<td>Ca</td>
<td>11.08</td>
<td>10.67</td>
<td>22.49</td>
<td>19.43</td>
<td>8.29</td>
<td>9.85</td>
</tr>
<tr>
<td>FYM</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>11.59</td>
<td>12.90</td>
</tr>
<tr>
<td>Average</td>
<td>16.42</td>
<td>15.38</td>
<td>28.45</td>
<td>23.34</td>
<td>11.85</td>
<td>13.12</td>
</tr>
</tbody>
</table>

Soil acidification had no serious impact on the potato yields. The minor difference in the yield of tubers between CaNPK and NPK treatments was recorded only. Deficiencies of phosphorus and potassium exerted similar negative influence on the potato yield. Potatoes grown in monoculture responded better than rye to fertilization with manure. However, the yield in the treatment with manure only was significantly lower than in the CaNPK treatment.

Nitrogen balance

The same amounts of nitrogen have been applied in all rotations and all treatments except treatment CaPK + manure in rotation E. Nitrogen uptake by crops
**Table 5. Nitrogen balance in the years 1996-2009, depending on crop rotation and fertilization**

<table>
<thead>
<tr>
<th>Balance N</th>
<th>Fields</th>
<th>A</th>
<th>E</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>N dose in min. fertil. kg · ha⁻¹</td>
<td>CaPK</td>
<td>CaNPK</td>
<td>CaPK</td>
<td>CaNPK</td>
</tr>
<tr>
<td>in. FYM kg · ha⁻¹</td>
<td>-</td>
<td>90</td>
<td>-</td>
<td>77</td>
</tr>
<tr>
<td>N uptake total kg · ha⁻¹</td>
<td>33,6</td>
<td>79,4</td>
<td>65,2</td>
<td>98,6</td>
</tr>
<tr>
<td>from fertilizers kg · ha⁻¹</td>
<td>-</td>
<td>45,8</td>
<td>-</td>
<td>33,4*</td>
</tr>
<tr>
<td>%</td>
<td>-</td>
<td>50,9</td>
<td>-</td>
<td>43,3*</td>
</tr>
<tr>
<td>N dose- N uptake from fertilizers kg · ha⁻¹</td>
<td>44,2</td>
<td>-</td>
<td>43,6</td>
<td>-</td>
</tr>
<tr>
<td>Soil N content changes in 0-65cm (1996-2009) kg · ha⁻¹</td>
<td>-1,5</td>
<td>-0,2</td>
<td>7,0</td>
<td>-5,4</td>
</tr>
<tr>
<td>N balance release kg · ha⁻¹</td>
<td>32,1</td>
<td>-38,4</td>
<td>65,0</td>
<td>-36,6*</td>
</tr>
<tr>
<td>loses kg · ha⁻¹</td>
<td>-</td>
<td>42,7</td>
<td>-</td>
<td>47,5*</td>
</tr>
<tr>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*from mineral fertilizers only in the rotation E*
Crop yields and nitrogen balance in long-term fertilization experiments

on CaNPK treatment was the highest in rotation E (99 kg N · ha$^{-1}$) and rather similar in rotations, A, and D (74-79 kg N · ha$^{-1}$). Uptake of nitrogen from mineral fertilizers and/or manure (in rotation D only) was calculated from the difference of uptake in treatments CaNPK, (Ca+manure) against the treatment CaPK. This amount was used to compute the coefficient of nitrogen utilization from fertilizers. The coefficient was in the range of 51.0% to 53.4% for mineral nitrogen and equals only 38% for nitrogen from manure.

The release of nitrogen from the soil in rotations A, and D, as well as from manure and leguminous crops residues, in rotation E, has been calculated as the sum of N uptake in the CaPK treatment and changes in the content of total nitrogen in soil, between the years 1996 and 2009. The amount of nitrogen released from the soil itself was 20.4 and 32.1 kg N·ha$^{-1}$, in rotations D and A, respectively and from soil enriched in manure and leguminous crops residues 65 kg N ·ha$^{-1}$, in rotation E.

The losses of nitrogen from fertilizers have been calculated as the difference between nitrogen input and output in the form of uptake by crops and increase of N content in the soil profile. This losses amounted to 42.4 – 47.5 kg N ·ha$^{-1}$ from mineral fertilizers and 82.7 kg N·ha$^{-1}$ from manure.

Discussion

Average yield of rye in arbitrary rotation (A) and in monoculture (D) are similar in a long term period (1976-2009) and for the last 14 years. It proved that rye tolerates cultivation in monoculture. Similar relationships have been also observed in other long-term fertilization experiments [Garz 1994]. The highest yields of all crops, for the last 14 years were obtained in the rotation E with manure and leguminous crops. It seems, that nitrogen from leguminous crop residue and manure is a good alternative for nitrogen in mineral fertilizers. Fertilization with manure and legumes crops alleviated a negative effect of soil acidification. A similar relationship has been observed in many fertilization experiments [Stumpe 1990] as much higher than under phosphorus and potassium. The lowest crops yield and nitrogen uptake by crops were on the CaPK treatment. Crops took up in this treatment 25.8-33.6 kg N · ha$^{-1}$ yearly from soil. This amount derives from activity of soil bacteria and/or from air deposition. It must be taken into consideration, that at the Central Poland N deposition from atmosphere with wet rainfall amounts to 17-20 kg N · ha$^{-1}$ yearly [Sapek 1997, Sosulski et al. 2005] and on the site of East Germany amounts to 50 kg · ha$^{-1}$ · year$^{-1}$ [Körtschens 1999]. However nitrogen deposition to arable land from atmosphere at Rothamstedt amounts to 43 kg N · ha$^{-1}$ · year$^{-1}$ (14.2 kg N · ha$^{-1}$ in wet and 29.1 kg N · ha$^{-1}$ in dry deposition) [Powlsion 1994]. In the experiment in Skierniewice crops removed 8-11 kg P · ha$^{-1}$ · year$^{-1}$ in the treatment CaNK, [Szara 2011] and 35-45 kg K · ha$^{-1}$ · year$^{-1}$ in treatment CaNP from non-exchangeable forms [Stępień 2011].
Nitrogen balance includes uptake of this element by crops in rotation and in rye monoculture, input of nitrogen in mineral fertilization and in manure as well as changes of total nitrogen content in the soil profile during 14 years. Utilization of N from mineral fertilizers by crops was rather low (51-54%) and from manure, very low (38%). In the previous period (1961-1995) crops took up much higher amounts of N from mineral fertilizers than from manure [Mercik et al. 1999]. Similar results have also been recorded in other long term experiments [Christensen 1989, Leithold 1993, Körschens et al. 1994, Merbach et al. 2002, Mercik et al. 2001].

Our results show a little higher total nitrogen content in Ap soil layer in CaNPK treatment as compared with not fertilized plots CaPK. It is due to the fact, that over 40% of nitrogen applied in mineral fertilizers and over 80% from mineral, and organic fertilizers was lost to the underground water or to the atmosphere. Migration of significant quantities of nitrogen from the arable layer of the soil deeper into the soil profile has also been recorded in other long-term experiments [Leithold 1993, Körschens et al. 1994].

Conclusions

1. Rye and potato yields are highest when the crops are cultivated in rotation with manure and a leguminous crop, markedly lower when grown without natural fertilizers, and lowest when the crops are cultivated in monoculture. Over the last several decades yields have been rather stable.
2. The increase in yields due to nitrogen fertilization is much higher in the plant rotation without manure and without leguminous crops than in the rotation with these sources of nitrogen.
3. There was a much lower crop response to phosphorus and potassium deficiencies than to nitrogen deficiency. However, the increases in the yields of grain crops were more dependent on phosphorus fertilization (15%) than potassium fertilization (12%), while for potatoes an inverse relationship was obtained (19% and 23%).
4. During the last 14 years, nitrogen fertilization has caused only a slight increase in the nitrogen content in the soil (3.7-7 kg N · ha⁻¹).
5. The losses of nitrogen from ammonium nitrate in the system of exclusively mineral fertilization of plants grown in rotation and in rye monoculture are similar and amounted to 42-43%. The largest amounts of nitrogen are lost from the soil fertilized annually with manure (about 83% of the N dose).

References

Crop yields and nitrogen balance in long-term fertilization experiments


Stępień, W., 2011. Bezpośrednie i następce działanie potasu w doświadczeniach wieloletnich. Praca habilitacyjna SGGW (w druku).


EVALUATION OF PLANT NUTRITIONAL STATUS BY THE CND METHOD: CASE OF SUGAR BEET

Przemysław Barłóg
University of Life Sciences, Poznań, Poland

Abstract

The CND-clr (Compositional Nutrient Diagnosis into centered log ratios) diagnostic norms were evaluated by analyzing nutritional status of sugar beet cultivated under different field conditions. Experiments were carried out in years 2001-2003 at commercial farms located in Czempin (Wielkopolska, Poland). The following factors were investigated: manure application (-FYM, +FYM), sodium rate (0, 12.5, 25 and 50 kg Na ha\(^{-1}\)) and type of the sodium fertilizer (NaCl, \(\text{Na}_2\text{SO}_4\) and \(\text{NaNO}_3\)). For diagnostic purposes, leaf blades at the stage of 7\(^{th}\) leaf (BBCH 17) and at the well-developed rosette stage (BBCH 43) has been analyzed.

It has been shown that CND indices depended on the prevailing external conditions during the growing season and plant’s growth stage. Experimental factors have exerted only a secondary effect on sugar beet nutritional status. Plants fertilized with sodium were characterized by best and lowest nutrient imbalance indices \(\text{CND}_{-r^2}\), which resulted mainly from the highest share of sodium and low shares of calcium in the CND-clr complex. Relationships between nutrient concentration and white-sugar yields were affected by plant growth stage and weather conditions. The transformation of „pure” nutrient contents into CND-clr indices have increased \(R^2\) values for tested relationships. The best fit was obtained in the growth period, when the nutrient composition of leaves differed considerably from standard values. The positive role of sodium in sugar beet yielding, was pronounced mainly at BBCH 17, as compared to potassium, which revealed at BBCH 43. No significant interaction has been found for the pair „manure and Na treatments”. Furthermore, the obtained data have shown that on the treatment without manure, the application of sodium exerted a significantly more pronounced effect on CND \(I_{\text{Na}}\) indices as compared to the treatment with manure.

Key words: sugar beet, sugar yield, CND method, sodium fertilization
Przemysław Barłóg

Introduction

There is a close relationship between the chemical composition of sugar beet plants and their yielding potential. Among all plant nutrients, the most important is nitrogen [Hergert 2010]. This nutrient strongly determines the biomass and quality of sugar beet taproots. However, the efficiency of nitrogen depends also on water availability and the content of other nutrients in plant tissues. Potassium and sodium play a specific role in sugar beet metabolism and yielding [Cakmak 2005, Haneklaus et al. 1998, Wakeel et al. 2010]. The role of both nutrients in regulating the tolerance to water stress is well agreed. However, the effect of sodium on nitrogen management still is controversial. As a matter of fact, this element participates in transportation of nitrates from roots to leaves, but otherwise strongly reduces the activity of several other enzymes, including nitrate reductase [Subbarao et al. 2003]. Nevertheless, plants well supplied both with potassium, and sodium better assimilates nitrogen from soil reserves as compared to that receiving sodium, only [Hansen 1994].

The stress imposed on plants is not attributed to the deficiency of one nutrient, but to the inadequate relationship between all of them. According to Haneklaus et al. [1998] losses of sugar beet yields, as a result of unfavorable K/Na ratio, reach 60% of the yielding potential in Germany. There is still a lack of data reporting the adequate ratios of nutrients in indicatory parts of sugar beet. The complex evaluation of plant nutritional status may be undertaken by using the DRIS (Diagnosis and Recommendation Integrated System, Sumner 1978), CND-clr (Compositional Nutrient Diagnosis into centered log ratios; Parent and Dafir 1992) or CND-ilr (Compositional Nutrient Diagnosis into isometric log ratios; Parent 2011) methods. The first method is the most popular and starts with calculating the DRIS norms followed by the indices involving all possible ratios of a given nutrient to others (dual ratios). The evaluation may also be extended to dry matter content and then the method is designated as MDRIS [Hallmark et al. 1987]. For the CND-clr method, the first analysis starts with complexes consisting of a large number of nutrients. Moreover, the calculations must involve a so-called filling value (R). In the DRIS method, norms are based on ratios between two nutrients including the coefficient of variation, while in the CND-clr method, the logarithms of ratios between a given nutrient and complex of all other nutrients including standard deviation. Parent (2011) proposed to make the isometric log ratio (ilr) transformation for compositional data. The ilr partitions are defined a priori by a conceptual model elaborated from current knowledge to facilitate the interpretation of results. A binary partition of nutrients reflecting multiple interactions is the analog to a dual ratio since one or many nutrients show up in the numerator and denominator of the ratio. Irrespective of the applied methods, nutritional norms allow to calculate nutritional indices. In both DRIS and CND methods, as lower the index, values, the better level of plant nutritional status. A close relationship has been found between DRIS and CND-clr indices [Khiari et al. 2001b, Parent 2011]. However, as results from a few investigations, CND indices
explain better differences in plant yielding as compared to the DRIS or MDRIS methods [Costa da Silva et al. 2004, Khiari et al. 2001c]. The advantage of the CND method is also the possibility of calculating a nutrient imbalance index (CND_\textsuperscript{r^2}). Since CND_\textsuperscript{r^2} values are characterized by chi-square (\(\chi^2\)) distribution, then there is a possibility of comparing the nutritional status of a given crop’s canopy with critical CND_\textsuperscript{r^2} values elaborated for the general population [Khiari et al. 2001a, Bélanger et al. 2005].

The evaluation of sugar beet nutritional status can be undertaken at the beginning of July (BBCH 43) or at the stage of rows closing onset (BBCH 16/17) [Bergmann 1992, Jaszczołt 1994]. For both growth stages CND-clr norms were calculated, and critical ranges of indices were elaborated based on the control subpopulation, for sodium, also [Barłóg 2009]. The next step of the investigations and another aim of the paper is to determine the role of sodium in shaping plant nutritional status and the relationships between CND indices and the yield level of sugar beet.

**Materials and Methods**

Field’s experiments with sugar beet were carried out in the years 2001–2003 at the commercial farm in Czempin (52°07’N; 16°45’E). The following factors were investigated: manure application (-FYM; +FYM), sodium rate (0; 12.5; 25 and 50 kg Na ha\textsuperscript{-1}) and the type of sodium fertilizer (NaCl; Na\textsubscript{2}SO\textsubscript{4} and NaNO\textsubscript{3}). Sodium fertilizers were applied two weeks before sugar beet sowing. Manure was applied at the rate of 30 t ha\textsuperscript{-1}, whereas PK fertilizers at rates of 26.5 kg P ha\textsuperscript{-1} and 116 kg K ha\textsuperscript{-1}. Nitrogen rate amounted to 120 kg N ha\textsuperscript{-1} (2 x 60 kg N ha\textsuperscript{-1}, applied as ammonium saltpeter, 34%). Nitrogen incorporated in soils was also considered in treatments with sodium applied as NaNO\textsubscript{3}. Field’s experiments were arranged as a randomly established block system, replicated four times, with the total area of 54 m\textsuperscript{2}.

The experiment has been carried on light soils. Soil pH for the years 2001 - 2003 was 5.3; 5.8 and 7.0, respectively. The high contents of available phosphorus, potassium and magnesium (79; 89; 114 mg P kg\textsuperscript{-1}; 150; 171; 121 mg K kg\textsuperscript{-1} and 63; 60; 77 mg Mg kg\textsuperscript{-1}), and a medium content of sodium, (6.7; 4.3; 9.9 g Na kg\textsuperscript{-1}) were recorded (by standard methods). The growth conditions for sugar beet, mainly in August and September were the worst in 2003 years. The sum of rainfalls for these months was 40 mm, only, while in 2002 its amounted to 150–169 mm. The yearly rainfalls for 2001–2003 amounted, 553, 633 and 412 mm respectively.

Sugar beet plants were sampled at the stage of 7\textsuperscript{th} leaf (BBCH 17, approximately in mid June,) and at the well-developed rosette stage (BBCH 43, the beginning of July) [Meier 2001]. In the first-stage chemical analysis concerned leaf blades of the 5\textsuperscript{th} leaf, whereas in the second, blades of young, but fully developed leaves. The sample, representing a given experimental treatment consisted of 15–20 individual
leaves of randomly selected plants. In the samples, total concentration of N, P, K, Na, Ca and Mg was determined. At the technological maturity (BBCH 49) plants were harvested from an area of 10 m$^2$. Qualitative parameters were determined in 20, randomly selected roots, and then the recoverable sugar yield was calculated [Buchholz 1995].

Nutritional CND-clr indices were calculated based on norms elaborated in years 1997–2004 for 408 sugar beet fields within the Wielkopolska region. For leaf blades of the 5$^{th}$ leaf (growth stage BBCH 17) the norms are as follows:

\[
\begin{align*}
V^*_N &= 1.009 \pm 0.211; \\
V^*_P &= -1.818 \pm 0.200; \\
V^*_K &= 1.063 \pm 0.202; \\
V^*_{Na} &= -1.028 \pm 0.362; \\
V^*_{Ca} &= -1.111 \pm 0.334; \\
V^*_{Mg} &= -1.955 \pm 0.320; \\
V^*_R &= 3.839 \pm 0.169
\end{align*}
\]

and for leaves collected at the BBCH 43 growth stage:

\[
\begin{align*}
V^*_N &= 0.719 \pm 0.147; \\
V^*_P &= -1.592 \pm 0.274; \\
V^*_K &= 0.794 \pm 0.166; \\
V^*_{Na} &= -1.065 \pm 0.464; \\
V^*_{Ca} &= -1.138 \pm 0.386; \\
V^*_{Mg} &= -1.612 \pm 0.262; \\
V^*_R &= 3.894 \pm 0.147
\end{align*}
\]

[Barłóg 2009].

