Anna KUCZUK, Janusz POSPOLITA
Politechnika Opolska, Katedra Techniki Cieplnej i Aparatury Przemysłowej
e-mail: a.kuczuk@po.opole.pl; j.pospolita@po.opole.pl
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MODELING OF SOIL NITROGEN CONTENT UNDER CONDITIONS OF DIVERSE AGRICULTURAL CROPS

Summary

The paper presents a mathematical model of nitrogen migration in soil. Nitrogen changes were modeled over a period of 21 months, taking into account the change of the cultivated plants, nitrogen uptake by plants during their growth and depending on soil moisture, fertilization and changing weather conditions. The equation of the mathematical model was solved by the finite difference method. The obtained results were verified with the soil laboratory data. The quantitative compatibility was obtained in the case of the upper layer of soil profile (0-30 cm) and qualitative - for the deeper layer (30-60 cm). The mathematical model allows taking into account many different impacts on the content of $N_{min.}$ in the soil. It can be a helpful tool in forecasting its changes and determining the time and level of fertilization. This is of particular importance when the weather conditions undergo radical, long-term changes.
***Key words**: mineral nitrogen, soil, mathematical modeling*

MODELOWANIE ZAWARTOŚCI AZOTU W GLEBIE W WARUNKACH RÓŻNYCH UPRAW ROLNICZYCH

Streszczenie

W pracy przedstawiono model matematyczny migracji azotu w glebie. Modelowano zmiany azotu w okresie 21 miesięcy, uwzględniając zmianę uprawianych roślin, pobór azotu przez rośliny w trakcie ich wzrostu oraz w zależności od wilgotności gleby, nawożenie i zmienne warunki atmosferyczne. Równanie modelu matematycznego rozwiązano metodą różnic skończonych. Otrzymane wyniki zweryfikowano z danymi badań laboratoryjnych gleby. Uzyskano ilościową zgodność w przypadku górnej warstwy profilu glebowego (0-30 cm) oraz zgodność jakościową dla warstwy głębszej (30-60 cm). Opracowany model matematyczny pozwala uwzględnić wiele różnych oddziaływań na zawartość $N_{min.}$ w glebie. Może stanowić pomocne narzędzie w prognozowaniu jego zmian i określeniu czasu oraz poziomu nawożenia. Ma to szczególne znaczenie, gdy warunki pogodowe ulegają radykalnym, długookresowym zmianom.
***Słowa kluczowe**: azot mineralny, gleba, modelowanie matematyczne*

1. Introduction

Nitrogen constitutes one of the basic and necessary ingredients needed for plant vegetation. High crop yield is often referred to as the direct reason associated with the intensive fertilization with nitrogen compounds. The nitrogen compounds undergo a number of transformations in the soil, depending on the type and composition of the fertilizer that is applied. Nitric nitrogen is directly absorbed by plants. Other forms of nitrogen and especially urea undergo chemical reactions stimulated by enzymes and bacteria before it attains a form that is biologically available to plants. Biomass residues found in the soil as well as organic fertilizers undergo gradual mineralization and transformation into nitrates. In addition, a continuous exchange of nitrogen in its molecular form and its gaseous compounds with the atmosphere takes place in the environment.

The use of precise doses of fertilizers is an important aspect in terms of the needs of crops as well as for the reasons associated with the conservation of the environment. The ease with which nitrogen compounds can be removed from soil with water results from the potential for leaching of its excess into the environment, leading to contamination of groundwater.

There are a large number of methodologies applied for calculating nitrogen resources in soil. The variety of these methods ranges from relatively simple balance methods [18] and also includes complex mathematical models applying differential equations of water circulation in soils along with nitrogen, taking into account both the supply of fertilizers and the nitrogen intake by the plants [5, 8, 20]. In terms of mathematical models, the circulation of water in soil is described by the Richards equation [2, 7, 11, 15, 17, 22], in which the relation between soil pressure and moisture content is most often expressed in terms of the van Genuchten power function [21]. In some works, nitrogen retention is considered separately for individual ion groups [6, 14].

