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NITROGEN LEACHING FROM SOILS IN THE ASPECT OF ITS BALANCE

Summary

Nitrogen is the basic element directly affecting plant yielding. This causes that it is widely used as a component of mineral fertilizers. With increased doses of mineral nitrogen, only a certain part of it is used by plants. The rest goes into the environment, polluting the environment. The study attempts to determine changes in the nitrogen content in the arable layer and to determine the nitrogen flux leached from the soil. The research was carried out over a year and a half for three fields with different soils, under different crop conditions. Relations between soil moisture, suction pressure and unsaturated water conductivity were determined for the tested soils. In the mathematical model of water movement in soil, the Richards equation and the equation for the flow of soil solution were used. The source elements of the equations include water and nitrogen uptake by plants. There is a very clear correlation between precipitation and a stream of nitrogen deep into the soil. Soil physical properties play a very important role. The total amount of nitrogen washed out into the soil was determined. It is respectively 14.4 kg· ha^{-1} for clay soil and 75.5 and 91.4 kg·ha^{-1} for sandy soils with the same rainfall. In addition, the results were referred to the gross nitrogen balance of the studied fields.
***Keywords**: soil, nitrogen leaching, nitrogen balance*

WYMYWANIE AZOTU Z GLEBY W ASPEKCIE JEGO BILANSU

Streszczenie

Azot jest podstawowym pierwiastkiem, który bezpośrednio wpływa na plonowanie roślin. Powoduje to, że jest on powszechnie stosowany jako komponent nawozów mineralnych. Przy zwiększonych dawkach azotu mineralnego tylko pewna jego część zostaje wykorzystana przez rośliny. Reszta przechodzi do otoczenia zanieczyszczając środowisko. W pracy podjęto próbę wyznaczenia zmian zawartości azotu w warstwie ornej oraz określenia strumienia azotu wymywanego z gleby. Badania przeprowadzono w okresie półtorarocznym dla trzech pól o różnych glebach w warunkach różnorodności upraw. Dla badanych gleb wyznaczono zależności między wilgotnością gleby, ciśnieniem ssącym i przewodnością wodną w stanie nienasyconym. W modelu matematycznym ruchu wody w glebie zastosowano równanie Richardsa oraz równanie ciągłości przepływu roztworu glebowego. W członach źródłowych równań uwzględniono pobór wody i azotu przez rośliny. Istnieje bardzo wyraźna korelacja między opadami a strumieniem azotu w głąb gleby. Bardzo duże znaczenie odgrywają właściwości fizyczne gleby. Wyznaczono sumaryczną ilość azotu wymytego w głąb gleby. Wynosi ona odpowiednio 14,4 kg·ha^{-1} dla pyłu gliniastego oraz 75,5 i 91,4 kg·ha^{-1} dla gliny piaszczystej, przy takich samych opadach. Dodatkowo odniesiono wyniki do bilansu azotu brutto gleby badanych pól.
***Słowa kluczowe**: gleba, wymywanie azotu, bilans azotu*

1. Introduction – production potential and environmental role of nitrogen – an overview

Nitrogen forms the key element that is responsible for the control of the composition, diversity, dynamic characteristics and performance of many land, freshwater and marine ecosystems [1]. It also acts as an essential nutrient for plants and also the basic element of many components of their cells, in particular of the ones concerned with the photosynthetic apparatus. The importance of this nutrient is evidenced by the fact that as a result of its deficiency, plant development tends to be poor, the color of the whole plant, due to limited chlorophyll production and the reduction of photosynthesis, is pale, yellow-green, leaves have a small surface, and the plant stems and the blades are thin and low [2]. This directly leads to poor plant growth as well as the results expressed in yields. In the conditions marked by nitrogen deficiency, plant roots may also have the ability to increase the total surface of the root system, as they try to exert more effort by directing root growth towards soil layers that are more abundant in nutrients. The issue is not limited to negative consequences of nitrogen deficiency in terms of the volume of production. In terms of the productivity aspect, the excess of this element can significantly reduce plant growth, increase its susceptibility to diseases, pests and decrease quality of crops [3-6]. Excess nitrogen forms the cause of its overgrowth, which increases the weight and leaf surface of plants. At the same time, the poor base formation of the blade, the plant has a tendency to fall over (in particular in the conditions of strong winds and rains).