At the first step, filling value (R) was calculated, next geometric mean (G) and centered log ratio ($V_x$) in the plant under diagnosis [Parent and Dafir 1992]:

\[
\begin{align*}
R &= 1000 – (N + P + K + Na + Ca + Mg) \\
G &= (N \times P \times K \times Na \times Ca \times Mg \times R)^{1/d+1} \\
V^*_N &= \ln(N/G); \\
V^*_P &= \ln(P/G); \\
V^*_K &= \ln(K/G); \\
.........; \\
V^*_R &= \ln(R/G)
\end{align*}
\]

where, N, P, K, ... nutrients concentrations (g kg$^{-1}$), R – filling value, 1000 dry weight of plants (g), G – geometric mean, d – number of tested nutrients, ln natural logarithm.

CND indices were calculated according to the algorithm:

\[
I_x = (V^*_x - V^*_x)/SD^*_x
\]

where, $I_x$ index of the nutrient „x” in the plant under diagnosis; $V^*_x$ value of the centered log ratio of nutrient „x”; $V^*_{x}$ mean value of the CND norm of the nutrient „x”; $SD^*_x$ standard deviation of CND norm of the nutrient „x”.

The nutrient imbalance index $\text{CND}_r^2$ has been calculated by the summation of squares values of indices for the particular nutrients:

\[
\text{CND}_r^2 = F^*_N + F^*_P + F^*_K + F^*_{Na} + F^*_{Ca} + F^*_{Mg} + F^*_R.
\]

The CND$_r^2$ values were distributed like chi-square values ($\chi^2$) for $d + 1$ degree of freedom. It is possible, based on the critical ranges, to establish the probability of achieving a fixed yield of a given crop plant (Khiari et al. 2001b).

The statistical evaluation of the effect of experimental factors was undertaken by the application of the analysis of variance for a two-factorial experiment (i.e., manure and sodium application). Differences within objects were compared by the Tukey’s test at $\alpha = 0.05$, and interactions between factors were evaluated by the analysis of correlation and nonlinear regression, (STATISTICA 8).
Evaluation of plant nutritional status by the cnd method: case of sugar beet

Results

Concentration of mineral elements in the leaf blade of the 5th leaf (BBCH 17), depending on the vegetative season ranges between: 49–62 g N kg⁻¹; 2.9–4.0 g P kg⁻¹; 50–61 g K kg⁻¹; 7–8.8 g Na kg⁻¹; 7.1–7.6 g Ca kg⁻¹ and 3.9–5.8 g Mg kg⁻¹. When comparing these values with nutritional norms, it appears that plants were optimally supplied with nitrogen, phosphorus, potassium and sodium. In 2001, concentrations of calcium and years 2001 and 2002 concentration of magnesium was even higher than the range considered as optimal [Barłóg 2009].

Table 1. CND-clr indices; blades of 5th leaf, BBCH 17 (mean for 2001–2003)

<table>
<thead>
<tr>
<th>Year/ treatments</th>
<th>CND-clr indices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_\text{Na}$</td>
</tr>
<tr>
<td>2001</td>
<td>-0.217</td>
</tr>
<tr>
<td>2002</td>
<td>-0.215</td>
</tr>
<tr>
<td>2003</td>
<td>-0.345</td>
</tr>
<tr>
<td>-Fym</td>
<td>-0.446</td>
</tr>
<tr>
<td>+Fym</td>
<td>-0.073</td>
</tr>
</tbody>
</table>

Na kg Na ha⁻¹

NaCl

<table>
<thead>
<tr>
<th></th>
<th>$I_\text{Na}$</th>
<th>$I_\text{K}$</th>
<th>$I_\text{Ca}$</th>
<th>$I_\text{Mg}$</th>
<th>$I_\text{P}$</th>
<th>$I_\text{N}$</th>
<th>$I_\text{R}$</th>
<th>CND $r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.588</td>
<td>0.079</td>
<td>0.597</td>
<td>1.353</td>
<td>-0.373</td>
<td>-0.446</td>
<td>-0.287</td>
<td>3.775</td>
</tr>
<tr>
<td>12.5</td>
<td>-0.492</td>
<td>0.090</td>
<td>0.388</td>
<td>1.368</td>
<td>-0.426</td>
<td>-0.406</td>
<td>-0.283</td>
<td>3.667</td>
</tr>
<tr>
<td>25</td>
<td>-0.245</td>
<td>0.086</td>
<td>0.077</td>
<td>1.326</td>
<td>-0.427</td>
<td>-0.402</td>
<td>-0.314</td>
<td>2.746</td>
</tr>
<tr>
<td>50</td>
<td>0.001</td>
<td>0.083</td>
<td>-0.338</td>
<td>1.092</td>
<td>-0.415</td>
<td>-0.367</td>
<td>-0.292</td>
<td>2.583</td>
</tr>
</tbody>
</table>

Na₂SO₄

<table>
<thead>
<tr>
<th></th>
<th>$I_\text{Na}$</th>
<th>$I_\text{K}$</th>
<th>$I_\text{Ca}$</th>
<th>$I_\text{Mg}$</th>
<th>$I_\text{P}$</th>
<th>$I_\text{N}$</th>
<th>$I_\text{R}$</th>
<th>CND $r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>-0.375</td>
<td>0.140</td>
<td>0.239</td>
<td>1.128</td>
<td>-0.372</td>
<td>-0.410</td>
<td>-0.296</td>
<td>2.363</td>
</tr>
<tr>
<td>25</td>
<td>-0.143</td>
<td>0.086</td>
<td>-0.025</td>
<td>1.274</td>
<td>-0.377</td>
<td>-0.460</td>
<td>-0.316</td>
<td>2.584</td>
</tr>
<tr>
<td>50</td>
<td>0.065</td>
<td>0.101</td>
<td>-0.262</td>
<td>0.694</td>
<td>-0.312</td>
<td>-0.414</td>
<td>-0.278</td>
<td>1.436</td>
</tr>
</tbody>
</table>

NaNO₃

<table>
<thead>
<tr>
<th></th>
<th>$I_\text{Na}$</th>
<th>$I_\text{K}$</th>
<th>$I_\text{Ca}$</th>
<th>$I_\text{Mg}$</th>
<th>$I_\text{P}$</th>
<th>$I_\text{N}$</th>
<th>$I_\text{R}$</th>
<th>CND $r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>-0.472</td>
<td>0.126</td>
<td>0.388</td>
<td>1.469</td>
<td>-0.408</td>
<td>-0.452</td>
<td>-0.314</td>
<td>3.603</td>
</tr>
<tr>
<td>25</td>
<td>-0.296</td>
<td>0.103</td>
<td>0.111</td>
<td>1.132</td>
<td>-0.355</td>
<td>-0.429</td>
<td>-0.279</td>
<td>2.460</td>
</tr>
<tr>
<td>50</td>
<td>-0.048</td>
<td>0.077</td>
<td>-0.285</td>
<td>0.752</td>
<td>-0.302</td>
<td>-0.365</td>
<td>-0.255</td>
<td>1.562</td>
</tr>
</tbody>
</table>

Means within column with the same letter are not significantly different at $\alpha = 0.05$ (Tukey test)
The values of CND indices depended mainly on the growth season (Tab. 1) and showed the following sequences:

- **2001:** \( I_N < I_R < I_Na < I_Ca < I_K < I_Mg \)
- **2002:** \( I_P < I_R < I_N < I_Na < I_Ca < I_K < I_Mg \)
- **2003:** \( I_P < I_Na < I_N < I_R < I_K < I_Ca < I_Mg \)

Indices with values close to „0“ are marked in bold, whereas those out of critical ranges are underlined [Barłóg 2009]. Potassium indices for years 2001 and 2003 were very close to the nutritional standard, whereas for calcium, this property appeared in 2002. Plants were moderately balanced with phosphorus, nitrogen and magnesium. The first two nutrients represented a deficiency status while an excess of magnesium was recorded. By considering the nutrient imbalance index, one may conclude that sugar beet was optimally/better fed in 2003 in comparison to 2001 (Tab. 1).

Application of manure has significantly affected indices of \( I_{Na} \) and \( I_{Ca} \) (Tab. 1), at the growth stage BBCH 17. The induced by manure changes of indices followed the sequence:

- **FYM:** \( I_{Na} < I_N < I_P < I_R < I_Ca < I_Mg \)
- **+FYM:** \( I_N = I_P < I_R < I_Ca < I_Na < I_K < I_Mg \)

Nitrogen Index \( (I_N) \) for the +FYM plot was the lowest as compared with the remaining ones. In addition, manure application increased its value beyond the critical values (-0.403). At the same time, \( I_{Ca} \) index decreased and was close to the optimal range (-0.123 and +0.123). Manure application has increased \( I_{Na} \) values, but simultaneously decreased \( I_{Mg} \). The considered factor, i.e., manure, has led to a decrease of CND \( r^2 \) value. Sodium application modified significantly \( I_{Na} \) and \( I_{Ca} \) indices. The best values of indices were obtained for sodium in treatments with the highest its rate, irrespective of the type of the fertilizer. In the case of \( I_{Ca} \), the same was observed for intermediate Na rate. Consequently, this factor has positively influenced CND \( r^2 \) values, particularly when 50 kg Na ha\(^{-1}\) was applied as NaCl or NaNO\(_3\) (Tab. 1). No significant interaction has been found for the pair „manure and treatment with Na“. Furthermore, the obtained data have shown that on the plot without manure, the application of sodium exerted a significantly more pronounced effect on \( I_{Na} \) indices as compared to the respective plot, but with manure (Fig. 1).

Indices \( I_{Na} \) and \( I_{Ca} \) were negatively correlated \((r = -0.81***, n = 60)\). This relationship was stronger than for „pure” concentration of both nutrients considered together \((r = 0.50***, n = 60)\). Stronger relationship was also obtained for correlation coefficients between \( I_{Na} \) and \( I_{Mg} \) \((r = -0.12 \text{ and } -0.42*; \text{ respectively, } n = 60)\), and \( I_{Na} \) and \( I_N \) in 2001 \((r = 0.66*, n = 20 \text{ and } r = 0.80***; n = 20)\).
At BBCH 43, nutrient concentrations were as follows: 38–41 mg N kg\(^{-1}\); 3.6–4.8 mg P kg\(^{-1}\); 34–41 mg K kg\(^{-1}\); 6.2–11.8 mg Na kg\(^{-1}\); 5.6–7.4 mg Ca kg\(^{-1}\); 3.7–6.9 mg Mg kg\(^{-1}\). When compared to the norms, it appeared that nutrient’s concentration in sugar beet plant was also optimal at this growth stage [Barlóg 2009]. For the years of investigations, CND indices followed the sequences:

2001: \(I_N < I_{\text{Na}} < I_{\text{K}} < I_{\text{R}} < I_{\text{P}} < I_{\text{Mg}}\)

2002: \(I_N < I_{\text{Na}} < I_{\text{R}} < I_{\text{K}} < I_{\text{Ca}} < I_{\text{P}} < I_{\text{Mg}}\)

2003: \(I_N < I_{\text{K}} < I_{\text{P}} < I_{\text{R}} < I_{\text{Ca}} < I_{\text{Na}} < I_{\text{Mg}}\).

As reported in the sequences listed above, sugar beet at BBCH 43 contained high amounts of Mg and P during 2001–2002, and Na in 2003. For each year of study nitrogen concentration was less balanced, i.e., expressing the lowest values of indices, which were mostly beyond the critical range. Therefore, nitrogen became the critical growth factor. Moreover, plants were slightly Na-imbalanced in 2001–2002 years (Tab. 2).

Indices of CND\(_{r^2}\) presented the worst values in 2001, but the best in 2003. At the BBCH 43, the application of manure exerted a week the least effect on indices as compared to BBCH 17. This factor has significantly influenced \(I_{\text{K}}\) and \(I_{\text{Ca}}\) indices. On the other hand, sodium fertilization did not significantly influence CND indices, as compared this factor. It has been observed that \(I_{\text{Na}}\) indices increased, and \(I_{\text{Ca}}\) decreased along with increasing Na rates (Tab. 2). This phenomenon suggests an occurrence of antagonism between these two nutrients. A significant correlation coefficient \((r = -0.82**; n = 40)\) between these two parameters was obtained, but after rejecting data of 2003. Indices \(I_{\text{Na}}\) and \(I_{\text{K}}\) correlated negatively \((r = -0.70**; n = 60)\).
Table 2. CND-clr indices at the BBCH 43 growth stage (mean for 2001–2003)

<table>
<thead>
<tr>
<th>Year/treatments</th>
<th>$I_{Na}$</th>
<th>$I_{K}$</th>
<th>$I_{Ca}$</th>
<th>$I_{Mg}$</th>
<th>$I_{P}$</th>
<th>$I_{N}$</th>
<th>$I_{R}$</th>
<th>CND$_{r}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>-0.288$^b$</td>
<td>-0.265$^{ab}$</td>
<td>-0.559$^a$</td>
<td>2.210$^b$</td>
<td>0.122$^{ab}$</td>
<td>-0.799$^a$</td>
<td>-0.238$^a$</td>
<td>6.58$^b$</td>
</tr>
<tr>
<td>2002</td>
<td>-0.634$^a$</td>
<td>-0.021$^b$</td>
<td>0.182$^b$</td>
<td>0.964$^a$</td>
<td>0.394$^b$</td>
<td>-0.736$^a$</td>
<td>-0.268$^a$</td>
<td>2.67$^a$</td>
</tr>
<tr>
<td>2003</td>
<td>0.451$^c$</td>
<td>-0.450$^a$</td>
<td>0.391$^c$</td>
<td>0.597$^a$</td>
<td>-0.196$^a$</td>
<td>-0.729$^a$</td>
<td>-0.193$^a$</td>
<td>1.67$^a$</td>
</tr>
<tr>
<td>-Fym</td>
<td>-0.172$^a$</td>
<td>-0.320$^a$</td>
<td>0.159$^b$</td>
<td>1.219$^a$</td>
<td>0.122$^a$</td>
<td>-0.746$^a$</td>
<td>-0.222$^a$</td>
<td>3.86$^a$</td>
</tr>
<tr>
<td>+Fym</td>
<td>-0.142$^a$</td>
<td>-0.170$^b$</td>
<td>-0.150$^a$</td>
<td>1.294$^a$</td>
<td>0.091$^a$</td>
<td>-0.763$^a$</td>
<td>-0.244$^a$</td>
<td>3.42$^a$</td>
</tr>
<tr>
<td>NaCl kg Na ha$^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>-0.345$^a$</td>
<td>-0.211$^a$</td>
<td>0.190$^a$</td>
<td>1.265$^a$</td>
<td>0.098$^a$</td>
<td>-0.731$^a$</td>
<td>-0.212$^a$</td>
<td>3.724$^a$</td>
</tr>
<tr>
<td>12.5</td>
<td>-0.391$^a$</td>
<td>-0.225$^a$</td>
<td>0.340$^a$</td>
<td>1.223$^a$</td>
<td>0.136$^a$</td>
<td>-0.766$^a$</td>
<td>-0.208$^a$</td>
<td>4.295$^a$</td>
</tr>
<tr>
<td>25</td>
<td>-0.178$^a$</td>
<td>-0.262$^a$</td>
<td>0.045$^a$</td>
<td>1.458$^a$</td>
<td>0.083$^a$</td>
<td>-0.804$^a$</td>
<td>-0.223$^a$</td>
<td>4.192$^a$</td>
</tr>
<tr>
<td>50</td>
<td>-0.059$^a$</td>
<td>-0.229$^a$</td>
<td>-0.074$^a$</td>
<td>1.262$^a$</td>
<td>0.094$^a$</td>
<td>-0.753$^a$</td>
<td>-0.257$^a$</td>
<td>3.511$^a$</td>
</tr>
<tr>
<td>12.5</td>
<td>-0.215$^a$</td>
<td>-0.211$^a$</td>
<td>0.118$^a$</td>
<td>1.188$^a$</td>
<td>0.127$^a$</td>
<td>-0.760$^a$</td>
<td>-0.235$^a$</td>
<td>3.528$^a$</td>
</tr>
<tr>
<td>Na$_2$SO$_4$ 25</td>
<td>0.013$^a$</td>
<td>-0.301$^a$</td>
<td>-0.094$^a$</td>
<td>1.346$^a$</td>
<td>0.073$^a$</td>
<td>-0.737$^a$</td>
<td>-0.269$^a$</td>
<td>3.528$^a$</td>
</tr>
<tr>
<td>50</td>
<td>0.056$^a$</td>
<td>-0.292$^a$</td>
<td>-0.349$^a$</td>
<td>1.042$^a$</td>
<td>0.139$^a$</td>
<td>-0.694$^a$</td>
<td>-0.213$^a$</td>
<td>2.915$^a$</td>
</tr>
<tr>
<td>12.5</td>
<td>-0.382$^a$</td>
<td>-0.224$^a$</td>
<td>0.066$^a$</td>
<td>1.365$^a$</td>
<td>0.109$^a$</td>
<td>-0.786$^a$</td>
<td>-0.231$^a$</td>
<td>3.905$^a$</td>
</tr>
<tr>
<td>NaNO$_3$ 25</td>
<td>-0.153$^a$</td>
<td>-0.250$^a$</td>
<td>0.058$^a$</td>
<td>1.179$^a$</td>
<td>0.121$^a$</td>
<td>-0.744$^a$</td>
<td>-0.233$^a$</td>
<td>3.431$^a$</td>
</tr>
<tr>
<td>50</td>
<td>0.086$^a$</td>
<td>-0.245$^a$</td>
<td>-0.254$^a$</td>
<td>1.241$^a$</td>
<td>0.084$^a$</td>
<td>-0.771$^a$</td>
<td>-0.249$^a$</td>
<td>3.379$^a$</td>
</tr>
</tbody>
</table>