The present work contains an attempt to model the variations in mineral nitrogen content in soil in an arable land. For the purposes of modeling, two basic layers were identified in the soil profile: 0-30 cm and one that is 30 cm below ground level. Hydraulic conductivity tests were performed for each of the layers in the saturated and unsaturated soils and the retention curve was developed. The above changes were modeled for the case of two different crops characterized by different root system – maize for grain and winter wheat cultivated in the consecutive years. The results of alternations in the nitrogen concentration over the 21-month period were compared to the results of laboratory tests involving nitrogen content measurement in soils.

2. Materials and methods

2.1. Mathematical model of nitrogen transport in soil

We can assume that major content of the nitrogen volume located in the soil takes the form of the soil solution and this nitrogen is carried with water. The mathematical model of nitrogen migration in the soil was formulated in the form of the Richards equation (1), which describes the flow of water in the porous medium, and applying differential equation for the mass conservation of nitrogen. These equations are supplemented by the applicable initial and boundary conditions, as well as expressions accounting for the conductivity of unsaturated soil and its suction pressure which form the functions of moisture content in the soils. Both equations have source terms. In the Richards equation, the source term describes the water uptake by the plants. In the mass conservation equation developed for nitrogen, the source term accounts for nitrogen supply into the soil and its uptake rate by plants. The mathematical issue is considered as non-stationary and one-dimensional.

Richards equation after transformations accounting for the negative value of suction pressure in $\boldsymbol{z}$ axis pointing towards the soil surface, takes the form:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial h_s(\theta)}{\partial z} \right) - \frac{\partial K(\theta)}{\partial z} - S(\theta) \,. \tag{1}$$

In the above equation, θ stands for the soil moisture defined as a volumetric water content in the soil volume, $\boldsymbol{K(\theta)}$ stands for hydraulic conductivity of unsaturated soil. The $\boldsymbol{h_s}$ value is the suction pressure of soil, and $\boldsymbol{S(\theta)}$ forms the source term. The relation between soil moisture and $\boldsymbol{K(\theta)}$ and $\boldsymbol{h_s(\theta)}$ was described by application of polynomial functions, which were formulated on the basis of the results of research of soil samples delivered for the purposes of the testing.

The water intake by plants depends on the size of root mass and its distribution in soil and is relative to soil moisture [9]. The mass of the roots and their increase over time depend on the type of cultivated plant and the level of its development. The equation for mass conservation (continuity of the soil solution) is given by the formula (2) [9],

$$\frac{\partial \rho}{\partial t} = \frac{\partial\left(D_d \dfrac{\partial \rho}{\partial x} \right)}{\partial z} - \frac{\partial(\rho v)}{\partial z} + q \,, \tag{2}$$

where $\boldsymbol{\rho}$ is the nitrogen density per unit of soil solution, $\boldsymbol{D_d}$ forms the dispersion-diffusion coefficient, accounting for diffusion and hydrodynamic dispersion that is relative to the flow velocity [9]. The quantity $\boldsymbol{v}$, in the equation denotes the mean velocity of the particle flux containing nitrogen, $\boldsymbol{\rho v}$ forms the Darcy's flux. The present calculations applied the relation (3) following [9]:

$$D_d = \alpha(\theta) \cdot \frac{f}{\theta} + \frac{D_{dyf}}{\tau} \,, \tag{3}$$

where $\boldsymbol{\alpha(\theta)}$ is the dispersion coefficient, $\boldsymbol{f}$ **–** is the density of the water flux discharged through the horizontal soil profile, $\boldsymbol{D_{dyf}}$ forms the molecular diffusion coefficient of nitrogen ions in the water solution, $\boldsymbol{\tau}$ forms the curvature coefficient of soil pores.

In comparison to $\boldsymbol{q}$, the source term in equation (2) accounts for the input of nitrogen into the soil after the mineral and organic fertilizers are applied, nitrogen originating from the degradation of organic matter (plowed catch crops, dead plants roots), as well as nitrogen absorbed from the air together with atmospheric precipitation as well as nitrogen uptake by plants.