In addition to the productivity aspect, inadequate nitrogen management can lead to many hazards and losses related to the environment and social aspect [1, 7-12], since quality of the natural environment and human health are known to be adversely affected by pollution of soil, land and groundwater, eutrophication, odors from natural fertilizers, contamination with nitrogen compounds of food products. Other environmental problems and losses arise out of nitrogen accumulation in drinking water or food, or indirect changes in the diversity of ecosystems and biodiversity and the so-called external costs of agricultural production. In accordance with the data in the Report by Clean Baltic Coalition [13], soil and water pollution due to biogenic factors currently forms a major environmental problem, and is known to particularly result from large-scale animal farming. It turns out that plant production generates about 30% of nitrogen emission into the environment, whereas in the case of animal production losses of this element can reach up to 75%.

Other studies also demonstrates that nowadays only 47% of the active global nitrogen input to croplands is absorbed by the cultivated crops, compared with 68% in the 1960s. At the same time, the ratio of synthetic nitrogen use increased nine times over the same period. This may mean one thing that more than half of the nitrogen used to fertilize plants is generated into the environment [14]. In turn, according to [15], agricultural activity in Poland is a serious hazard for the waters in the Baltic Sea basin. Nitrogen, but also phosphorus and other pollutants are carried into the Baltic Sea, among others with river water or surface and subsurface runoff along the coast, and the residence time of these substances in the Baltic Sea corresponds to the time of water exchange determined a period of about 25-30 years.

In terms of both agricultural production and the reduction of nitrogen migration from soils, it is very important to control plant production on the basis of updated results of soil testing that demonstrate the nutrient demand of plants, including the content of mineral nitrogen. The knowledge regarding the soil nitrogen content can provide measurable economic savings on the farm, but can also limit the negative impact of excessive fertilization on the environment.

In addition, knowledge with regard to the impact of the use of forecrops, catch crops or organic fertilizers introduced on fertilizer management plays an important role. In particular, the ability to biologically bind nitrogen by legume plants is one of the most sustainable approaches to provide follow-up plants the necessary nitrogen requirements [16]. In addition to the sources of nitrogen mentioned above, it is also necessary to bear in mind that this element is constantly supplied with precipitation.

2. Nitrogen balance on a farm

The degree of the environmental hazard resulting from an inadequate application of nitrogen fertilizers is evidenced by the fact that since 2017 the entire area of Poland has been considered to be threatened by water pollution caused by nitrogen compounds coming from agricultural sources. The provisions of the Nitrates Directive 91/676/EEC [17] have been implemented into Polish law by virtue of the Water Law Act [18] and the Regulation including the adoption of the "Action Program to reduce water pollution by nitrates from agricultural sources and to prevent further pollution", the so-called "nitrate program" [19]. This program defines criteria and requirements for agricultural producers, including periods of fertilization, doses and techniques of nitrogen fertilization, preparation of a nitrogen fertilization schedule. Admissible nitrogen input was also determined in it. The nitrogen fertilization program forms the basic tool that can be applied to determine the adequacy of fertilization, and it should be implemented based on the data from the so-called simplified nitrogen balance, where the equation for determining the minimum mineral nitrogen input ($N_{min.}$) is applied in the form (1):

$$\text{Dose of } N_{min} = \frac{Y \cdot P_i - \sum N_{os} \cdot E_f - C_{f,i}}{0{,}7}, \qquad (1)$$

where:

Y – yields [$t \cdot ha^{-1}$],
P_i – specific intake N by a plant [$kg\ N \cdot t^{-1}$],
N_{os} – nitrogen derived from other sources [$kg\ N \cdot ha^{-1}$],
E_f – fertilizer equivalent,
$C_{f,i}$ – correction to account for plant used as forecrops and intermediate crops [$kg\ N \cdot ha^{-1}$].