Means within column with the same letter are not significantly different at $\alpha = 0.05$ (Tukey test)

Relationships between nutrient concentration and CND indices at BBCH 17 and yields of white sugar are listed in Table 3. More significant relationships were obtained in 2001, when CND indices explained the best differences in plant yielding as did „pure” nutrient concentration (Tab. 3).
Table 3. White sugar yield as a function of nutrient content and CND indices – values of correlation coefficients (n = 20)

<table>
<thead>
<tr>
<th>Element/Index</th>
<th>Stage BBCH 17</th>
<th>For mean</th>
<th>Stage BBCH 43</th>
<th>For mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2001</td>
<td>2002</td>
<td>2003</td>
<td></td>
</tr>
<tr>
<td>Na</td>
<td>0.82***</td>
<td>0.48*</td>
<td>0.60**</td>
<td>0.74***</td>
</tr>
<tr>
<td>K</td>
<td>-0.05</td>
<td>-0.01</td>
<td>-0.26</td>
<td>-0.13</td>
</tr>
<tr>
<td>Ca</td>
<td>-0.84***</td>
<td>-0.05</td>
<td>-0.28</td>
<td>-0.75***</td>
</tr>
<tr>
<td>Mg</td>
<td>-0.72***</td>
<td>0.08</td>
<td>0.09</td>
<td>-0.42</td>
</tr>
<tr>
<td>P</td>
<td>-0.30</td>
<td>0.23</td>
<td>-0.16</td>
<td>-0.05</td>
</tr>
<tr>
<td>N</td>
<td>0.51*</td>
<td>0.10</td>
<td>0.32</td>
<td>0.39</td>
</tr>
<tr>
<td>$I_{Na}$</td>
<td>0.84***</td>
<td>0.42</td>
<td>0.64**</td>
<td>0.77***</td>
</tr>
<tr>
<td>$I_{K}$</td>
<td>0.59**</td>
<td>-0.40</td>
<td>-0.56*</td>
<td>-0.20</td>
</tr>
<tr>
<td>$I_{Ca}$</td>
<td>-0.85***</td>
<td>-0.23</td>
<td>-0.39</td>
<td>-0.76***</td>
</tr>
<tr>
<td>$I_{Mg}$</td>
<td>-0.72***</td>
<td>0.03</td>
<td>0.07</td>
<td>-0.46*</td>
</tr>
<tr>
<td>$I_{P}$</td>
<td>0.53*</td>
<td>0.01</td>
<td>-0.38</td>
<td>-0.06</td>
</tr>
<tr>
<td>$I_{N}$</td>
<td>0.70**</td>
<td>-0.27</td>
<td>-0.02</td>
<td>0.35</td>
</tr>
<tr>
<td>$I_{R}$</td>
<td>0.59**</td>
<td>-0.37</td>
<td>-0.36</td>
<td>-0.03</td>
</tr>
<tr>
<td>CND $r^2$</td>
<td>-0.75***</td>
<td>-0.15</td>
<td>-0.43</td>
<td>-0.58**</td>
</tr>
</tbody>
</table>

* , ** , *** - significant level for p ≤ 0.05; 0.01; 0.001; respectively

Fig. 2. White sugar yield in 2001 as a function of $INa$, $IN$ and $IMg$ indices at the BBCH 17 growth stage (n = 20)

In this year plants with high-yielding potential were characterized by $I_{Na}$, $I_{Mg}$ and $I_{N}$ indices, approaching zero (Fig. 2). A similar trend was also obtained for $I_{K}$ and $I_{P}$ indices, but for $I_{Ca}$ indices, highest yields were harvested for its level of -1.0.
On average, for three years of study, indices $I_{Na}$ and $I_{Ca}$ were found to influence the most the differences in sugar beet yields. The correlation coefficient between sugar yield and variables ($I_{Na}$ and $I_{Ca}$) representing all fertilization treatments were $r = 0.77^{***}$ and $r = 0.76^{***}$ (n = 20), respectively. In the treatment without manure, these relationships were more pronounced ($r = 0.80^{***}$ and $r = 0.82^{***}$; n = 10) as compared with the treatment with manure ($r = 0.46$ and $r = 0.48$).

Irrespective of the season, sugar yield increased along with decreasing CND$_{r^2}$ values (Tab. 3). However, the best relationship ($R^2$) was obtained in 2001 (Fig. 3).

![Fig. 3. White sugar yield as a function of CND$_{r^2}$ values at the BBCH 17 growth stage (n=20)](image)

At the stage BBCH 43 significant relationships between sugar yield and the chemical composition of plants were obtained in two consecutive growth seasons, 2001 and 2003. The main nutrients, which decided for the yield of sugar beet were potassium and calcium (Tab. 3). The elaboration of $I_{Na}$, $I_{Ca}$ and $I_{Mg}$ indices enabled a best assessment of biomass production, than assuming „pure” nutrient concentration in plants. However, this did not concern potassium. The obtained $I_K$ values explained well differences in yields, mainly between the manure treatments (Fig. 4).
Evaluation of plant nutritional status by the cnd method: case of sugar beet

Discussion

The values of CND-clr indices depended basically on a given growth season and sugar beet stage of development. Since the plant, indicatory parts at early growth stages are the most sensitive to changes of soil nutrient concentrations, this is why high values of $I_{\text{Mg}}$, $I_{\text{Ca}}$, and also $I_{\text{K}}$ were obtained at the stage of BBCH 17. However, the values of the remaining indices depended less on soil fertility, as recorded for $I_{\text{P}}$. At the first stage, a highest and negative influence of sodium fertilization on the content of cations, calcium, mainly, was observed. This result is confirmed by other papers [Wakeel et al. 2009]. The cause of this phenomenon should be searched out in the slight uptake of sodium, being disturbed by the competition with K$^+$, Ca$^{2+}$ and Mg$^{2+}$ ions [Mäser et al. 2002].

Weakest correlations between cations at the BBCH 43 growth stage implies that factors other than soil, have been acting. The increase of the $I_{\text{Na}}$ index in 2003 and its negative correlation with $I_{\text{K}}$ may be explained not only by the highest concentration of Na in soils, as compared with previous years, but also by unfavorable weather conditions. Under conditions of water shortage, sugar beet plants accumulate more sodium than potassium [Mäck and Hoffmann 2006].

As shown in the conducted experiments, the strength and direction of interactions between sugar yield and the values of nutritional indices depended on the vegetative season and a given nutrient. For some years, significant relationships were proven and support the legitimacy of making the evaluation of plant nutritional state
based on CND-clr indices. This concerns year 2001. For this particular year, the transformation of single nutrient concentration into CND-clr indices has raised $R^2$ of the investigated relationships. Less explicit data were obtained for both remaining years, where a plant represented a nutritional status closer to the standard – to a theoretical CND_r$^2$ values for high-yield subpopulation [Barłóg 2009]. This results from the fact, that for indices close to zero, any deviations of nutrient ratios from the optimal are slight and do not significantly influence the amount of harvested yield [Sumner 1979]. The positive role of sodium in sugar beet cropping, revealed mainly at early growth stage, as compared potassium. This result is in line with observations of physiological phenomena running in sugar beet leaves [Niazi et al. 2004].

In the light of the literature, the causes of the positive effect of sodium on sugar beet yield should be searched out via nonspecific reactions, resulting from the permutation of K functions by Na, and next the redistribution of K ions to sites more active physiologically or with highest requirements towards this nutrient [Subbarao et al. 2001, Wakeel et al. 2009]. Hence, sodium may participate in the translocation of nitrogen in plants [Subbarao 1999]. Some authors, have pointed out, that sodium may directly be involved in nitrates transportation [Garcia-Sanchez et al. 2000]. The improvement of plant resistance to water stress should result in an efficient assimilation of nitrogen [Hampe and Marschner 1982].

Data of the current study have revealed a slight effect of Na fertilization on $I_N$ indices. The lack of response may imply, that this nutrient shaped the most the chemical composition of old leaves, i.e. plant parts not evaluated in the current study [Mäck and Hoffmann 2006].

The theoretical CND_r$^2$ thresholds for high-yield subpopulation of sugar beet, for leaf blades of the 5th leaf at the BBCH17 and young leaves at the BBCH43 amounted respectively, 5.3 and 5.4 [Barłóg 2009]. Below these values, the state of plant balance in terms of nutrients has increased the probability of harvesting sugar yield higher than 9.4 Mg ha$^{-1}$. In the case of the current field trial, the yielding potential of plant was even higher. Generally, the CND_r$^2$ was smaller than theoretical CND_r$^2$ thresholds. The real sugar yields for the consecutive growth seasons followed: 9.8; 8.1 and 6.9 Mg ha$^{-1}$. Therefore, sugar beet has realized its yielding potential only in 2001, but for the next years (2002 and 2003), the causes of low yields were not related to nutritional factors. In 2002, sugar beet plantation was infected by Cercospora beticola, whereas in 2003, a water shortage took place during the vegetative growth period.

**Conclusions**

1. The CND-clr method allowed determining the upset of nutrient ratios, whereas the evaluation made by using „single” nutrient concentration has shown proper ranges for most of them.
2. Application of sodium has improved the mineral chemical balance of plants at BBCH 17 growth stage, due to increased Na share, and simultaneous a decrease of Ca in the multi-nutrient CND-clr complex.

3. Relationships between white sugar yield and nutrient concentration depended on sugar beet stage of growth as well as years of investigations. The transformation of nutrient concentrations into CND-clr indices as a rule increased $R^2$ values for tested relationships.

4. CND$_r^2$ indices may be used not only for evaluating the degree of nutrient imbalance in plants, but also for making a reliable prediction of crop plant yield.

References


dr hab. Przemysław Barłóg
Department of Agricultural Chemistry and Environmental Biogeochemistry
University of Life Sciences
Wojska Polskiego 71F
60-625 Poznań, Poland
e-mail: przembar@up.poznan.pl
Abstract

In over 40-year experiment localized in Czarny Potok near Krynica (20°54’53” E; 49°24’35” N) at an altitude of about 720 m a.s.l., the effect of diversified mineral fertilization on sward yield was investigated against the background of cultivation measures. The vegetation period in the area of the experiment lasts from April until September (150-190 days), and the weather conditions reveal a considerable rainfall variability. In order to present the results, the whole 42-year period of the investigations was divided into twelve stages according to conducted cultivation measures. The stage comprises the year in which the measure was initiated and the subsequent years, i.e. it’s direct or residual effect. The level of fertilization had a marked effect on the crop yield but caused a slight shift in the time at which the highest yields were obtained. Among the cultivation measures the greatest diversification of yield, especially from the second cut was caused by two-year breaks in fertilization. Restoring the yield forming potential was associated with a high variability in the subsequent years. Liming or micro elements application stabilized or increased the yields in the long run but the restoration of the yield forming potential of the hay meadow based on mineral fertilization is difficult, particularly in conditions of intensive nitrogen fertilization.

Key words: long-term fertilizer experiment, mountain meadow.

Introduction

Meadow’s sward responses to agricultural measures in a specific way. Undoubtedly, besides soil natural fertility, the level of fertilizer’s doses, mainly nitrogen is the factor which to the greatest extent modifies yields and their quality. It results, among the others from both direct and indirect influence of fertilization on the sward botanical composition. In the past, the effect of fertilization on grasslands was studied in various habitats, soil and climatic conditions [Spiegelberger et al. 2006, Honsova et al. 2007]. These effects are usually considerable on low yielding meadows, and such the habitats are far more susceptible to errors caused by methods of their management. Environmental aspects resulting from nitrogen utilization are
important in the scale of farm and region. Therefore, improving the fertilization methods seems significant particularly for grassland in the mountain areas. In spite of the common opinion about their considerable soil buffering, as a result of cultivation measures, these areas may contribute to excessive component losses, which decreases the economic effect and threatens the natural environment.

Mountain meadows are the important source of fodder for farm animals, particularly considering feed preparation for winter storage. The optimum levels of nitrogen fertilization may be different not only considering the habitat fertility and botanical composition, but also in conditions of different systems of meadow cutting. Bochi Brum et al. [2009] think that a negative effect of nitrogen fertilization on growth of legumes would be less pronounced in a three, not two-cut system. Biodiversity of permanent grasslands is commonly considered an important element of maintaining productivity and contributes to fodder quality improvement. This aspect is more and more frequently taken into account while considering the succession or recession of species due to the land use and natural processes. In some fertilizer experiments on grasslands in Europe, irrespective of obvious differences due to the habitat properties, factors somewhat similar to be researched in our experiment, were investigated [Rothamsted, 2006, Kopeć, 2000]. The experiments have been conducted against the background of fertilization with a single factor, with liming, with breaks in fertilization or discontinuing it. Frequently, the authors of the experiments came to the conclusion that the fertilizer dose must be diminished. It resulted from various reasons, e.g. changes in the soil chemistry or to a lesser degree from changes in fertilizer assortment available on the market. Undoubtedly, also due to the modifications mentioned above, results of long-term experiments provide a valuable base of information about the environment.

The aim of this paper was to determine the levels and trends of meadow sward dry mass yields over 42 years of the mountain static experiment with diversified fertilization against the background of liming. The results may contribute to planning and practical farming of mountain meadows with regard to their durability and sustainable management.

**Material and methods**

The experiment [Mazur, Mazur, 1972] is located in Czarny Potok near Krynica, (20°54′53″E; 49°24′35″N) at an altitude of about 720 m a.s.l. at the foot Jaworzyna Krynicka Mt. in the south-eastern massif of the Beskid Sądecki Mts. on aslope with 7° inclination and NNE aspect. The experiment was set up in 1968 on a natural mountain meadow of *Nardus stricta* L. and *Festuca rubra* L. type with a considerable share of the dicotyledonous. The soil from the experimental area was classified to acid brown soils developed from the Magura sandstone with granulometric composition of light silt loam (the following % of fractions: 1-0.1 mm40; 0.1-0.02 mm37; > 0.02 mm23)
Yield forming effects of cultivation measures in long-term fertilizer experiment on grass sward and characteristic three genetic horizons: AhA (0-20 cm humus horizon), ABr (21-46 cm browning horizon) and BbrC (47–75 cm parent rock). Detailed experiment data were presented in the previous papers [Kopeć 2000], in Tab. 1 and Fig. 1.

**Table 1. Soil properties before the experiment**

<table>
<thead>
<tr>
<th>Layer</th>
<th>pH\textsubscript{H2O}</th>
<th>pH\textsubscript{KCl}</th>
<th>Hh</th>
<th>Hw.</th>
<th>P</th>
<th>K</th>
<th>Exchangeable ions [mg \cdot kg(^{-1}) soil]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[cmol (+) kg(^{-1}) soil]</td>
<td>[mg kg(^{-1}) soil]</td>
<td>Ca</td>
</tr>
<tr>
<td>0-10 cm</td>
<td>5.20</td>
<td>4.38</td>
<td>4.42</td>
<td>0.46</td>
<td>4.8</td>
<td>112.0</td>
<td>680</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>5.58</td>
<td>4.48</td>
<td>4.04</td>
<td>0.65</td>
<td>2.6</td>
<td>23.3</td>
<td>540</td>
</tr>
</tbody>
</table>

The one factorial experiments experiment, carried on in 5 replications included 8 fertilizer treatments (Tab. 2).

**Table 2. Fertilization scheme in the static experiment in Czarny Potok**

<table>
<thead>
<tr>
<th>Fertilizer objects</th>
<th>Annual dose of the element in series 0Ca and +Ca (1985, 1995, 2005) kg \cdot ha(^{-1})</th>
<th>Nitrogen fertilizer</th>
<th>Microelements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P</td>
<td>K</td>
<td>N</td>
</tr>
<tr>
<td>„0“</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N(_1)</td>
<td>-</td>
<td>-</td>
<td>90 ammonium nitrate</td>
</tr>
<tr>
<td>P</td>
<td>39.24</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PK</td>
<td>39.24</td>
<td>124.5</td>
<td>-</td>
</tr>
<tr>
<td>PK+(N_{1an})</td>
<td>39.24</td>
<td>124.5</td>
<td>90 ammonium nitrate</td>
</tr>
<tr>
<td>PK+(N_{1u/an})</td>
<td>39.24</td>
<td>124.5</td>
<td>90 urea to 2004/ ammonium nitrate from 2005</td>
</tr>
<tr>
<td>PK+(N_{2an})</td>
<td>39.24</td>
<td>124.5</td>
<td>180 ammonium nitrate</td>
</tr>
<tr>
<td>PK+(N_{2u/an})</td>
<td>39.24</td>
<td>124.5</td>
<td>180 urea to 2004/ ammonium nitrate from 2005</td>
</tr>
</tbody>
</table>

0 mikroe. – without microelements; P = 39.24 kg P, K = 124.5 kg K; a.n. ammonium nitrate; u. urea; 0 Ca unlimed series; + Ca limed series
Since autumn 1985 the experiment, at the same doses of NPK fertilizers, has been conducted in two series, without liming and with lime application. In 1995 and 2005 liming was repeated. In 1985 and 2005 years the dose of limestone was calculated according to 0.5 Hh and in 1995 according to 1 Hh. In the years 1974–1975 and 1993–1994 no mineral fertilization was applied, and the research was limited to determining the sward yield and its chemical composition.