2.2. Method applied to solve equations of the model

Equations forming the mathematical model were solved using the finite difference method [9, 10, 13] with the help of an original program written in algorithmic lg-FORTRAN. The finite difference method is effectively applied to solve numerous problems in mathematics and physics, including fluid flow in porous media.

To obtain solution of the equations (1) and (2) of the mathematical model in time, the first order explicit method was applied. Non-linear diffusion term in these equations were approximated applying the central differences. The derivative $\frac{\partial K(\theta)}{\partial z}$ in equation (1) was approximated on the basis of two adjacent points on the mesh (due to the considerable local variations in the conductivity). The derivative of the nitrogen transport (Darcy's flux) was approximated in a similar manner in equation (2), but the approach taken with regard to approximation was adapted to account for the return of the mean velocity of the solution in these points in the computational region. The details of the differential method applied in equation (1) can be found in [10, 11].

For the case of nitrogen compounds, the initial condition involves the experimentally determined nitrogen content in the following soil profiles: 0-30, 30-60 and 30-90 cm. The nitrogen content ($\boldsymbol{\rho}$) in the 0-5 cm soil profile forms the boundary condition. This value is derived on the basis of the nitrogen input resulting from fertilization, precipitation, leaching of nitrogen delivered into the soil and mineralization of some of the organic matter.

2.3. Soil conditions, precipitation, agrotechnical measures, laboratory tests of soil condition

The observations and experiments were carried out on the arable land with an area of 1.20 ha, located in the Komorniki, Strzeleczki commune, Opolskie province. The research lasted from March 2014 to November 2015. Soil was extracted for the purposes of laboratory tests four times in 2014 and three times in 2015, from the soil profiles of 0-30, 30-60 and 60-90 cm. Soil laboratory tests carried out at the Chemical and Agricultural Station in Opole and their scope included:

a) granulatometric texture (sandy loam),
b) mineral nitrogen ($N_{min.}$) content using flow colorimetry method.

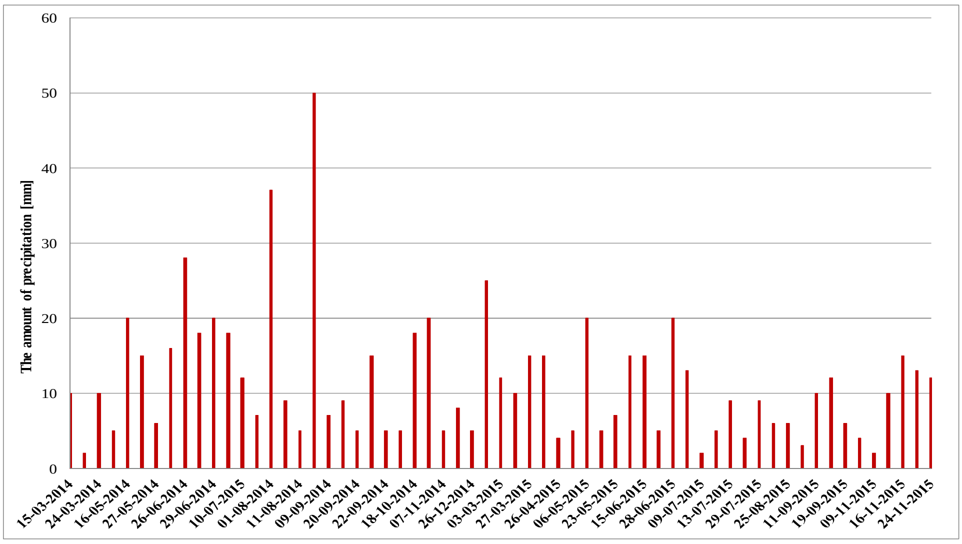
Additionally, the retention curve ($\boldsymbol{pF(\theta)}$) and the water conductivity curve of the unsaturated soil were determined in the laboratory of the Institute of Agrophysics of the Polish Academy of Sciences in Lublin. The numerical simulation applied:

a) data on the plants crops, including nitrogen removal together with these crops,
b) basic agricultural data: sowing and harvesting dates, doses and dates of nitrogen application, and the dates of soil sampling for research (Table 1),
c) weather information: precipitation (Fig. 1),
d) characterization of soil and moisture parameters (Figs. 2 and 3).