In 1968–1980 phosphorus and potassium fertilizers were applied in autumn. Since 1981, phosphorus fertilizers have been applied in spring, and potassium fertilizers in half dose in spring and half in summer, after the 1st cut. Phosphorus in the years 1968–1973 was in form of calcium thermophosphate (superthomasine) in the years 1975-1992 as triple superphosphate (46%) and since 2005 as enriched superphosphate (40%). In the whole period of the experiment 2/3 of the nitrogen fertilizers annual dose has been in spring at the beginning of vegetation and 1/3 of the dose about two weeks after 1st cut. In 1994, a single dose of 10 kg Cu and 8 kg Mg ha⁻¹ in solid fertilizers were applied. In the years 2000–2004 foliar fertilization was conducted (twice 2 dm³ ha⁻¹) using Mikrovit-1 fertilizer. The fertilizer contained in 1 dm³: 23.3 g Mg; 2.3 g Fe; 2.5 g Cu; 2.7 g Mn; 1.8 g Zn; 0.15 g B and 0.1 g Mo. In the 2005–2007 periods, 0.5 g B per 1 h was supplied to the soil every year, whereas in the spring, 2008, 5 kg Cu, Zn and Mn ha⁻¹ and 0.5 kg of Co and Mo ha⁻¹ were added.

Vegetation period in the experimental area lasts from April to September (150–190 days). The weather conditions (Tab. 3) indicate a considerable rainfall variability.

Table 3. Statistical characteristics of precipitation and temperatures for the period 1968–2008

<table>
<thead>
<tr>
<th>Parametr</th>
<th>Precipitation [mm]</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I–XII</td>
<td>IV–IX</td>
</tr>
<tr>
<td>Arithmetical mean</td>
<td>876.4</td>
<td>568.5</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>198.7</td>
<td>138.0</td>
</tr>
<tr>
<td>Range 25-75% of cases</td>
<td>733.2–990.0</td>
<td>461.5–658.2</td>
</tr>
</tbody>
</table>

Yields of sward fresh masses were harvested from each plot twice a year (at the turn of June and July and in September), in the initial period from the area of 42 m² and when liming was introduced from a 21 m² plot. After dry mass determination yield, samples were converted into t d.m. ha⁻¹.

During over a 40-year period of the experiment various aims were set and research hypotheses were put forward. For the sake of presentation, the whole period
of research (42 years) was divided into several-year stages (Tab. 4) according to the applied cultivation measures. The stages cover the year of the measure application as the subsequent years i.e. its direct and residual effect.

**Table 4. Stages of the experiment**

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Period</th>
<th>Description of the stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1968–1970</td>
<td>3-year period of introducing fertilization</td>
</tr>
<tr>
<td>2</td>
<td>1971–1973</td>
<td>3-year period of experiment continuation</td>
</tr>
<tr>
<td>3</td>
<td>1974–1976</td>
<td>1st break in fertilization (for two years) and the year of fertilization resumption</td>
</tr>
<tr>
<td>4</td>
<td>1977–1980</td>
<td>4-year period after resumption of fertilization</td>
</tr>
<tr>
<td>5</td>
<td>1981–1984</td>
<td>4-year period of fertilization continuation</td>
</tr>
<tr>
<td>6</td>
<td>1985–1988</td>
<td>4-year period of fertilization continuation after introduction of liming</td>
</tr>
<tr>
<td>7</td>
<td>1989–1992</td>
<td>4-year period of fertilization continuation</td>
</tr>
<tr>
<td>8</td>
<td>1993–1995</td>
<td>2nd break (2years), introduction of a single grazing, the year of NPK resumption, Cu and Mg application and repetition of liming</td>
</tr>
<tr>
<td>9</td>
<td>1996–1999</td>
<td>4-year of fertilization continuation</td>
</tr>
<tr>
<td>10</td>
<td>2000–2004</td>
<td>5-year period of fertilization continuation with annual twofold application of foliar microelement fertilization</td>
</tr>
<tr>
<td>11</td>
<td>2005–2007</td>
<td>3-year period of fertilization continuation, replacement of urea by ammonium nitrate, fertilization B applied every year</td>
</tr>
<tr>
<td>12</td>
<td>2008–2009</td>
<td>2-year period of fertilization continuation with a single soil treatment with Zu, Zn, Mn, Co and Mo.</td>
</tr>
</tbody>
</table>

In the first period, which covered the years 1968–1975, the research focused on the effect of various levels of fertilization on the yield and quality of grassland sward established as a result of natural turfing of abandoned arable land. It was the period of fertilizer industry development in Poland. The agricultural usefulness of ammonium nitrate and urea as a new fertilizer in Poland, has been compared. Nutrient doses were comparatively high; however, plant nutrient requirements for a potential yield were taken into account. At that time agriculture in mountain conditions was rather extensive and intensification process pursued only slowly. Therefore, in the period 1974-1975 fertilization was ceased, assuming a residue effect of applied nutrients. Two years later fertilization was resumed on the same level at the native...
treatments. The former researches show diversification of botanical composition and soil properties, which indicated a necessity sward liming. After seventeen years, fertilization with sodium carbonate was applied, assuming an improvement in soil pH and supplementing sodium content in the sward. Since 1985, the experiment was conducted in two series: without liming and with limestone application (Fig. 1) in 10-year cycles.

Economic transformation, which took place in Poland in the nineties of the 20th century caused a dramatic decline in fertilizer’s consumption in the whole country. It has been decided to mimic these changes on the scale of the experiment. Therefore, another break in fertilization for two years was administered. Another change was to include the single sheep grazing in the experiment. The liming was repeated in 10-year cycles (1995, 2005). While seeking possibilities of restoring yield forming potential in the subsequent years attention was focused on magnesium and microelement deficiencies. Magnesium and copper were supplied once to the soil and then foliar application of the multi microelements fertilizer was used for five years. In 2005, boron was added to the soil and then a set of basic microelements in doses, which should have improved their bioavailability previously limited by a systematic removal of these elements with the yield. The main aim of all agronomic measures was maintaining the grassland productive potential, by their influence on the quality of sward and the soil properties has been analyzed as well. The polygon of the experiment was also used in research on nutrient leaching, changes in humus content, microbial and enthomofauna activity and to determine heavy-metal cycling in agrocenosis.
Results

From the beginning of the experiment (stage 1), it was noted that fertilization had a significant effect on the dry mass yields of meadow swards (Fig. 2).

At the first three-year stage of the experiment, it was found that fertilization levels caused diversification of yields, leading to a considerable increase in yields at bigger nitrogen doses. The greatest yield obtained in the experiment at this stage was over 5-fold larger than in the series without liming and referred to the treatments receiving 180 kg N+PK. Nitrogen applied against the PK fertilization background increased the yields from 2.1 to 2.8-fold, depending on the dose. At the second stage, an average increase in yield on individual treatments, against the average value from the first stage, was the highest for fertilization with P (32%) and PK (70%). At full fertilization using a dose of 90 kg N kg\(^{-1}\) the increase was only between 12 and 20% because of bigger yields obtained earlier. The total yield on the other treatments was within the error limits of standard deviation.

Mountain meadow yielding during the 2-year period of the 6-year residual effect (1968–1974) of fertilization depended on the degree to which the plants utilized elements from previously used fertilizers. The two-year break in fertilization radically
diminished production potential of the meadow sward. Residual effect of nitrogen fertilization was small and pronounced only in the first year. Full fertilization with an increased nitrogen dose had the weakest residual effect, while PK fertilization had the strongest effect. As it has been demonstrated by the range of inside dispersion, yield forming potential of meadow sward yields after reintroduction of the fertilization was restored only several years after resuming fertilization at stages 4 and 5.

In the previous paper, the authors of the experiment, Mazur and Mazur [1984] registered the greatest yield in the 14th year of the experiment, and these were 10 fold larger in comparison with the yields gathered before the fertilization. However, this was the year when the yield of 14.5 t d.m. ha\(^{-1}\) was harvested. The highest efficiency of fertilization was obtained when double doses of nitrogen (180 kg N ha\(^{-1}\)) were applied. Average annual yields on these treatments during the period of two stages (4–5) were the biggest for the period of the whole experiment and ranged from 10.29–10.76 t d.m. ha\(^{-1}\) and 1st cut on the level of 5.91–6.46 t d.m. ha\(^{-1}\).

Usually, yield variability, represented as internal dispersion at individual stages, was small on treatments receiving unilateral fertilization. On treatments where full fertilization was used for 1st cut, particularly with 180 kg N+PK dose, variability was considerable. In the first place, differences in yield between years on a level of about two tons of dry mass per hectare were registered when the biggest yields were harvested. Along with the reduction of yielding, a decline in the internal dispersion occurred on the individual treatments, except for the sward response at the stage after third liming, including boron fertilization [stage 11].

After 25 years of the experiment, an attempt was made to forecast yielding based on determined second degree polynomial functions [Kopeć and Mazur 1995]. A growing trend of yields was noted in this period on the treatment where phosphorus and potassium fertilization was applied. A lack of significance of yielding trend was characteristic on the treatments with unilateral nitrogen or phosphorus fertilization. Forecasting of yielding based on results for 25 years of the experiment was burdened with a big error resulting from considerable rainfall and temperature variability in individual months. A long-term effectiveness of liming was proven for diversified sward of treatments fertilized with balanced doses of mineral fertilizers [Kopeć et al. 1997]. These results were not unanimously corroborated in the present synthesis. Present investigations revealed only a slight effect of liming on meadow sward dry mass yields over a longer period of time. Average for 24-year yields (Tab. 5, Fig. 3) comprising three-fold liming did not differ significantly on individual treatments between the limed series and the series without liming.
Only in the sward fertilized with 180 kg N+PK in the case of both fertilizers, differences in sward dry mass yields were registered between the limed series and the series without liming. The tendency concerned 1st cut, which had only slight influence on the difference in the annual total yield. At stage 12, a positive effect of combined microelement fertilization and liming was pronounced. Significance level in the independent sample test (Tab. 5) was always higher than 0.05, but the smallest for fertilization with ammonium nitrate dosed 180 kg N+PK. Differences between average yields on treatments fertilized with 180 kg N were 0.45 and 0.57 t d.m. ha\(^{-1}\) and on treatments fertilized with 90 kg N+PK 0.15 and 0.24 t d.m. ha\(^{-1}\). These results show that a greater liming effect was more marked on more intensively fertilized treatments. Most probably species diversification of sward caused by liming and occurrence of grass species better utilizing nitrogen, causes an increase in the yield.
Table 5. Statistics of yields on fertilizer treatments obtained after introduction of liming (from 1985 to 2009, stages 6–12, n = 24)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PK</th>
<th>PK+N₁an</th>
<th>PK+N₂an</th>
<th>PK+N₁u/an</th>
<th>PK+N₂u/an</th>
<th>N₁an</th>
<th>P</th>
<th>„0”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetical mean</td>
<td>4.88</td>
<td>5.86</td>
<td>6.15</td>
<td>5.96</td>
<td>6.14</td>
<td>3.96</td>
<td>3.53</td>
<td>2.79</td>
</tr>
<tr>
<td>Median</td>
<td>5.20</td>
<td>5.52</td>
<td>6.15</td>
<td>5.65</td>
<td>5.96</td>
<td>3.99</td>
<td>3.34</td>
<td>2.70</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.18</td>
<td>1.43</td>
<td>1.42</td>
<td>1.44</td>
<td>1.40</td>
<td>1.01</td>
<td>0.91</td>
<td>0.57</td>
</tr>
<tr>
<td>Sum</td>
<td>117.13</td>
<td>140.72</td>
<td>147.48</td>
<td>143.01</td>
<td>147.46</td>
<td>95.11</td>
<td>84.69</td>
<td>66.88</td>
</tr>
<tr>
<td>V%</td>
<td>24.21</td>
<td>24.34</td>
<td>23.05</td>
<td>24.16</td>
<td>22.71</td>
<td>25.50</td>
<td>25.75</td>
<td>20.42</td>
</tr>
<tr>
<td>Minimum</td>
<td>2.95</td>
<td>2.32</td>
<td>2.55</td>
<td>2.88</td>
<td>2.50</td>
<td>2.23</td>
<td>1.99</td>
<td>1.62</td>
</tr>
<tr>
<td>Maximum</td>
<td>6.99</td>
<td>8.08</td>
<td>9.22</td>
<td>8.90</td>
<td>9.07</td>
<td>6.59</td>
<td>5.97</td>
<td>3.73</td>
</tr>
<tr>
<td>Range 25-75% of cases</td>
<td>3.76-5.98</td>
<td>5.05-6.99</td>
<td>5.52-6.89</td>
<td>5.03-6.96</td>
<td>5.29-7.08</td>
<td>3.42-4.45</td>
<td>3.06-4.09</td>
<td>2.33-3.19</td>
</tr>
<tr>
<td>Arithmetical mean</td>
<td>5.10</td>
<td>6.10</td>
<td>6.72</td>
<td>6.11</td>
<td>6.59</td>
<td>4.25</td>
<td>3.56</td>
<td>2.76</td>
</tr>
<tr>
<td>Median</td>
<td>5.18</td>
<td>5.88</td>
<td>6.64</td>
<td>5.70</td>
<td>6.76</td>
<td>4.25</td>
<td>3.40</td>
<td>2.81</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.98</td>
<td>1.40</td>
<td>1.49</td>
<td>1.41</td>
<td>1.58</td>
<td>0.97</td>
<td>0.98</td>
<td>0.53</td>
</tr>
<tr>
<td>Sum</td>
<td>122.37</td>
<td>146.37</td>
<td>161.39</td>
<td>146.61</td>
<td>158.21</td>
<td>101.96</td>
<td>85.41</td>
<td>66.19</td>
</tr>
<tr>
<td>V%</td>
<td>19.31</td>
<td>22.91</td>
<td>22.21</td>
<td>23.05</td>
<td>24.02</td>
<td>22.84</td>
<td>27.42</td>
<td>19.14</td>
</tr>
<tr>
<td>Minimum</td>
<td>3.39</td>
<td>3.24</td>
<td>3.28</td>
<td>3.30</td>
<td>2.66</td>
<td>2.31</td>
<td>2.51</td>
<td>1.45</td>
</tr>
<tr>
<td>Maximum</td>
<td>6.80</td>
<td>8.95</td>
<td>9.03</td>
<td>8.33</td>
<td>9.95</td>
<td>6.24</td>
<td>6.82</td>
<td>3.54</td>
</tr>
<tr>
<td>Range 25-75% of cases</td>
<td>4.59-5.92</td>
<td>5.17-6.99</td>
<td>5.98-7.72</td>
<td>5.08-7.35</td>
<td>5.59-7.47</td>
<td>3.52-4.99</td>
<td>2.78-4.20</td>
<td>2.48-3.10</td>
</tr>
<tr>
<td>p – independent test</td>
<td>0.490</td>
<td>0.567</td>
<td>0.174</td>
<td>0.717</td>
<td>0.304</td>
<td>0.324</td>
<td>0.912</td>
<td>0.856</td>
</tr>
</tbody>
</table>
Three cuts of sward may be justified by production, economic and environmental factors in the mountain conditions. A better fodder quality may be achieved in this way (more *Fabaceae* plants), and the environmental effect of large nitrogen doses may be limited. The competition between grasses, and *Fabaceae* plants would favor a higher utilization of nutrients applied with fertilizers. However, under conditions in Poland, it requires a change of the whole harvest technology as well as keeping farm animals. Still, in the long run, application of conservative liming and microelements would be an absolute necessity. Due to diversified botanical composition of the meadow community, it is difficult to point out a specific microelement which should balance the deficiency resulting from the soil abundance. In the sustainable farming on mountain hay meadows, the increase in productivity achieved through fertilization and practical management of this measure should be treated as the basic tools in protection of the natural environment, i.e. the such factors as species biodiversity or a hazard of underground water pollution [Hooper et al. 2005, Isselstein et al. 2005]. Spiegelberger et al. [2006] stated that even short-lasting and slight disturbances may have a long-lasting effect on mountain grasslands. Effects of these changes occur despite a considerable richness of species, which is commonly perceived as an indicator of high resistance [Hooper et al. 2005]. Various long-term results of liming and soil fertilization on the sward botanical and soil microorganisms composition indicates that resistance of mountain grasslands may differ depending on the kind of changes caused in the ecosystem. It was suggested that soil pH would be an indicator of mountain ecosystem resistance. Syntheses of research papers [Hooper et al. 2005, Isselstein et al. 2005, Hajcman et al. 2007] suggest that ecosystem resistance is conditioned by many elements, among others: soil nutrient abundance, ecosystem functions or ecological diversification. It is thought that the time necessary to regain ecosystem balance after disturbance is similar to the time of nutrient turnover in the system. Ecosystem resistance may be particularly small in the face of extreme environmental condition’s effect. It may differentiate not only ecosystems but also their components and processes within the same ecosystem. For instance: recovering vegetal cover may be relatively fast, whereas recovering botanical composition of plants may be much slower.

Researches conducted in Czarny Potok point to a necessity for long-term experiments on grasslands because they allow to determine deviations from trends in individual variants. Some of the effects of applying the experimental factors, including fertilizers, may be determined many years after their application. Wasilewski [1998] reached similar conclusions stating that fertilizer renovation measures on grasslands have a positive effect in a longer perspective than the 3-year period of studies, particularly in the case of big nitrogen doses.
Conclusions

1. The level of fertilizer dose has a significant effect on the crop yield simultaneously causing a slight shift in time at which the highest yields are obtained.
2. The other cultivation measures generally cause similar response of the sward measured by the yield from individual treatments. The greatest diversification is caused by two-year breaks in fertilization, particularly in 2nd cut yields, whereas restoration of the yield forming potential is connected with a considerable variability in the subsequent years.
3. Doses of calcium or microelement fertilizers assumed on the basis of recommendations stabilize or increase yields in the long run.
4. Reconstruction of the yield forming potential of abandoned meadow using of mineral fertilization is difficult, especially in the conditions of intensive nitrogen fertilization.

References


Yield forming effects of cultivation measures in long-term fertilizer experiment on grass sward


Prof. dr hab. Michał Kopeć
Department of Agricultural and Environmental Chemistry, University of Agriculture in Krakow
Al. Mickiewicza 21, 30-120 Kraków
m.kopec@ur.krakow.pl
DIAGNOSTICS OF FERTILIZATION REQUIREMENTS IN A SITE-SPECIFIC FERTILIZER MANAGEMENT

Alicja Pecio

Institute of Soil Science and Plant Cultivation – State Research Institute, Puławy

Abstract

The paper presents selected results of the investigations carried out since 1997 in the Baborówko Experimental Station (near Poznań) belonging to the Institute of Soil Science and Plant Cultivation – State Research Institute in Puławy, Poland. The experiment has been conducted with the method of scientific observations. The experimental field of 50 ha area has been split into three plots on which winter rape, winter wheat and spring barley were grown in succession. On the area of the whole field, 403 observation points have been permanently marked using GPS device. In these points, every third year, the soil samples were collected from the plow layer. These samples were analyzed for pH, soil organic matter SOM and the content of available phosphorus, potassium and magnesium. Soil map has been drawn in the scale 1:500 and granulometric soil composition was estimated in the samples with laser method. Crop yields have been harvested by combine harvester provided with continuous yield meter and GPS device. The yield map prepared by the combine computer was approximated to the yield in the observation points.

In the paper, the results concerning soil analysis performed in 2008 years and the average yields of crops for the years 2000-2002 are presented. The main aim of the research was to calculate the relation between soil properties and the relation between soil properties and the crop yields, and to develop the maps of fertilizer rates with recognition of variation of soil properties within the experimental field. The doses of phosphorous, potassium and magnesium fertilizers were calculated based on spatial variability of nutrients content in soil and changeability of crop yields. Quantity of fertilizers used in compliance to the precision agriculture and according to a traditional system was compared. It was stated that the consumption of fertilizers in both systems has been very similar. However, differentiation of fertilizer’s consumption in conditions of ES Baborówko was quite meaningful.

Key words: soil variability, scientific observation, site specific fertilization, variability of fertilizer rate, fertilizer utilization
Introduction

The concept of adoption the agricultural measures, especially fertilization to the soil differentiation within the field became increasingly common. In the literature, this type of management is named as site-specific agriculture or not very correctly as precision agriculture [Berry 1998]. Differentiation of agronomical measures, including fertilizer rates, is based on the recognition of field spatial variability [Franzen et al. 2002, Hejting 2011, Sawyer 1994]. This procedure aims to limit fertilizers use, increase their efficiency, and in consequence, to increase the field productivity [Boyer 2011, Havlin and Heiniger 2009].

The first in Poland Experimental Station focused on the site-specific agriculture was established at Baborówko in 1990. The main aim was to recognize spatial and temporal variability of basic soil properties on the area of about 50 ha production field. In the paper, some data on the differentiation of soil agrochemical properties and crop productivity are presented. The purpose of the study was to check out if differentiation of fertilizer rates on the area of production field enables to limit fertilizer’s doses in comparison to the traditional method with uniform fertilization.

Material and Methods

The experimental field (about 50 ha) was set up in 1992 at Baborówko Experimental Station of IUNG-PIB located near Szamotuły in monotonous agricultural landscape of Wielkopolska in Western Poland. The field was split into three plots on which winter rape, winter wheat and spring barley have been grown in succession. Soil agricultural map in 1:500 scales was drawn and a net of observation points in the grid of 36 x 36 m was established by GPS. The total number of the points equaled to 403. In these points soil samples from plough layer were taken each third year. The samples were analyzed for pH, content of organic matter, and available forms of phosphorus, potassium and magnesium. The crops were harvested by Massey Ferguson combine equipped with continues yield meter and GPS, which enabled yield mapping. It was one of the first “satellite” cereal crops combine in Poland and certainly the first one used in-field experimentation. After harvest, the straw of each crop was cut and ploughed into soil with no addition of nitrogen. On the area of the whole field, the uniform traditional plough tillage system and integrated fertilization and plant protection specific for cultivated crops were applied. Because no manure was used, the straw and mineral fertilizers were the only source of nutrients. Fertilizer doses were calculated based on NawSald advisory system developed at IUNG-PIB for each of 403 observation point.
Results

Basic soil properties

Soils on the area of the experimental field were differentiated mainly by soil texture and soil suitability complex. In the plough layer, light soils of sandy clay (pgl), clay sand (pgm) and clay (gl) prevailed (fig. 1).

Fig. 1. Map of soil texture

Fig. 2. Map of soil usability complexes
Most of the soils belonged to rye very good (4), rye good (5) and rye poor complexes. Some areas were also covered by soils of wheat good complex (fig. 2).

In 2008 year, granulometric soil composition analysis by new in Poland laser method was completed in the soil samples taken from observation points. The analysis was performed in Agrochemical Laboratory at Lublin, Poland. The results integrated to soil agronomical categories are presented in the form of a point diagram (fig. 3). The figure shows light and very light soils on the most field area.

![Map of soil categories](image)

**Fig. 3. Map of soil categories**

**Agrochemical soil properties**

Soil samples were taken from plough layer of observation points every third year. Soil samples were analyzed for pH and the content of available forms of phosphorus, potassium and magnesium. Every sixth year, the content of soil organic matter content was determined. From the beginning of investigation agrochemical soil properties have been determined five times and humus content three times. In the paper, the results of agrochemical soil analysis completed in 2008 are presented. The results are presented in the form of point diagrams as classes of pH and the nutrient contents.

Soil on the majority of the field was slightly acid or neutral (fig. 4). Only in some points it was acid. Throughout 15 years history of experimental field lime or dolomite lime was applied twice. However, the soil reaction still showed high variation on the area of the field.
Available phosphorus content was also differentiated. The content ranged from low to very high and showed spatial irregularity on the area of the field. Despite high phosphorus fertilizer doses during 15 years, the content of available forms of phosphorus systematically decreased. In the following crop rotations, coefficient of variation didn’t change, either.
The content of available potassium was also strongly differentiated on the area of the experimental field (fig. 6). Contrary to the phosphorus, soils with medium and high potassium content prevailed. At the study period, mean available potassium content increased but a coefficient of variability was stable. Even relatively high doses of potassium supplied with fertilizers did not align the soil abundance in this nutrient on the area of production field.

**Fig. 6. Map of available potassium content**

**Fig. 7. Map of available magnesium content**
The content of available magnesium was high or very high on the majority of the field area (fig. 7). The small areas were characterized by medium content of the nutrient. High soil abundance in magnesium resulted from magnesium lime applied twice in the first years of the study. However, during 12 following years after liming soil abundance in magnesium slightly decreased.

Soil organic matter content ranged from 0.6 to 2.2 % (median 1.14) and was rather low according to European standards (fig. 8). High variability of SOM content resulted from different soil types, including black earths, and differentiation of soil texture. In the 15 years period organic matter content was determined three times, and it showed increasing tendency. It might be explained by high quantity of rape and cereal straw ploughed into soil every year. Therefore, it might be concluded that the agricultural system without farmyard manure and leguminous makes possible to maintain a constant SOM content providing that straw of the crops is not removed from the field.

Fig. 8. Map of the soil organic matter SOM content

The above soil parameters were integrated into one synthetic index of soil fertility, proposed by Filipiak (2011). Its values ranged from -3.98 to 8.23 with 0.23 median (fig. 9). The index explained almost 70% of general variation of the analyzed agrochemical soil properties. The usefulness of the index is proven by significant correlation (R=0.44) with relative crop yields, content of potassium (R=0.84), magnesium (R=0.77) and organic matter (R=0.91). It did not depend on soil reaction nor phosphorus content. This might be explained by stable soil reaction on the whole field and by high or very high abundance of available phosphorus.
Fig. 9. Synthetic index of soil fertility, including pH, the content of available P, K, Mg and the content of soil organic matter

Soil productivity (relative yields)

Fig. 10. Map of the relative soil productivity
The whole production field was split into three crop rotation fields, where winter rape, winter wheat and spring barley were cultivated each year. For many reasons as including other crops on small areas or accidents of the combine yield meter, the field productivity was estimated based on the date from 2000-2002. The interpretation included nine crop yields (three years and three crops). Spatial field productivity was expressed in each observation point by the deflection percent from mean yield for the whole field, and digital map was developed (fig. 10).

The productivity of the experimental field varied from 50 to 200% of mean productivity based on nine crop harvests. Due to small differentiation of stable soil properties (soil texture and agricultural usefulness) on a majority of the field area its productivity was differentiated in the smaller range from 75 to 125% of mean value.

**Fertilization requirements in traditional and precision agriculture systems**

Uptake of nutrients in the traditional tillage system was calculated on the base of mean yields of cultivated crops (tab. 1). Fertilization requirements were estimated by multiplying nutrient uptake with crop yield by coefficients adequate to the most typical content of a nutrient. The coefficient equaled to 1 for mean content of phosphorus, 0.75 for high content of potassium and 0.5 for very high content of magnesium.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Yield t·ha⁻¹</th>
<th>Nutrient uptake (kg·ha⁻¹)</th>
<th>Fertilizer requirements (kg·ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P</td>
<td>K</td>
</tr>
<tr>
<td>Winter rape</td>
<td>3.18</td>
<td>21.6</td>
<td>27.7</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>6.52</td>
<td>23.5</td>
<td>26.2</td>
</tr>
<tr>
<td>Spring barley</td>
<td>3.71</td>
<td>13.0</td>
<td>17.8</td>
</tr>
</tbody>
</table>

In calculations of fertilizer doses for precision agriculture purposes nutrients contents determined in the soil of 403 observation points were considered. Phosphorus content ranged from the very low (<5.0 mg P₂O₅·100 g⁻¹ of the soil) to the very high (>20.1 mg P₂O₅·100 g⁻¹ of the soil). Content of potassium ranged from 5.1 to 30.8 mg K₂O·100 g⁻¹ of the soil and was adequate for ranges from low to very high content. Magnesium content ranged from low (2.6) to very high contents. Estimation of soil
abundance in potassium and magnesium, according to Polish rules, considered soil agronomical category.

Crop yields in observation points were determined on the basis of mean crop yield obtained on the area of the whole field and relative value in a point. For each observation point nutrient uptake was calculated as a ratio of yield and unit uptake. Ranges of the yields and uptake are presented in table 2.

**Table 2. Ranges of the crop yields and uptake of nutrients in the precision agriculture system**

<table>
<thead>
<tr>
<th>Crop</th>
<th>Yield (t·ha⁻¹)</th>
<th>Nutrient uptake (kg·ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Winter rape</td>
<td>1.67 – 4.37</td>
<td>11.4 – 29.7</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>3.43 – 8.95</td>
<td>12.4 – 32.2</td>
</tr>
<tr>
<td>Spring barley</td>
<td>1.95 – 5.08</td>
<td>6.8 – 17.8</td>
</tr>
</tbody>
</table>

Requirements of fertilization were calculated as a ratio of nutrient uptake in a specific observation point and coefficient adequate for soil abundance in the point. The ranges of the fertilizer requirements adequate for doses of mineral fertilizers are included in table 3. Comparing to the doses estimated according to the traditional recommendation system the doses calculated according to the precision agriculture system ranged from 29 to 167% for phosphorus, from 40 to 184% for potassium and from 61 to 234% for magnesium.

**Table 3. Ranges of crop fertilization requirements in the precision agriculture system**

<table>
<thead>
<tr>
<th>Crop</th>
<th>Fertilizer dose (kg·ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P₂O₅</td>
</tr>
<tr>
<td>Winter rape</td>
<td>14.3 – 82.7</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>15.5 – 89.8</td>
</tr>
<tr>
<td>Spring barley</td>
<td>8.6 – 49.5</td>
</tr>
</tbody>
</table>

The following pictures (fig. 11) present the differences between nutrient doses calculated for precision agriculture and according to traditional recommendations for winter rape. Negative values show the areas where mean dose for the whole field was too high comparing doses calculated for specific points on the base of a nutrient soil content. Positive values indicate too low mean doses comparing real requirements.
Fig. 11. The difference between the nutrient dose in precision and traditional agriculture

It was assumed that if the dose calculated in the traditional system varies from the precision system in a point no more than 10% it can be recognized as optimal. According to such assumption phosphorus doses in 25% of points were recognized as optimal, in 27 points as understated and in 48%, they were overstated comparing to requirements. In the case of potassium, the doses were optimal in 28% of points and 36% under- and overstated. Magnesium dose was well adjusted in 35% of points, in 55% it was understated and in 10% - overstated comparing requirements. The percentage of points equals to the percentage of the field area.

Consumption of fertilizers
Fertilizer consumption in the traditional system was calculated as a ratio of fertilizer dose and field area. In precision agriculture, total fertilizer consumption for the field was calculated as a sum of consumption on the specific areas represented by observation points (403 units, 1296 m² each). Such way is reasonable since observation points were located in the tops of 36 x 36 m square and therefore, each point represented the same area. Fertilizer consumption is presented in table 4.

**Table 4. Fertilizer consumption in kg per field**

<table>
<thead>
<tr>
<th>Crop</th>
<th>Fertilization system</th>
<th>P₂O₅ (kg)</th>
<th>K₂O (kg)</th>
<th>MgO (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter rape</td>
<td>traditional</td>
<td>2585</td>
<td>1300</td>
<td>358</td>
</tr>
<tr>
<td></td>
<td>precision</td>
<td>2355</td>
<td>1354</td>
<td>446</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>traditional</td>
<td>2806</td>
<td>1318</td>
<td>367</td>
</tr>
<tr>
<td></td>
<td>precision</td>
<td>2609</td>
<td>1372</td>
<td>457</td>
</tr>
<tr>
<td>Spring barley</td>
<td>traditional</td>
<td>1552</td>
<td>836</td>
<td>226</td>
</tr>
<tr>
<td></td>
<td>precision</td>
<td>1410</td>
<td>869</td>
<td>279</td>
</tr>
</tbody>
</table>

Marked differences in fertilizer consumption in traditional and precision fertilization systems were obtained only in the case of phosphorus. In precision system, phosphorus consumption for winter wheat would be lower by 7% e.g. about 200 kg P₂O₅ than in the traditional system. In the case of spring barley and winter rape, the saving of phosphorus fertilizers would equal to 9%, what means 142 and 230 kg P₂O₅ respectively. The consumption of potassium fertilizers in the precision system would be by 4% higher than in the traditional system, what is adequate to 54 kg K₂O for wheat, 33 kg K₂O for barley and 54 kg K₂O for rape. Relatively, the highest differences were related to magnesium fertilizers. According to precise recommendations, their consumption would be higher by about 24% than according to traditional recommendations. In absolute values, it would equal to 90 kg MgO for wheat, 53 kg MgO for barley and 88 kg MgO for rape.

**Summary**

In 1979 Experimental Station Baborówko, belonging to the Institute of Soil Science and Plant Cultivation was set up with the aim of introducing new methods of experimentation on the big fields applying precision agriculture approach. The Station was provided with the first in Poland combine harvester equipped with the continuous yield meter and the GPS device. Experimental field 50 ha in the area was marked with GPS by 403 fixed points for conducting the regular observation of soil and canopy properties. The field was split into three plots on which winter rape, winter wheat and spring barley have been grown in succession. In the observation points soil samples are collected in three-years intervals and analyzed for the pH, soil organic matter SOM, and the content of available forms of phosphorus, potassium.
and magnesium. In the paper, the results of soil analysis in the samples collected in 2008 and the average crop yields for the years 2000-2002 are presented. The doses of phosphorous, potassium and magnesium fertilizers were calculated. Because of the large variability of the content of macronutrients in the soil (from very low to very high content of phosphorus and from low to very high content of potassium and magnesium) and the variability of yields (from 60 to 140% of the average yield the large changeability of the doses of fertilizers was significant. When comparing the doses calculated with regard of the changeability of the field with doses appointed in the traditional way, it was affirmed that uniform fertilization on the whole area of the field causes “over fertilization” with phosphorus near 50% of the field and about 27% of the area receives too low doses of fertilizers. The third part of the field area receives optimum doses of potassium, 1/3 of the field receives too low doses and 1/3 - too high doses of potassium. The total utilization of fertilizers in the site specific system of fertilization is near the same as in the traditional way of fertilization. Precise method of fertilization does not reduce significantly consumption of fertilizers.

References


Dr hab. Alicja Pecio, prof. nadzw.
Department of Plant Nutrition and Fertilization
Institute of Soil Science and Plant Cultivation – State Research Insttitute
Czartoryskich 8, 24-100 Pulawy, Poland
e-mail: alap@iung.pulawy.pl
USEFULNESS OF COMPOST FROM MUSHROOMS SUBSTRATE FOR FERTILIZATION OF MISCAN TUS PLANTATION

Beata Rutkowska, Wiesław Szulc

Warsaw University of Life Science

Abstract

At the Experimental Station in Skierniewice belonging to the University, three types of compost have been produced based on the mushroom substrate, remaining after the mushroom growing cycle. The first type is compost made exclusively from the mushroom substrate. The second type is the substrate mixed with sewage sludge, and the third one from the substrate mixed with cereal straw. The content of nutrients in composts was evaluated against nutrient requirements of one-year Miscantus crop. Application of composts in accordance with the guidelines of the Nitrate Directive would satisfy the nutrient demand of Miscanthus for N, P, Ca and Mg at a yield of 20 t dry mass ha⁻¹. However, the composts were poor in potassium what suggests supplementing them with this nutrient.