Table 1. Agrotechnical measures associated with the application and removal of nitrogen, sampling schedule
Tab. 1. Zabiegi agrotechniczne związane z wnoszeniem i wynoszeniem azotu, terminy poboru gleby

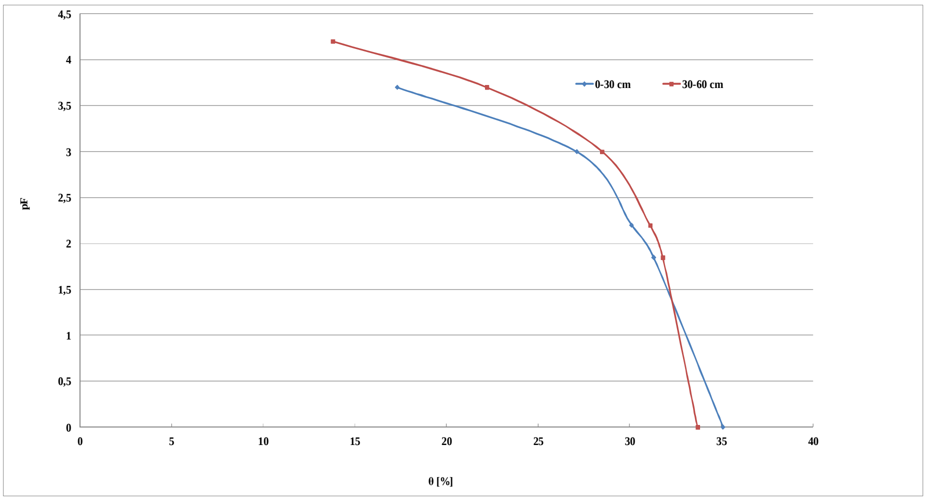
Day	Type of operation	Used $N_{min.}$ [kg·ha^{-1}]	Additional information
06.03.2014	soil sampling for research		
10.03.2014	plowing catch crop		mustard
22.04.2014	corn sowing		80000 seeds·ha^{-1}
22.04.2014	mineral fertilisation	134	urea 46% + NPK (ammonium 5%) + ammonium sulphate 32%
12.06.2014	soil sampling for research		
12.08.2014	soil sampling for research		
27.10.2014	corn harvesting		yield: 12500 kg·ha^{-1}
31.10.2014	soil sampling for research		
31.10.2014	natural fertilisation	64	liquid manure 20 m^3·ha^{-1}
05.11.2014	winter wheat sowing		200 kg·ha^{-1}
05.11.2014	mineral fertilisation	10	NPK (ammonium 5%)
23.02.2015	soil sampling for research		
07.03.2015	mineral fertilisation	44.2	ammonium sulphate 26%
24.03.2015	mineral fertilisation	34.4	ammonium sulphate 32%
15.05.2015	mineral fertilisation	41.6	ammonium sulphate 32%
18.05.2015	mineral fertilisation	2.3	urea 46%
30.06.2015	soil sampling for research		
29.07.2015	winter wheat harvesting		yield: 7000 kg·ha^{-1}
09.09.2015	soil sampling for research		