Key words: mushroom substrate, compost, Miscanthus, sewage sludge

Introduction

Mushroom substrate remaining after growing of mushrooms, makes valuable source of organic matter and plant nutrients. If correctly prepared, i.e. disinfected at the temperature of 70°C, it is free of pests, fungal pathogens and weed seeds. Therefore, it has been recommended as organic fertilizer in vegetable and fruit production, establishment and maintenance of protective green areas and for field crops [Kryńska et al. 1983]. Rak et al. [2001] and Jankowski et al. [2004] proved its suitability for fertilizing meadows and pastures. Make use of such materials for fertilizing agricultural land is in compliance with EU regulations to recover 60% of the organic wastes. Another way for utilizing remained mushroom substrate is composting with the addition of other products such as sewage sludge, cereal’s straw and others. This procedure allows simultaneously for disposal of substrate and for obtaining a high value marketable products [Niżewski et al. 2006, Rao et al. 2007]. In the paper, the results of researches on the content of nutrients in three types of mushroom substrate derived composts against the nutrient’s requirements of Miscanthes crop are presented.
Material and methods

Composts have been prepared from the mushroom substrate at the Experimental Station Skierniewice in three heaps made of substrate itself, substrate with sewage sludge and substrate with rye straw (Table 1).

**Table 1. Component weight and proportions in heaps**

<table>
<thead>
<tr>
<th>Component</th>
<th>Heap 1</th>
<th>Heap 2</th>
<th>Heap 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry matter kg</td>
<td>Proportion %</td>
<td>Dry matter kg</td>
</tr>
<tr>
<td>Spent mushroom substrate</td>
<td>513</td>
<td>100</td>
<td>428</td>
</tr>
<tr>
<td>Sewage sludge</td>
<td>-</td>
<td>-</td>
<td>263</td>
</tr>
<tr>
<td>Rye straw</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sum</td>
<td>513</td>
<td>100</td>
<td>691</td>
</tr>
</tbody>
</table>

The components were laid down in layers forming the composting heaps. The heaps have been processed aerobically using tractor aerator. The composting continued for about 100 days. Nitrogen and carbon contents in components, as well as in ready to use composts, were determined using the C:N appliance manufactured by the ThermoElementar. The contents of P, K, Mg, Ca and Cd, Cu, Pb and Zn were recorded after mineralization in the mixture of HNO₃ and HClO₄ acids, in the 5:2 weight proportions, by AAS method using the ThermoElementar appliance.

Results and discussion

The chemical composition of components shows a great variability (Table 2). Organic carbon content in the component’s dry matter was the highest in rye straw and the lowest in mushroom substrate. The reverse was true for total nitrogen, which content was the highest in mushroom substrate. Consistently, the carbon to the nitrogen ratio has been the narrowed in mushroom substrate and the widest in rye straw. The rate of organic waste decay in the composting process depends on the C/N ratio. It was demonstrated by Eland et al. [2001], that in a compost heap, a minimal C/N ratio to activate microbiological processes is necessary. Mushroom substrate was very rich in calcium and rich in potassium, while the content of phosphorus was low. The highest phosphorus content has been recorded in sewage sludge which in
Usefulness of compost from mushroom substrate for fertilization of miscanthus plantation

Turn was very poor in potassium and calcium. The content of heavy metals, except zinc was the highest in sewage sludge though even in this component it remains below the permissible level.

**Table 2. Properties of the components used for composting**

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Mushroom substrate</th>
<th>Sewage sludge</th>
<th>Rye straw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry matter</td>
<td>g · kg⁻¹</td>
<td>330.0</td>
<td>127.0</td>
<td>850.0</td>
</tr>
<tr>
<td>Organic carbon</td>
<td>g · kg⁻¹ d.m.</td>
<td>260.0</td>
<td>433.6</td>
<td>588.6</td>
</tr>
<tr>
<td>Total nitrogen</td>
<td></td>
<td>20.4</td>
<td>13.7</td>
<td>5.4</td>
</tr>
<tr>
<td>C/N</td>
<td>-</td>
<td>12.8</td>
<td>31.6</td>
<td>109</td>
</tr>
<tr>
<td>Total phosphorus</td>
<td></td>
<td>11.2</td>
<td>32.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Total potassium</td>
<td>g · kg⁻¹ d.m.</td>
<td>15.8</td>
<td>1.7</td>
<td>10.6</td>
</tr>
<tr>
<td>Total calcium</td>
<td></td>
<td>75.3</td>
<td>1.5</td>
<td>2.3</td>
</tr>
<tr>
<td>Cd</td>
<td></td>
<td>0.4</td>
<td>4.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Cr</td>
<td></td>
<td></td>
<td>66.7</td>
<td>-</td>
</tr>
<tr>
<td>Cu</td>
<td>mg · kg⁻¹ d.m.</td>
<td>24.1</td>
<td>144.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Ni</td>
<td></td>
<td>21.3</td>
<td>19.9</td>
<td>15.8</td>
</tr>
<tr>
<td>Pb</td>
<td></td>
<td>4.4</td>
<td>43.4</td>
<td>3.2</td>
</tr>
<tr>
<td>Zn</td>
<td></td>
<td>319.1</td>
<td>143.1</td>
<td>8.2</td>
</tr>
</tbody>
</table>

The content of nutrients in mature compost was, to some extent, different from this in the components (Table 3). The compost made solely from the mushroom substrate was impoverished in nitrogen and to some degree in carbon, which resulted in broadening the ratio C/N. The content of other nutrients, but Zn remains practically on the same level. In comparison to the substrate, this compost was poorer in Zn.
Table 3. Contents of elements in mature composts

<table>
<thead>
<tr>
<th>Type of compost</th>
<th>Content in g · kg⁻¹</th>
<th></th>
<th></th>
<th></th>
<th>C/N</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N-total</td>
<td>Corg</td>
<td>P-total</td>
<td>K-total</td>
<td>Ca-total</td>
<td>Mg-total</td>
<td>Pb</td>
<td>Cd</td>
</tr>
<tr>
<td>mushroom substrate</td>
<td>15.1</td>
<td>246</td>
<td>6.8</td>
<td>12.7</td>
<td>73.8</td>
<td>4.4</td>
<td>16.3</td>
<td>2.87</td>
</tr>
<tr>
<td>mushroom substrate + sludge</td>
<td>18.4</td>
<td>225</td>
<td>7.0</td>
<td>8.9</td>
<td>44.8</td>
<td>4.1</td>
<td>12.2</td>
<td>16.6</td>
</tr>
<tr>
<td>mushroom substrate + straw</td>
<td>12.4</td>
<td>276</td>
<td>6.7</td>
<td>11.2</td>
<td>59.6</td>
<td>4.6</td>
<td>22.3</td>
<td>3.59</td>
</tr>
</tbody>
</table>

Two other composts have been substantially enriched with nitrogen and impoverished in carbon. As the consequence the ratio C/N narrowed appreciably to almost the optimal level. Another positive aspect of composting was to standardize the content of macro nutrients and to reduce the content of heavy metals in the sewage sludge as an initial component. In the compost with sewage sludge, the concentration of heavy metals did not exceed the standard values for waste intended for application in agriculture [The Decree of the Minister of Agriculture and Rural Development 2008]. Therefore, composting of mushroom substrate with sewage sludge may provide an efficient way for safe disposal of the waste potentially harmful to the environment [Krzywy et al. 2002, 2008].

The application of composts in line with the guidelines of the Nitrate Directive would satisfy nutrient requirements of Miscantus with regard to N, P, Ca and Mg at a yield of 20 t dry matter · ha⁻¹ (Table 4). However, the composts have been poor in potassium and should be supplemented with the extra amount of this element. As it was shown by other authors [Iżewska et al. 2007, Kalembasa 2006, Kalembasa and Malinowska 2009], Miscantus crop takes up large amounts of potassium relative to other macro elements, i.e. three to five times more than nitrogen and ten times more than phosphorus.
Table 5. Amounts of macro elements in kg \cdot ha^{-1} applied in composts against the nutrient's uptake by Miscanthus crop with the yield 20 t d.m. ha^{-1}

<table>
<thead>
<tr>
<th>Compost type</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Compost dose t d.m. \cdot ha^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spent mushroom substrate</td>
<td>170</td>
<td>77.1</td>
<td>143</td>
<td>831</td>
<td>49.8</td>
<td>11.26</td>
</tr>
<tr>
<td>Spent mushroom substrate + sewage sludge</td>
<td>64.5</td>
<td>82.2</td>
<td>414</td>
<td>38.0</td>
<td>9.24</td>
<td></td>
</tr>
<tr>
<td>Spent mushroom substrate + straw</td>
<td>92.0</td>
<td>153</td>
<td>817</td>
<td>63.0</td>
<td>13.71</td>
<td></td>
</tr>
<tr>
<td>Uptake by Miscanthus crop</td>
<td>94</td>
<td>4.5</td>
<td>186</td>
<td>80</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

**Conclusions**

1. The composts obtained from spent mushroom substrates exhibit good parameters concerning the high content of plant nutrients and low content of heavy metals.
2. The composts could meet the nutrient requirements of Miscanthus plantations, except to low content of potassium. Due to high demand of Miscanthus for this element the composts should be produced with the addition of potassium, or potassium fertilizers should be apply directly to Miscanthus plantations.

**References**


---

Dr hab. Beata Rutkowska  
Warsaw University of Life Sciences (SGGW)  
Dept. of Agricultural Chemistry  
Nowoursynowska 159 Str.  
02–776 Warsaw, Poland  
E-mail: beata_rutkowska@sggw.p
DIVERSITY OF MINERAL NITROGEN CONTENT IN SOIL IN THE REGION CLOSE TO NITROGEN PLANT IN PULAWY

Tadeusz Filipek, Karolina Falkowska

University of Life Sciences in Lublin

Abstract

The paper presents studies on the impact of environmental degradation caused by the emission and immission of gaseous and dust pollutants from the Nitrogen Plant in Pulawy on the content and dynamics of mineral nitrogen compounds in the soils of the surrounding area. Studies showed that in the transect SW ↔ NE the content of N-NH$_4^+$ and N-NO$_3^-$ in the soil varied depending on the distance from the emitter, soil depth layer, plant cover, the period during the growing season, and year of study. Along the distance from the emitter to 2500 m in the north-east (NE), content of mineral forms of nitrogen significantly decreased in the soil layer 0–5cm and to a lesser extent, in soil layer 5–20 cm.

Key words: N-NH$_4^+$ and N-NO$_3^-$ in soil, Nitrogen Plant in Pulawy, gaseous and dust contaminations

Introduction

In the environment, undisturbed by human activity, the cycle of nitrogen is natural, without causing undesirable side effects. It is since its resources are effectively used and incorporated into the circulation of matter and energy (Curtin and Wen 1999, Fotyma et al.2002, Koc et al. 1997, Mercik et al. 1995, Sosulski and Łabętowicz 2007, Strzemińska and Błaszczyk 2004).

However, in the areas under emission and deposition of industrial pollutants, the excess of nitrogen compounds contributes to the disturbances in the global circulation of this element in the environment (Kotowska and Włodarczyk 2005, Sapek et al. 2002, Starck 2008). Today, in some ecosystems subjected to intense pressure from civilization the amount of anthropologically-bound nitrogen introduced into the environment far exceeds the amount of N fixed in natural conditions (Loginow et al. 1987, Starck 2008). Natural reaction to stress usually manifests itself is often a delay, then a sudden, multiple and unpredictable consequences CTB (Chemical Time Bomb), particularly when it is affected by several additional factors and processes.
The aim of the study was to clarify how many years of environmental degradation caused by the emission and imission of gaseous and dust pollutants from the Nitrogen Plant in Pulawy influenced the content and dynamics of mineral nitrogen compounds (NH$_4^+$N and NO$_3^-$N) in the soils of the surrounding ecosystems.

**Materials and Methods**

The nitrogen content of NH$_4^+$N and NO$_3^-$N in soil was studied in the years 2007 to 2009, in three periods of vegetation, April, July and October. Soil samples have been collected from six layers of the soil profile, 0–5, 5–20, 20–40, 40–60, 60–80, 80–100 cm in various distances, 160 m, 260 m, 400 m, 800 m, 1500 m, 2500 m, in a transect to the northeast (NE) from Nitrogen Plant Pulawy. The point of a reference (control C) object has been located on the opposite side from the factory (SW), where due to the prevailing wind direction, the pressure of pollution was the lowest. The content of mineral nitrogen in soil samples extracted from soil with 1% solution of K$_2$SO$_4$ was determined by the colorimetric method, ammonium with Nessler reagent and nitrate with sodium salicylate. The significance of variability of nitrogen NH$_4^+$N and NO$_3^-$N content in soils were assessed statistically using analysis of variance and Tukey’s test with probability 0.05.

**Results**

Soils in the impact area of Nitrogen Plant in Pulawy were characterized by a loose granulometric composition and acidic and very acidic reaction. The average pH in H$_2$O fluctuated in the range from 3.7 to 5.0, while pH in KCl 1 mol dm$^{-3}$ solution from 2.9 to 4.1. Strong acidification of the soils was mainly related to intense and prolonged (40 years) deposition of acid creating compounds both in the form of wet and dry precipitation. In addition, soils were acidified because of small buffer capacity due to naturally acidic nature and low abundance of clay and base cations in sediments, from which soils were formed.

In the period from spring to autumn, during the three years of the study significant variation in the content of mineral forms of nitrogen in the impact zone of the Nitrogen Plant was observed (Fig. 1 and 2). The mineral nitrogen content (NH$_4^+$N and NO$_3^-$N) in the soils changed substantially depending on the distance from the emission source, the experimental objects, depth of soil layer, and years of research and time of sampling.
Diversity of mineral nitrogen content in soil in the region close to nitrogen plant in Pulawy

Figure 1. Mean contents of $\text{NO}_3^-$-N mg kg$^{-1}$ in soils, depending on the year and time of sampling.

Figure 2. Mean contents of $\text{NH}_4^+$-Nw mg kg$^{-1}$ in soils, depending on the year and time of sampling.
The content of NH$_4^+$-N in the surface layer (0–5 cm) of soil decreased with increasing distance from the emission source (Table 1). The lowest average content of ammonium in soils was in the control point, and the greatest one in soil from the point 260 m away from the Nitrogen Plant. The study showed no clear impact of the distance from the emission source on the content of ammonium nitrogen in 5–20 cm layer of soils.

**Table 1. The content of NH$_4^+$-N in mg kg$^{-1}$ in the upper layers of soil**

<table>
<thead>
<tr>
<th>Depth (A) cm</th>
<th>Distances from ZA Pulawy, N-E, (B) in m</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>160</td>
</tr>
<tr>
<td>0 - 5</td>
<td></td>
<td>2,60</td>
</tr>
<tr>
<td>5 - 20</td>
<td>0,70</td>
<td>1,96</td>
</tr>
<tr>
<td>Mean Średnie</td>
<td>1,90</td>
<td>3,60</td>
</tr>
</tbody>
</table>

LSD (p. 0.05) A - 0.28, B – 0.58 A x B – 0.82

In all research sites, the content of NH$_4^+$-N was higher in the surface layer 0–5 cm of soil than 5–20 cm layer. The most important difference between the concentration of ammonium nitrogen in these layers was recorded at the points located closest to the emitter (160 and 260 m). The content of ammonium nitrogen in these objects was three times lower in the layer of 5–20 cm. By contrast, in control object differentiations of NH$_4^+$-N content between depths were not significant. High concentration of NH$_4^+$-N in the upper layer of soil was associated with ammonia and dust emissions and reducing fertilizer ammonium ion movement into the soil profile.

The study also found significant differences between the concentration of ammonium nitrogen at the various layers of the soil profile. Significant differences occurred between the surface layer (0–5 cm) and subsurface (5–20 cm), and the other depths. The highest contents were recorded at the soil surface, while the lowest ones in layer of 40–60 cm. Relatively high, its value at a depth of 80–100 cm to be associated with the fact that as a result of high deposition of pollutants in the form of ammonia is the movement of this nitrogen form together with the rainwater into the soil profile. Distribution of NH$_4^+$-N in the soil profile was characterized by a decreasing trend of ammonium concentration with increasing depth and with greater enrichment of soil levels of research objects, regardless of the distance from the Nitrogen Plant. In general, small variations in the nitrogen content of this form in deeper layers between objects testify to its low mobility and limited movement into the soil profile (Fig. 3).
The studied soils were characterized by low abundance of NH$_4^+$-N compared to NO$_3^-$-N (Table 1 and 2) as evidenced by a nitrification occurring, despite the low pH. This could lead to a decidedly low content of NH$_4^+$-N in the deeper layers of the soil profile. The accumulation of NO$_3^-$-N nitrogen, as the result of deposition in sites located close to Nitrogen Plant, reduced N-uptake by plants and microorganisms increased the leaching of nitrates into the deeper layers of the soil profile.

Table 2. The content of NO$_3^-$-N mg kg$^{-1}$ in the upper layers of soil

<table>
<thead>
<tr>
<th>Depth (A)</th>
<th>Distances from Nitrogen Plant Pulawy, N-E, (B) in m</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C 160 P1  260 P2  400 P3  800 P4  1500 P5  1900 P6  2500 P7</td>
<td></td>
</tr>
<tr>
<td>0 - 5</td>
<td>2,0  33,7  50,3  8,4  18,2  17,1  25,4  17,8</td>
<td>21,8</td>
</tr>
<tr>
<td>5 - 20</td>
<td>1,9  18,8  20,0  2,5  6,8  3,1  8,6  7,1</td>
<td>8,5</td>
</tr>
<tr>
<td>Mean</td>
<td>2,0  26,3  35,1  5,4  12,5  10,1  17,0  12,4</td>
<td>15,1</td>
</tr>
</tbody>
</table>

LSD (p. 0.05) A – 1.68  , B – 3.34  A x B – 4.75

The content of NO$_3^-$-N in soils was characterized by high changeability (Table 2). Mean content of nitrogen in the form of nitrates (V) fluctuated in a very broad range from about 5 mg kg$^{-1}$ to 35 mg kg$^{-1}$. The study also found significant differences between the concentration of nitrate nitrogen in soil, and the distance from the
emission source. The highest content of $\text{NO}_3^-$ 26.3 and 35.1 mg kg$^{-1}$ were found in the soil located near sources of emissions (160m and 260m), while the lowest in the control object (2 mg kg$^{-1}$). The mean content of nitrate nitrogen in soil from P1 object was 13 times, while from P2 object 17.5 times higher than in control. Between P7 object located farthest from the emitter, and the control was 6-fold difference. Compared to other research objects, relatively low concentrations of $\text{NO}_3^-$ was characterized by an object P4 (reclaimed dune), which is mainly combined with favorable conditions for mobile nitrate leaching. Overall, the impact of distance from the emitter on the concentration of nitrates (V) in soil was strongly marked in the areas closest to the Nitrogen Plants. In remote places nitrates content was also affected by other factors related to the processes responsible for the transformation of nitrogen in the soil.