Source: own study / Źródło: opracowanie własne



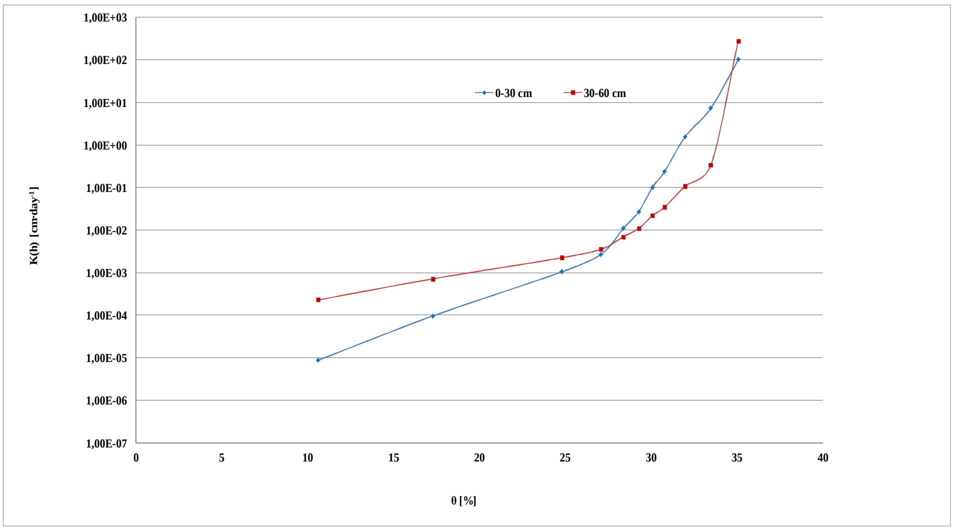
Source: own study / Źródło: opracowanie własne

Fig. 1. Intensity of precipitation between March 2014 and November 2015
Rys. 1. Wysokość opadów w okresie od marca 2014 do listopada 2015 r.



Source: own study / Źródło: opracowanie własne

Fig. 2. Moisture and retention characteristics of layers (0-30 cm and 30-60 cm) in examined soil
Rys. 2. Wilgotnościowa i retencyjna charakterystyka warstw (0-30 cm i 30-60 cm) badanej gleby



Source: own study / Źródło: opracowanie własne

Fig. 3. The water conductivity of the layers (0-30 cm and 30-60 cm) of the examined soil
Rys. 3. Przewodność wodna warstw (0-30 cm i 30-60 cm) badanej gleby

An assumption was made in the study that the growth of the root structure occurs linearly with the increase in the green mass of the cultivated plants. For winter crops, it was adopted that this increase occurs mainly in the spring season. In addition, an assumption regarding an increase in the uptake of water by the roots of plants along with an increase in their mass was taken for the analysis. The source term in equation (1) is expressed by the formula (4):

$$S(\theta) = Tp \cdot \gamma(\theta) \cdot \beta \,, \qquad (4)$$

where ***Tp*** expressed the potential transpiration per unit of root mass, ***γ(θ)*** forms a coefficient that relates to the water uptake with the moisture content in soil. This approach is very similar to the one that was adopted in [1] where reference is made to Feddes et al. [4], and coefficient ***γ*** is related to the soil suction pressure, including an identification of five range of the value of h_s. On the basis of the observations performed in actual soil profiles, we learnt that the density of the root mass assumes its greatest value in the top 40-cm stratum of soil. In [23] it is stated that the dry root mass is proportional to the dry mass of green matter. This value depends on the time (day) of vegetation and current and potential transpiration. Stockle and Campbell [19] applied a cone-shaped root mass distribution, whose base was on the soil surface. The study in [24] uses a logarithmic distribution of the root structure, which gets narrower deeper into the soil. The study in [24] uses a logarithmic distribution of the root structure, which get narrower deeper into the soil. The water uptake by the roots is described in the same way as in the work of Feddes et al. [4]. A compilation containing a very extensive list of mathematical models describing water uptake by roots can also be found in [12]. This list includes, among others, potential transpiration, soil suction pressure and, in very complex models, spatial mass distribution of the root structure.

The study in [3] contains transpiration that is accounted for by the source term $\alpha(h)S_{max}(z)$, a $S_{max} = \gamma \cdot (a - b(z))$. In this formula ***a*** represents the maximum water intake, and ***b(z)*** is the coefficient applied to reduce this value in connection with the decrease in the mass of the root structure along with the depth. The value of ***γ*** is assumed to be equal to 1 during the day and 0.2 at night.