**Discussion**

Elevated concentration of $\text{NH}_4^+$-N and $\text{NO}_3^-$-N in the surface layer of soil is related to emission of ammonia and fertilizer particulates, microbial oxidation of ammonium form and limited their movement into the soil profile. The resulting accuracy is confirmed by studies (Brożek 1985, Czępińska-Kamińska et al. 1999, Łabętowicz and Rutkowska 1996, Popławski and Filipiak 1981, Rutkowska et al. 2002), in which there was no ammonium ion movement into the soil profile even at high doses of nitrogen fertilizers.

Found in the study a high concentration of ammonia nitrogen in spring is associated with a lack of nitrogen uptake by plants, and higher temperatures, which could favorably affect the process of mineralization. According to Sapek (2006) acidic soil favors ammonification process, especially in the spring before moving the vegetation. Research temperate soils indicate that the ratio between the ions $\text{NH}_4^+$ and $\text{NO}_3^-$ is highly volatile. The share of ammonium ion in the mineral nitrogen in early fall is from 20–40% and is rising in the spring to about 30–60% (Fotyma 1995). The lowest content of ammonia nitrogen in October was associated with increased nitrification in the summer and early autumn, which is also confirmed by other studies in the impact area of Nitrogen Plant Pulawy.

Large variation between the content of ammonia nitrogen in the years of the study was observed only in April, while the remaining term of differentiation was not significant. The highest average content of $\text{NH}_4^+$-N was recorded in April in 2008 (8.2 mg kg$^{-1}$) and may be associated with higher emissions of ammonia in 2008 years compared with 2007 and 2009. Research of Kowalkowski and Kopron (2006) also indicate that the content of $\text{NH}_4^+$-N in soils of the area affected by the Nitrogen Plants is clearly dependent on the emission and immission of gaseous pollutants from the factory.

Large fluctuations in the concentration of nitrate ions (V) was probably associated with high changeability of chemical and physical properties of soils formed under
the pressure of industrial factors and their association with the influence of various abiotic and biotic factors of the environment. Nitrogen content is much more exposed to volatility in comparison to the ammonium salts due to greater mobility and the number and variety of processes, where they are affected in the soil. In addition to losses in the form of leaching, volatilization of gas forms (denitrification NO₃⁻-N to NO, N₂O, N₂) are easier effected diffusion and migration processes are more accessible, and collected by the plant (Kotowska and Wlodarczyk, 2005). Fotyma (1995) points out that under the conditions of the agricultural ecosystems, in addition to seasonal variation of NO₃⁻-N perceived through the years, there is also a large spatial heterogeneity within a field.

As a result, research has shown that natural objects were characterized by a higher concentration of nitrate ions compared to plots with cultivation of Scots pine, except that in autumn the differences were not noticeable. This relationship probably resulted from the highest dehydrogenase activity during the spring, which is a measure of overall soil biological activity. In July, between the surfaces of the research could be differences in the collection of nitrate ions by plants. Researches confirm that the NO₃⁻-N shows large fluctuations throughout the growing season, but about its dynamics in the growing season also determines the rhythm of development and collection of nitrate by plants.

The content of nitrate nitrogen in the soil profile showed a much greater diversity among research facilities and depths than in the case of ammonium nitrogen. This was associated with the fact that leaching of nitrates is much higher than the ammonium ion (Crawford and Glass 1998, Koc et al. 1997, Szczęsny 1997). In addition, granulometric composition with large majority of a sand fractions in soils favored moving down process. According to Herbst (Herbst et al. 1982) 10 mm rainfall in light textured soils causes the migration of about 7 cm, and only about 3 cm in heavy textured soils.

We observed a smaller reduction of nitrate nitrogen concentration in soils from the surface located in a forest with a high organic matter content, which can be associated with the greater use of these ions in various biochemical reactions and sorption processes (Boer and Kowalchuk 2001). Soil organic matter is mostly of a variable negative charge, which affects the dissociation reactions of functional groups OH and COOH. However, because of the wide range of dissociation constants of these groups, the charge can also be positive or zero and as a result of the existence of specific conditions affecting the reaction mechanism may occur to the retention of nitrate ions (Sapek 2006).

**Summary and Conclusions**

The studies of diverse content of mineral nitrogen NH₄⁺-N and NO₃⁻-N in soils close to the impact of the Nitrogen Plant in Pulawy, in the transect NE ↔ SW showed variability depending on all examined experimental factors: distance from the emitter
of gaseous and particulate pollutants, depth layer, vegetation covers the soil surface, the study period during the growing season, and year of study. Analytic and synthetic treatment of the obtained results allowed the following conclusions:

1. As the distance from the emitter to 2500 m in the north-east (NE) content of mineral forms of nitrogen, NH$_4^+$-N and NO$_3^-$-N significantly decreased in the layer 0–5 and to a lesser extent, in layer 5–20 cm.
2. In particular, a significant decrease of mineral nitrogen content in the soil was in the range of distances from the Nitrogen Plant Pulawy 260–400 m.
3. As the depth of soil layer the content of NH$_4^+$-N and NO$_3^-$-N significantly decreased up to 60 cm, and then followed by stabilization.
4. The nitrate content was more variable compared to the ammonium cation because of the greater quantity and variety of processes is likely to be applied to the soil and lead to losses.

Work funded research project of Ministry of Science and Higher Education No. N305 N 021736th

References


Czępińska-Kamińska, D., Rutkowski, A., Zakrzewski, S. 1999. Seasonal changes in the NH$_4^+$-N and NO$_3^-$-N content in forest soils. Rocz. Glebozn. 50. 4: 47–56 (in Polish)


Sapek, A., Sapek, B., Pietrzak, S. 2002: Circulation and nitrogen balance in Polish agriculture, Fertilizers and Fertilization 1, 100 – 121 (in polish)


In the paper paradigms of agricultural chemistry which occurred in the past, and after some time to a greater or lesser extent became obsolete, were presented. It was concluded that the achievements of the agricultural chemistry in the last 60 years, have been in close correlation with Polish socio-economic development. Today, the main paradigm of research and application in the field of agricultural chemistry as applied science is to conduct sustainable agriculture and sustainable nutrient management, which allow maintaining and even improving the quality and productivity of soils and crops.

**Key words:** agricultural chemistry, paradigms, science

**Introduction**

Since its creation (contractually 1840), agricultural chemistry has become a science, whose main interests are the elements (macro- and microelements, in recent decades also toxic elements) in natural and artificial ecosystems (agroecosystems). Their function is considered from the viewpoint of the development of soil fertility, production of biomass and quality of the crop and the impact on individual elements of the natural environment [Beegle et al., 2000; Duer, 1994; Filipek et al., 2003; Michna et al., 1991, Voisin, 1967]. By tracking cycles of chemical elements in agroecosystems agricultural chemistry examines the mutual interactions of the atmosphere, hydrosphere, pedosphere, fertilizers and plants [Fotyma et al., 2000; Igras, 2000; Mioduszewski et al., 2000; Sapek et al., 2002].

Understanding the cause-effect relationships between elements, mineral nutrients with the environment and plant growth and development is a prerequisite for understanding the chemical changes occurring in ecosystems which agricultural chemistry tries to steer through the use of natural, organic and mineral fertilizers to improve soil fertility and plant nutrition [Cwojdziński and Majcherczak, 1993;...
Methodological paradigms in research on agricultural chemistry from the creation of science


The general question of methodology, not the methods of the research in the field of agricultural chemistry, which pervades the pragmatic professional, and especially scholars, mainly concerns the development of this science in a historical perspective. It concerns answering the question, whether knowledge and understanding of agricultural chemistry and their use in practice to solve problems of quantitative and qualitative crop production and protection of the environment grew cumulatively, almost linearly, or developed for different dynamics going through successive cycles of development, in accordance with the “structure of scientific revolutions” [Kuhn, 2001; Hajduk, 2005; Grobler, 2006]. Cycles of scientific development comprise: the pre-paradigmatic period, paradigm, normal science, crisis and anomalies, extraordinary science, revolution in science and a new paradigm.

In attempting to answer these questions we will try to define paradigms of agricultural chemistry, which occurred in the past, and after some time, to a greater or lesser extent, became obsolete. In their place came a new premise that gave indications of anomalies and crises emerging in the pragmatic area and researches on agricultural chemistry.

First observations and researches – pre-paradigmatic science

The pre-paradigmatic period is characteristic of the early periods of scientific development, where facts are much more casual than the research that appears in the later development of science, when you separate the paradigm.

In agricultural chemistry, facts were related to the positive effects of many materials and substances such as manure, marl, and ash on plants. This effect has been known since ancient times. The consequences of their impact were known, but an attempt at explanation usually ended with statements that the main component of the building blocks of plants is water, which in the plant tissue is transformed into different substances. Theoretical considerations of Berbard Palissy (1510–1589) deal with the positive effects of salt on plants and soil depletion, but there was still no evidence verifying these phenomena [Goralski, 1965].

The first experiment, whose memory is preserved to this day, was a pot experiment of John Baptist van Helmont (1577–1644) with a willow tree watered with rainwater or distilled water, from which emerged the conclusion that the growth of plants was due to only water. Confirmation of these findings in England, Sweden, France, and Russia established this misguided theory among contemporaries and became a strong brake on the development of science dealing with plant nutrition and fertilization.

Over the next two centuries, despite many studies on plant nutrition and establishing the beneficial effects of many substances such as: saltpeter - Robert
Boyle (1627–1691), nitrate, ash, marl–Francis Home (1719–1813) and Johann Wallerius Gottschalk (1709–1785), water and air were still regarded as a source of food for plants. Despite great chemical discoveries made in the eighteenth century, including those of Joseph Priestley (1733–1804), Laurent Lavoisier Antoin (1743–1794), Saussure, Nicolas Theodore (1767–1845) and many assumptions that plants feed on mineral salts, the old established views still dominated, and emerging new concepts did not bring us any closer to clarifying the issue of plant nutrition.

An example is the humus theory of plant nutrition. Its creator, Albrecht Thaer (1752–1828) argued that plants feed on humus compounds from the soil, and mineral compounds are the only stimulants. Although the theory of Thaer was wrong and became a major constraint on progress in agricultural chemistry mineral fertilizer production, diverting attention from the mineral nutrition and fertilization of plants [Filipek et al., 2003; Goralski, 1965], it had a positive impact on the development of plant production in Germany and throughout Europe, as it placed emphasis on organic fertilizers, mechanical soil cultivation, the importance of fertilizer and fertility significance of legumes plants, which gave good results in practice.

Although research of John Ingenhousz (1730–1799), Jean Senebier (1742–1809) and Saussure had already shown that the building blocks of food plants were carbon dioxide (CO$_2$) and water, the humus theory gained great acclaim and popularity, especially among farmers.

None of the above-described studies, however, were of groundbreaking significance, did not form a theoretical basis, and did not become a system of standards, that is, in other words, general, abstract and more or less unambiguous directives of conduct for the supply of plant nutrient elements. They were not the foundation for creating the laws of science, specifically in terms of the rights in question. Based on the results of these studies generalizations or scientific theories could not be presented. In the case of natural science theories are created to systematize and rationalize the facts, explain the reasons of these facts and predict future events. So there was no presidency to build a pattern, a cognitive schema, model of research, scientific reasoning and practice for solving problems in the nutrition of plants. Therefore, there was not a methodological paradigm, or anything that could aspire to this role, i.e. research model. It seems then that all the facts which may contribute to the development of the discipline are equally important. As a result, in the early stages of the development of science, the facts are much more casual than research activity, which we know from the later period of development of science, when a separate research paradigm was created [Hajduk, 2005; Kuhn, 2001; Grobler, 2006].
First paradigm - agricultural chemistry as a normal science

The emergence of significant achievements in the form of a new theory or discovery of scientific laws in a particular area of research leads to a difference in approach to solving problems facing scientists. Such universally recognized scientific achievements, which, after some time become shining examples of scientific problem solutions are called paradigms in the general methodology of science. A paradigm can therefore be defined as a pattern, the most general model or a model example. This term is used in many sciences, in the above sense, but only in the form of basic assumptions. Thus, a paradigm is a set of concepts and theories forming the basis of science. A paradigm indicates that the accepted patterns of scientific practice, including theories, laws, research methods, and technical equipment make up the model which formed a separate science [Hajduk, 2005; Kuhn, 2001; Grobler 2006].

That’s how agricultural chemistry started. Its creator, Justus von Liebig (1803–1873), a chemist by training, introduced the theory of mineral nutrition of plants in 1840. The principal work “Die organische Chemie in ihrer Anwendung auf Agricultur und Physiologie” “Chemistry applied to Agriculture and Physiology” announced that all life processes in the organism are chemical reactions and in this way also nutrition and plant growth (Liebig 1840).

According to the mineral nutrition theory of Liebig plants feed on carbon dioxide absorbing CO$_2$ from the air through leaves and water and mineral compounds (ash), which are taken up by plant roots. Humus is not a necessary substance for plant growth and development. The organic compounds present only the relevant nutritional value for plants, which are minerals remaining after ashing; the nitrogen in these compounds does not provide any value.

Since the announcement and recognition of the theory, agricultural chemistry has become a “normal science” [Kuhn, 2001], which can solve problems regarding its interests. The term “normal science” means a study based on one or more of the scientific achievements of the past, which in the test area are considered as the foundation on which further cognitive and utilitarian practice is built. Such achievements must be sufficiently original and attractive to focus the attention of researchers scattered across various existing sciences or to the research, activities not associated to any science.

According to Liebig’s theory nutrients taken up by plants must be returned to the soil in the form of fertilizers. Crops require unequal quantities of the same nutrients (e.g., legumes - a lot of calcium, root - rich in potassium), and therefore, in order to reduce the depletion of soil, rotation of cultivated plants should be used. One nutrient cannot be replaced by another. Liebig wrongly assumed that ammonia is circulated in a similar way to CO$_2$, nitrogen is obtained by plants from air, and pushed nitrogen fertilization into the background.

Jean Baptiste Boussingault (1802–1887) corrected these views, demonstrating the strong influence of nitrogen fertilization on the growth of plants. He claimed that
despite the enormous stocks of nitrogen in the atmosphere, higher plants are not able to uptake and use it. Boussingault also rejected the possibility of nitrogen fixation by free living and symbiotic microorganisms, because his experiments were carried out on the calcined soil, and thus he destroyed microbes. In addition to nitrogen (ammonia and nitrate), his research involved also many other elements in soils and plants such as C, P, Cl, Si, K, Na, Ca, Mg, Mn, and Fe.

All contributors of agricultural chemistry: Albrecht Thaer, Justus von Liebig and Jean Baptiste Boussingault made mistakes: Thaer - overestimating the importance of humus and denying the mineral nutrition of plants, Liebig - overestimating the importance of ammonia in the atmosphere, and relegating to the background nitrogen fertilization, Boussingault - refusing legumes plants in symbiosis with Rhizobium bacteria - fixation of atmospheric nitrogen. However, each of them has contributed greatly to improve the production of crop biomass and laid the groundwork for the development of agricultural chemistry and physiology of mineral nutrition of plants [Filipek et al., 2003; Goralski 1965]. This also had a significant impact on the development of chemical industry, especially the production of fertilizers, agriculture, increase in the volume and quality of food, and consequently, an increase in the world’s population [Fotyma, 2010].

The dynamic development of the fertilizer industry

The theory of mineral nutrition of plants and Liebig’s Law of the Minimum have become direct prerequisites of the pragmatic research paradigm [Kuhn, 2001]: calibration of the abundance of the environment in nutrients for growth and development of plants, which founded modern fertilization. First, macronutrients were calibrated and, eventually, micronutrients, and trace sub-micronutrients and “beneficial elements” to plants. The theory and Liebig’s minimum law become a natural prerequisite to creating a “right of return” of Boussingault, speaking of the need to return soil nutrients collected by plants and removed with the yield. This law was later extended by Voisin (Voisin 1967, 2000), who claimed that not only the quantity of chemical elements, which were collected by plants should be returned, but also those bioavailable forms in the soil, which “disappeared” leached or immobilized) in the subsequent application of fertilizers. One of the consequences of these rights was the development of the fertilizer industry and agriculture, both directly and indirectly [Filipek et al., 2003].

Fertilizer recommendations proposed in the 1980s in Polish agriculture based on the right of return spoke of the application of - “overdoses of phosphorus and potassium” or doses “in reserve”, or “condensed doses” - doses of fertilizers exceeding the nutritional needs of plants in order to increase the abundance of available soil P and K, or reduce the costs associated with using fertilizers. They became a strong impetus for further development of agricultural chemistry as a science, and the fertilizer industry, agriculture and food production.
The first factory of phosphate fertilizers produced from bones, and sulfuric (VI) acid was established in the 1850s, first in England, then in Germany. England had already begun the application of natural mineral nitrogen fertilizer – Chilean nitrate. In China and India in the late nineteenth century, Indian saltpeter (KNO₃) was mined. At the end of the nineteenth century in Germany the potassium salt mining for fertilizer purposes began and a production technology of the ammonium sulphate from ammonia originating from coking plants was drawn up.

At the beginning of the twentieth century, intensive work began on the synthesis of nitrogen compounds, mainly of nitric (V) acid. The first efforts associated with this process were directed toward a method that uses air as a raw material. In 1899, Ignacy Mościcki (1867–1946) initiated work in Switzerland, using a modified electric arc to produce nitrogen oxides, which when dissolved in water turned into a solution of nitric (V) acid. Birkeland - Eyde (1903) worked on a similar method at that time in Norway, and Schönherr (1905) in Germany. Energy requirements using the electric arc method are so large that, despite the low price of a raw material (air), which only needs simple conditioning, even now, these technologies are not widely used.

Regardless of attempts at nitrogen and oxygen fixation in an electric arc research on the reduction of nitrogen with hydrogen was developed. Fritz Haber (1868–1934) and Carl Bosch (1874–1940) conducted such study on a large scale in Germany. As a result of thorough research suitable physicochemical condition for the synthesis of ammonia on an industrial scale was discovered. In 1913, the first high pressure ammonia synthesis plant in the history of the chemical industry was opened at BASF’s Ludwigshafen plant – Oppau [Filipek et al., 2003].

The makers of large-scale ammonia synthesis methods received Nobel prizes: Haber in 1918 for carrying out synthesis and Bosch in 1931 for the development and implementation of high pressure technology of chemicals. Germany’s Gerhard Ertl (1936) significantly improved these methods, clarifying the catalytic synthesis of ammonia, and received the Nobel Prize in 2007. Over nearly a hundred years since the first ammonia plant started working, the essential outline of this technology has not significantly changed.

The Polish economic situation and an increasing demand for fertilizers after 1918, covered largely by their imports, resulted in expansion of the plant in Chorzów and commencement of building a plant near Tarnów, which was launched in 1929. Nitrogen Works in Tarnów (“National Plant of Nitrogen Compounds in Mościce”) was a large and modern nitrogen plant on a global scale. In 1938, Tarnów Nitrogen Plant produced 17,200 tons of nitrogen bound in the form of calcium nitrate, ammonium nitrate, ammonium nitrate fertilizer, calcium ammonium nitrate, ammonia water, and others. In 1960, these plants provide 58,200 tons of nitrogen in the form of various nitrogen fertilizers.

In the early 1960s it was decided to build a large nitrogen conglomerate in Puławy, and after several years in Włocławek and then in the Police. In the seventies, five big nitrogen conglomerates worked in Poland. Chorzów during this time changed the profile of production, and the nitric acid plant ceased to function. Current production
of nitrogenous fertilizers in Poland is associated with five fertilizer plants, which include: Tarnów Nitrogen Plant (production since 1929), Kędzierzyn Plants (since 1945), Puławy Nitrogen Plants (1966–68), Włocławek Nitrogen Plants (1970–1975) and the Police Chemical Plants (1975–80).

The Polish industry of phosphorus fertilizers is concentrated in seven manufacturing plants in Gdańsk, Police, Ubocz, Tarnobrzeg, Luboń, Wrocław and Toruń, using raw materials for the production (phosphates, apatites) from import. Potassium fertilizers and raw materials for their production also come from import. Other fertilizers like magnesium, sulphur, trace elements produced in various forms (salts, chelates) and states (solid, liquid, and suspension) are used in a smaller quantity and are applied most frequently after reaching the level of fertilization of 100–120 kg NPK ha\(^{-1}\).

Research development on agricultural chemistry

Research on agricultural chemistry in Poland prior to independence in the inter-war period, was related mainly to mineral nutrition of plants, soils abundant in available nutrients and manure storage and use, as well as the quantity and quality of crop yield. Studies of a fundamental nature were carried out at universities, practical research in service laboratories. In the second half of the nineteenth century, the Chemical Laboratory of the Agricultural Society in Warsaw (at Służewiec) founded in 1862 was moved to Pulawy, and after twenty years of activity was closed. A little later similar agency was created in Poznań, Bydgoszcz, Sobieszyn, Kutno, Chojnów, and Dublany. In the first decade of the twentieth century, the agricultural chemical lab in the Department of Experimental Agriculture at the College of Agriculture in Kraków and the Chemical Workshop at the Museum of Industry and Agriculture in Warsaw were established. After independence in 1918, the services of chemical and agricultural research were done in laboratories in Poznań, Toruń, Cieszyn, Warsaw, Kraków and Dublany [Filipek et al., 2003; 2007].

In a study on agricultural chemistry after the Second World War, three main stages can be distinguished [Filipek et al., 2007].

The first phase from 1946 to 1965 includes research recording qualitative and quantitative status of soils in Poland. Extensive tests were carried out to determine the reaction state and soil abundance in the available forms of macronutrients, and then also, of micronutrients. To perform these studies 17 Provincial Stations of Agricultural Chemistry were established. Scientific care of these labs was in the hands of scholars from departments of agricultural chemistry (agricultural colleges) and researchers from the Institute of Soil Science and Plant Cultivation.

The second phase of research in agricultural chemistry and soil science has begun in the 70s of XX century. It was rebuilt from war damage, mainly built from the ground, the fertilizer industry, which led to a significant increase in fertilizer consumption in Poland. The main trend of research has focused on technological
use of fertilizers, and the main goal was to increase crop yields through the use of increasingly larger doses of mineral fertilizers.

The significant impact of fertilization on the yield of crops gave a strong incentive to begin an investigation of the influence of fertilization on yield quality [Faber, 1994; Smoczyński and Skibniewska, 1996; Starck, 2008]. The study focused on determining the threshold levels of nitrates, especially in feed and vegetables, and also studied other changes in chemical composition (content and composition of proteins, sugars, fat, vitamins, etc., mineral compounds primarily limiting the uptake of some ions and excessive accumulation of others) under intensive fertilization. Having a good understanding of soil nutrient abundance and plant responses to fertilization (quantitative and qualitative indicators of yield) developed systems (tabular first, then the computer) of farm advisory services, which gave rise to modern plant nutrition and fertilization.

The third stage started at the beginning of the 1980s and was associated with a huge interest in the ecological effects of chemical use in agriculture and the impact of industrial and traffic pollution on soil and crops. An assessment of the impact of dust and gaseous pollutants in the form of dry and wet deposit (SO$_2$, NO$_x$, NH$_3$) on agro-ecosystems was made. The impact of acid precipitation on soil and plants, with particular emphasis on the mobilization of aluminum and manganese in an acidic environment and their effects on living organisms in the soil, was recognized [Skowrońska and Filipek, 2007; Filipek and Skowrońska, 2009]. Deeper understanding of the effects of the strong acidification of soils helped to explain the decline in crop yield and low efficiency of fertilization on poorly buffered soils, depleted of nutrients in soil, and disregarded the low resistance to chemical degradation [Filipek, 2001; Łabętowicz and Szulc, 1999].

Much attention was devoted to new techniques of crop fertilization, mainly aimed at increasing utilization of nutrients from the fertilizer by plants and thus reducing the amount of fertilization and reducing the pressure on the environment. Technologies of foliar crop nutrition with nitrogen, magnesium and trace elements, often combined with plant protection treatments were developed.

The effects and extent of degradation of soil and groundwater due to industrial activities, mining, urbanization, deforestation and over-land drainage and inadequate fertilization were determined. Much attention was paid to the possible use of some wastes to fertilize and the rehabilitation of degraded soils. Criteria for assessing the usefulness and the rules of application, sewage sludge, waste water, organic waste of food industry, ashes, manure, straw, etc. were developed. Biotechnologies were developed to prepare compost from agricultural municipal, industrial wastes, and other organic substances.

The study included urban areas and those under strong pressure from industry. An evaluation of the content and proposed limit accumulation of heavy metals and other trace elements in soils was made. The role of different soil and climatic factors in the mobilization of native metal forms and deposits of anthropogenic origin were
developed [Kwiecień and Filipek, 2003]. Rates of accumulation of metals in different food chains were determined [Filipek et al., 2007].

Enhancing plant production and agriculture

Chemical fertilizers were found by Voisin (1967) to be one of the most important discoveries of mankind, which enabled increasing soil fertility and producing a more than fourfold increase in yields on average. Today, the efficiency of agricultural production is even greater because the high potential of biomass productivity resulting from the fertilization has been greatly enhanced through biotechnology, which has created highly productive crop varieties [Cordell et al., 2009]. Modern technologies of plant cultivation and effective methods of protecting crops against weeds, pests and diseases have created a highly efficient system described in the literature as: intensive, conventional, traditional, industrialized agriculture. Modern methods of high-efficiency agricultural production are based on precision crop cultivation technologies and application of fertilizers and plant protection products (precision agriculture), using satellite-transmitted data to improve agro-technologies.

According to the Central Statistical Office (GUS) in Poland between 1960 and 1985 the consumption of fertilizers increased almost linearly, reaching up to almost 200 kg of NPK per hectare. Consumption of nitrogen fertilizer at this time in Europe expressed per capita increased almost four-fold from 8.6 in 1960 to 33.0 kg N in 1990. In Poland, the increase was even greater, more than six-fold, from 6.0 kg to 39 kg N in 1990 [Fotyma, 2010].

Agricultural Chemistry, from the announcement of Liebig’s mineral nutrition theory and minimum law, which became the basis for extracting the calibration of the plant nutrient supply paradigm, developed intensively and became a “normal science” [Kuhn, 2001]. The paradigm earned its high status because it proved to be an effective means of resolving major problems identified as being particularly acute in the late nineteenth and early twentieth century, and for increasing food production and bringing about the liquidation of hunger and malnutrition, especially in the field of animal protein.

The success of the paradigm was based initially on the promise of more success, which selected examples confirmed, but not all. The paradigm has imposed new, more stringent tests to determine the subject of agricultural chemistry, and has created the conditions for the application of clearly determined investigation methodologies. At present, just like any other science, agricultural chemistry is characterized by an elaborated area of creative inquiry, expressed by clearly and precisely specialized terminology and continuously improved research methods. The paradigm for the calibration of plant nutrient supply gave direction for the development of the entire discipline of agronomy.
Crisis and anomalies in practice and research on agricultural chemistry

Adverse effects of the functioning of the paradigm for the calibration of plant nutrient supply began to appear simultaneously with an effective resolution of important issues related to increasing food production and liquidating hunger and malnutrition [Granli and Rockman, 1994; Laegried et al., 1999; Łabętowicz and Szulc, 1999; Marcinkowski, 1998; Mercik and Moskal, 2002; Mitchell et al., 1998]. The intensification of crop production created an upward spiral in the use of chemicals in agriculture.

Major nutrients applied at the beginning significantly varied the chemical properties of soils and plant biomass, and according to Liebig’s law fully increased demand for other mineral nutrients as “beneficial elements”, elements of beneficial effects, micronutrients, and even sub-micronutrients. In conditions of intensive cultivation, it became necessary to use: plant protection products, including chemical pesticides, growth regulators, retardants, desiccants, and adjuvants.

In agricultural chemistry, problems began to appear, anomalies, and crises, which primarily concerned changes in the properties of the environment for the growth and development of crops, and later the whole of the natural environment and quality of crops and raw materials for food production. The compaction of crops and changes in the chemical composition of plants intensified the development of pathogens. There were excessive concentrations of nitrates in vegetables and feed and instances of deterioration in food quality [Smoczyński and Skibniewska, 1996; Sosulski and Łabętowicz, 2007].

The use of intensive fertilization has caused an increase in the proton load - acidification, which in turn increased the mobilization of some toxic trace elements, and again limited bioavailability. In conditions of high acidity increased leaching of nutrients have been reported, which in the case of biogenic elements, especially nitrogen and phosphorus, lead to water eutrophication. Dispersion of mineral plant nutrients in the environment, particularly their movement into the waters, and in the case of nitrogen volatilization - into the atmosphere, has become one of the major problems in the governance and management of biogenic elements (nutrient management) [Cwojdziński and Majcherczak, 1993; Gonet et al., 1995, Igras, 2000; Pietrzak, 2001; Sapek, 1995].

Although the problems in the nutrient’s management have been recorded in agriculture for a long time and solutions to every problem at least partially anticipate a pre-crisis period, the explanation remained unseen. Awareness of adverse events, crises, became an important factor in the discovery of a new kind of challenge, a prerequisite for the acceptance of any changes to the theory.

Thus, the conditions for the emergence of new theories were created, a paradigm shift, creation of new patterns, patterns of pragmatic activity in research in the field of agricultural chemistry, which would contribute to solve these new problems. The conditions were preceded by a period of discussion and uncertainty, born from
the failure to solve problems on an almost global scale (\(N_2O, NO_x, NH_3, SO_2, H_2S\), increased loads and mobility of heavy metals in the environment, and increased the concentration of biogenic elements in water). Awareness of the unreliability of existing rules was the prelude to seeking new solutions that appear to be a direct response to the crisis.

Extraordinary solutions, new paradigms

Increasing problems with plant nutrition provoked extraordinary solutions that have been associated with biodynamic and ecological agriculture and began to appear in the agricultural sciences in the theory of religious and philosophical concepts underlining the close relationship of nature, especially the Earth - Human - the Universe, in accordance with which a person can activate forces aimed at enhancing the biological quality of agricultural products (e.g. compost dynamization). Crop production under organic-biological methods can achieve optimum yields of high quality - without the use of mineral fertilizers and pesticides, and with particular emphasis on crop rotation and use of green fertilizers. Natural minerals may be used in this method. There were also ideas of fertilization in organic farming based on bio-compost, humus, composted manure, green fertilizers and papilionaceous crops [Duer, 1994; Faber, 1994; Filipek and Skowrońska, 2009].

These solutions have become popular in recent decades, especially in societies of developed countries in which there was the intensive agricultural production based on chemicals used for crop intensification, where the negative effects of fertilization have apparently been revealed.

Particular attention has been devoted to studies of soil properties in terms of integrated crop production. It emphasizes the need for sustainable use of soil, and sustainability in agriculture should become the main direction of activities aimed at intensifying production [Fluent 2000, Duer 1994, Laegreid 1999, Starck 2008). This has led research centers to devote significant attention to the possibility of using native forms of nutrients by crops and improving conditions for nitrogen-fixing by microorganisms and microbes responsible for the transformation and macromolecular organic matter into simpler compounds available to plants. Methods to chemically degraded soil rehabilitation have been developed, suggesting the solubility limit of toxic substances by changing the pH (liming), complexation with organic substances (use of fertilizers and organic waste) sorption on the sorbents aluminosilicate or phytosanitary soil purification from the excess of heavy metals using plants called bio accumulators.

Modern technologies of crop production based on balanced fertilization and effective methods to protect crops against weeds, diseases and pests, that have set up efficient agriculture are known as systems: extensive, conventional, traditional, industrialized. These systems are built on: anthropocentrism, individual discipline,
concentration, dependence, competition, dominance in nature, course, and service. They are opposite to alternative technologies built on: ecocentrism, cooperation between scientific disciplines and specialties, decentralization, autonomy, the creation of community, harmony with nature, diversity, constraints, and optimization (Duer, 1997).

Optimal solutions in the governance and management of mineral nutrients of plants, taking into account aspects of production, both economic and environmental, propose a system of sustainable agriculture. Analyzing the conditions of production, economic and social sustainable system of agricultural production, three key concepts: sustainability, efficiency, equity, are considered.

- The concept of sustainability mentions the security needs of the current food production without the possibility of depletion of the next generation to ensure their own needs.
- The concept of preserving effectiveness refers to the optimum efficiency in the use of natural resources, and the means used to intensify crop production - especially manure, organic and mineral fertilizers.
- The concept of preserving justice, a guarantee of “equity” ensures the maintenance of efficiency, while at the same time fulfils the condition of fair distribution of the fruits of such a system of food production.

Currently being introduced and in the future will be an essential technological solution, supporting a sustainable farming system based on precision agriculture: precision resources management, computer-aided management, and prescription farming.

The realization of these intentions in relation to the economy of plant mineral nutrients can be achieved by:

- maintaining the adequate, accurate relationships between consumption of internal resources and external resources containing nutrients,
- integration of crop and animal production,
- recycling of food production and animal waste,
- crop rotations involving legumes plants.

Summary

Summing up the achievements of the agricultural chemistry in the last 60 years, we can conclude that they have been in close correlation with Polish socio-economic development. The development of industry, agriculture and social awareness of Poles created a demand for solving problems related to food security and the environment. The first stage involved an evaluation of quantitative soil resources in Poland; the second focused on increasing their fertility and productivity, and the third and last, focused on the protection of soil, water and the whole environment of agricultural production space.
Today, the main paradigm of research and application in the field of agricultural chemistry as applied science is to conduct sustainable agriculture and sustainable nutrient management, which allow maintaining and even improving the quality and productivity of soils and crops.

It should be further noted that achieving sustainability is a major concern not only of agriculture but also all society. These objectives can be achieved, leading to a balanced, comprehensive, rational management of natural resources and mineral nutrients in agriculture and the environment. Such management will allow for “the security needs of the current food production without the possibility of depletion of the next generation to ensure their own needs”.

References

Methodological paradigms in research on agricultural chemistry from the creation of science


Liebig, J., 1840: “Chemistry applied to Agriculture and Physiology” Friedrich Vieweg und Sohn Publ. Co., Braunschweig, Germany. (In German)


Prof. dr. hab. Tadeusz Filipek
Department of Agricultural and Environmental Chemistry,
University of Life Sciences in Lublin,
Akademicka 15, 20-950 Lublin, Poland,
tadeusz.filipek@up.lublin.pl