Following the insights in [9], it was assumed in this study that for the moisture level corresponding to the suction pressure of 0.5–5 m water head (i.e. for the range of pF from 1.7 to 2.7), water is readily available to plants and ***γ=1***. In the range of pF from 0 to 1.7, due to the excessive moisture content, the soil becomes anaerobic (***γ=0***). When the value of pF increases above 2.7, the availability of water decreases linearly until pF=4.2 (as a result, water becomes unavailable). Within this range, ***γ*** decreases linearly in the range of 1–0. The ***β*** coefficient is used to account for the linear increase of the mass of root structure accompanying plant vegetation. This does not involve the structure of the roots in the soil, as gradual plant development deeper into the soil profile is adopted.

The nitrogen uptake from the soil solution is accounted for in different manners. In the study [25], the results of Pedersen et al. [16] were used to express the term ***q*** by means of a function (5):

$$q = A\left(1 - e^{f(N\text{pot.}, A)}\right), \qquad (5)$$

where ***A*** coefficient is relative to the nitrogen demand by the green mass and wheat roots during vegetation, and $N_{pot.}$ – potential nitrogen demand. The dry plant mass was investigated by the above authors during the entire vegetation period. On the basis of the above referred to work by Pedersen [16], nitrogen uptake by the plants was determined in [24]. In turn, in [23], the source term ***q(t)*** was derived for each of the identified soil profiles (***Δz***). For each profile, it was presented in the form of the product of nitrogen concentration in the soil solution, a coefficient that accounts for the value of the soil suction pressure and the empirical function ***A(z,t)***, which defined the water uptake rate by corn.

In this article, the use of nitrogen by plants was determined globally on the basis of the resulting yields. The average nitrogen demand per 100 kg of the crop was adopted. The study also adopted an assumption that nitrogen uptake by plants lasts throughout the entire period in the vegetation season and is proportional to the water uptake rate by the roots.

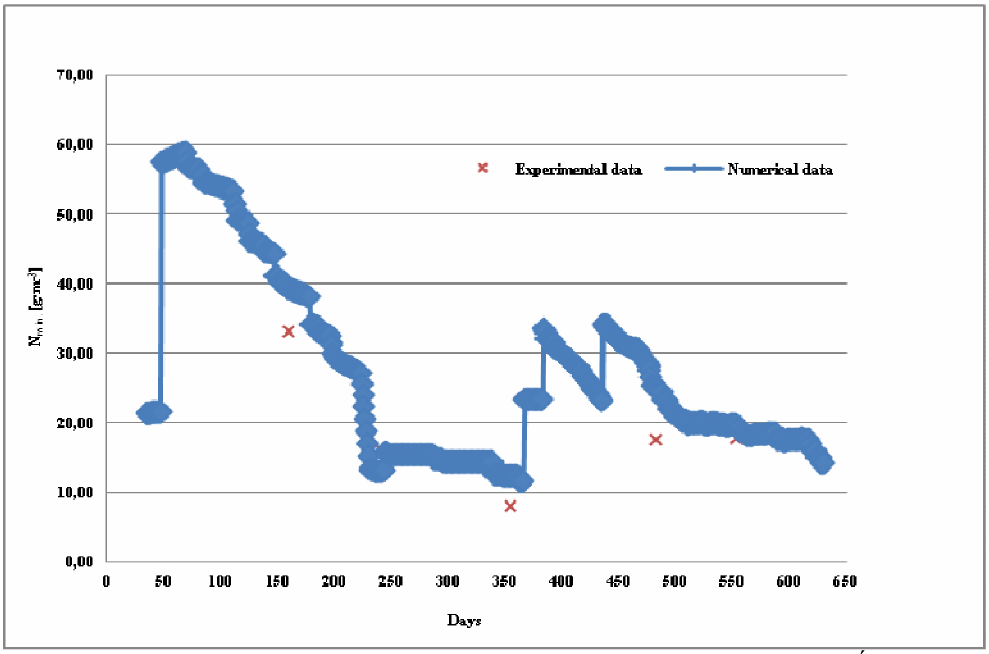
3. Results

The registrations of the variability of $N_{min.}$ content in the investigated soil were carried out in the period from March 2014 to November 2015. In this period, the main yield outputs applied two different crops (i.e. maize for grain and winter wheat). These crops are known to have different levels of nutrient demand and diverse biomass growth. The above had an influence on the variations in nitrogen content over time in the soil profiles. Another important consideration affecting nitrogen penetration deeper into the soil profile was associated with the variations in the volume of rainfall. The period of performed analysis was specific in terms of small levels of rainfall and a long period of drought, in particular in the summer 2015, which had an effect on the course of soil nitrogen content in the two analyzed vegetative periods.

Figs. 4 and 5 illustrate the course of the variability of $N_{min.}$ content in the 0-30 cm and 30-60 cm soil profiles. The numerical calculations were performed under the assumption that $N_{min.}$ content in the soil corresponds to the values resulting from the initial laboratory tests performed for the averaged soil samples derived from the 0-30, 30-60 and 60-90 cm soil profiles. In addition, it was also assumed that in the period from first day (initial soil sampling) to the 35th day of study , the content of $N_{min.}$ changed insignificantly. Therefore, in the figures below the first experimental value $N_{min.}$ during this period was adopted to be equal to the level that was recorded during the initial laboratory tests. At the same time, in the 0-30 cm soil profile, a considerable level of conformity between experimental and numerical data could be noted. The first increase in nitrogen content at this depth was recorded after the 48 days of the cultivation (i.e. at the time following the first mineral fertilization). The results of the subsequent laboratory tests indicate a gradual fall in the nitrogen content in the 0-30 cm soil profile. This was mainly related to the uptake of this element by maize, but was also related to its penetration deeper into the soil profile as a result of precipitation. In the period between the second (June 12, 2014) and the fourth (October 31, 2014) sampling, there were three days with increased levels of precipitation (June 26, 2014 – 28 mm, August 1, 2014 – 37 mm and September 1, 2014 – 50 mm). The total of precipitation in the analyzed period was 288 mm. The Fig. 4 shows a considerable decrease in the content in the 0-30 cm soil profile in that period. The lowest nitrogen content in 2014 corresponded to corn harvesting, which is reflected in the results of study derived from the fourth soil sampling.

At the same time, experimental results obtained from 30-60 cm profile (Fig. 5) demonstrate a slight increase in content corresponding to the period of increased rainfall in 2014. The achieved maize yield at the level of 12500 $kg \cdot ha^{-1}$ indicates the optimal plant use of nitrogen (both from mineral fertilization and from the plowed catch crop) and at the same time relatively small amounts of it were leaching deeper into the soil profile of 30-60 cm.

An increase in the nitrogen level which recovered slightly for the second time was determined in the 0-30 cm soil profile. This increase occurred as a result of the application of a liquid manure and following another round of mineral fertilization in the period from October 31, 2014 to November 5, 2014, before sowing winter wheat. The study noted a nearly constant and low N_{min} content in the autumn and winter seasons of 2014/2015, compared to the spring season of 2014. This could have been due to the previous use of this fertilizer during maize cultivation, coupled with precipitation which led to migration of part of the nitrogen to a deeper soil profile, but also from the slower mineralization process in the winter season of 2014/2015. The content of N_{min} increased again in the 0-30 cm soil profile and corresponded to the mineral fertilizations performed four times between the fifth and sixth soil sampling in 2015.



Source: own study / Źródło: opracowanie własne

Fig. 4. Variations of the value of $N_{min.}$in the 0-30 cm soil profile
Rys. 4. Przebieg zawartości $N_{min.}$ w warstwie 0-30 cm badanej gleby

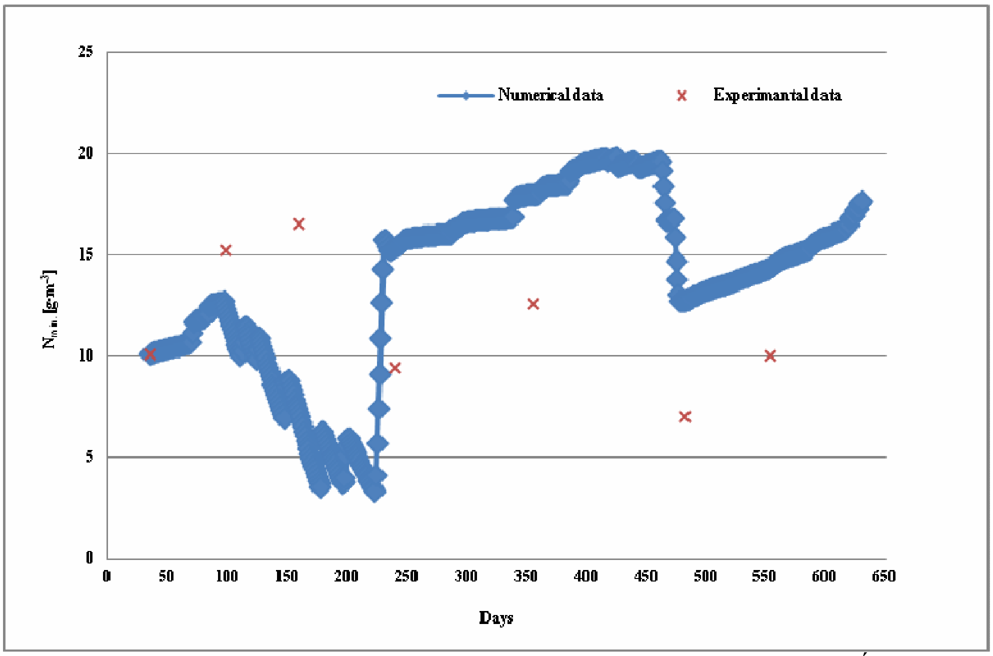


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Fig. 5. Variations in the value of $N_{min.}$ in the 30-60 cm soil profile
Rys. 5. Przebieg zawartości $N_{min.}$ w warstwie 30-60 cm badanej gleby

The variability in the $N_{min.}$ content in the 0-30 cm soil profile recorded in 2015 is considerably smaller. The cultivation of plants with different demands in terms of nutrients and additionally, the diverse weather conditions in 2015 (low precipitation and a considerable deficiency of moisture in soils, especially in the period from June to August) resulted in a significantly lower intensity of nitrogen penetration into the 30-60 cm soil profile in comparison to the previous year (Fig. 5).

The yield of winter wheat (7000 kg·ha^{-1}) can be considered as high and demonstrates an optimum use of the nitrogen that is available in the soil. Concurrently, in the deeper profile (30-60 cm), a greater discrepancy between experimental and simulation data can be recorded in the analyzed period. However, the dependence demonstrated by the increase or decrease in nitrogen content in the soil resulting from the application of fertilizers, uptake by the plants and leaching associated with rainfall was retained.

4. Conclusions

The results of the present study allow to draw the following conclusions:

1. The mathematical model that was developed provides a manner to account for a variety of effects and to determine $N_{min.}$ content as well as the variability of this content in soils with various characteristics and in conditions of growing various types of crops.
2. The model offers the determination of the effects of precipitation on the variable nitrogen content depending on the soil profile that is sampled. In particular, this effect could be noted in the periods corresponding to high levels of precipitation and drought, where the variability of $N_{min.}$ content is limited to the greatest extent.
3. The proposed model provides quantitatively similar results in the top soil profile (0-30 cm) as well as qualitative conformity of experimental and simulation results in the deeper soil profile (30-60 cm). This is due to the fact that the N_{min} content is lower in the samples derived from deeper soil profiles. The error associated with the determination of the nitrogen content is greater in terms of the relative ratio in the deeper soil profiles.
4. The growth and development of the root structure and the increase of biomass associated with diverse crops have an impact on variation in nitrogen content in the soil, although in the analyzed period weather condition plays a considerable role on these fluctuations in particular the ones recorded in the summer of 2015.
5. The obtained yields are high, which may indicate that the use of nitrogen is close to an optimum. The experimental studies carried out and calculations indicate a potentially small amount of $N_{min.}$ migrating outside the area occupied by the root structure.

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