Among the items in the above formula, intake of N_{min} is also taken into account in the soil profile of 0–60 cm. This value should be derived on the basis of the current soil tests. The purpose of the above approach is to determine only the N_{min} input. The assumption here is that the dose calculated in accordance with the recommendations of the "nitrate program" $N_{min.}$, should be safe for the environment and to secure the nutritional demand of plants. The simplified balance does not take into account, for example, precipitation or such a component as nitrogen introduction along with seed material. The difference between total nitrogen intake from various sources and its removal from soil is not analyzed here. Thus, the approach proposed in the "nitrate program" does not indicate how much nitrogen is left in the environment. Therefore, it is recommended here to apply the so-called nitrogen balance "on the surface of the field" (so-called "gross balance"). It offers the assessment of soil burden resulting from the total input of minerals [20]. In such calculation methodology, an assumption is made that the positive gross nitrogen balance in a given field, in the range of 30–70 kg $N \cdot ha^{-1}$ [21], is considered safe for the environment. However, the Code of Good Agricultural Practice indicates the need to keep to the lower figure in this range [22]. To emphasize the importance of the problem, often expressed by overstated results of this balance, we are inclined to analyzed the gross nitrogen balance sheets for European Union countries that have been compiled in recent years. According to OECD data (data for various countries refer to 2015 or 2016) [23], in many EU countries one can note that the recommended norm given by the good agricultural practice is exceeded (Fig. 1). Poland, with a balance sheet result in 2015 of 48 kg $N \cdot ha^{-1}$ of agricultural land (AL) may pose a threat even to the waters of the Baltic Sea basin. The location of catchment area in Baltic Sea basin influences the content of nutrients in its waters, with an example of the nitrogen balance for Norway in 2016 in the range of as much as 106 kg $N \cdot ha^{-1}$.

The above approach provide an idea regarding the scale of potential threats resulting from the excess amounts of nitrogen fertilizers applied in agriculture and its subsequent nitrogen migration.

The balance calculations involving gross nitrogen leaching used can have a varied degrees of detail. Nevertheless, all poof them take into account the type and amount of nitrogen intake and removal from the field. The main elements of the gross nitrogen balance according to the above methodology are included in the results presented in Fig. 2. A negative balance value indicates a decrease in soil fertility and vice versa a positive value - it means a hazard resulting from soil, water and air pollution by nitrogen derivatives.

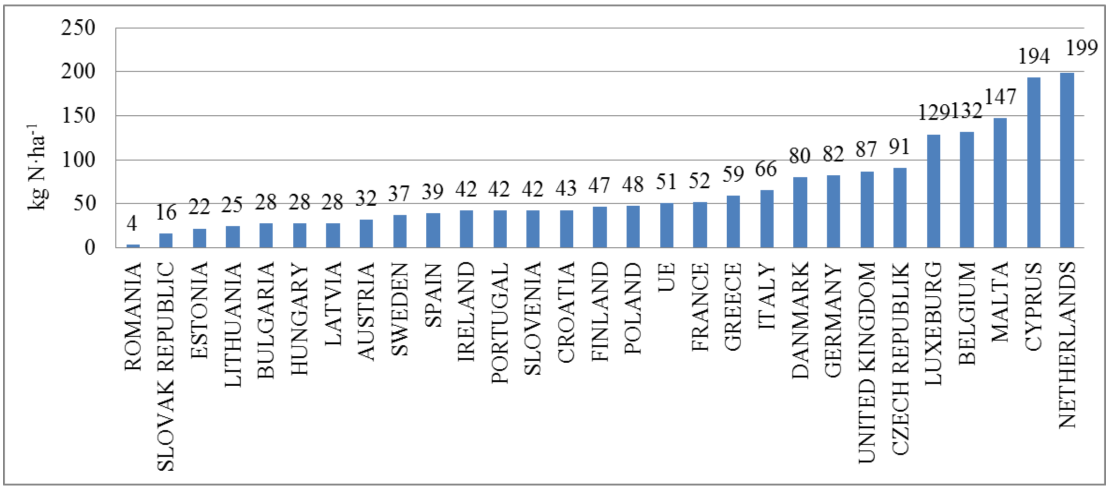
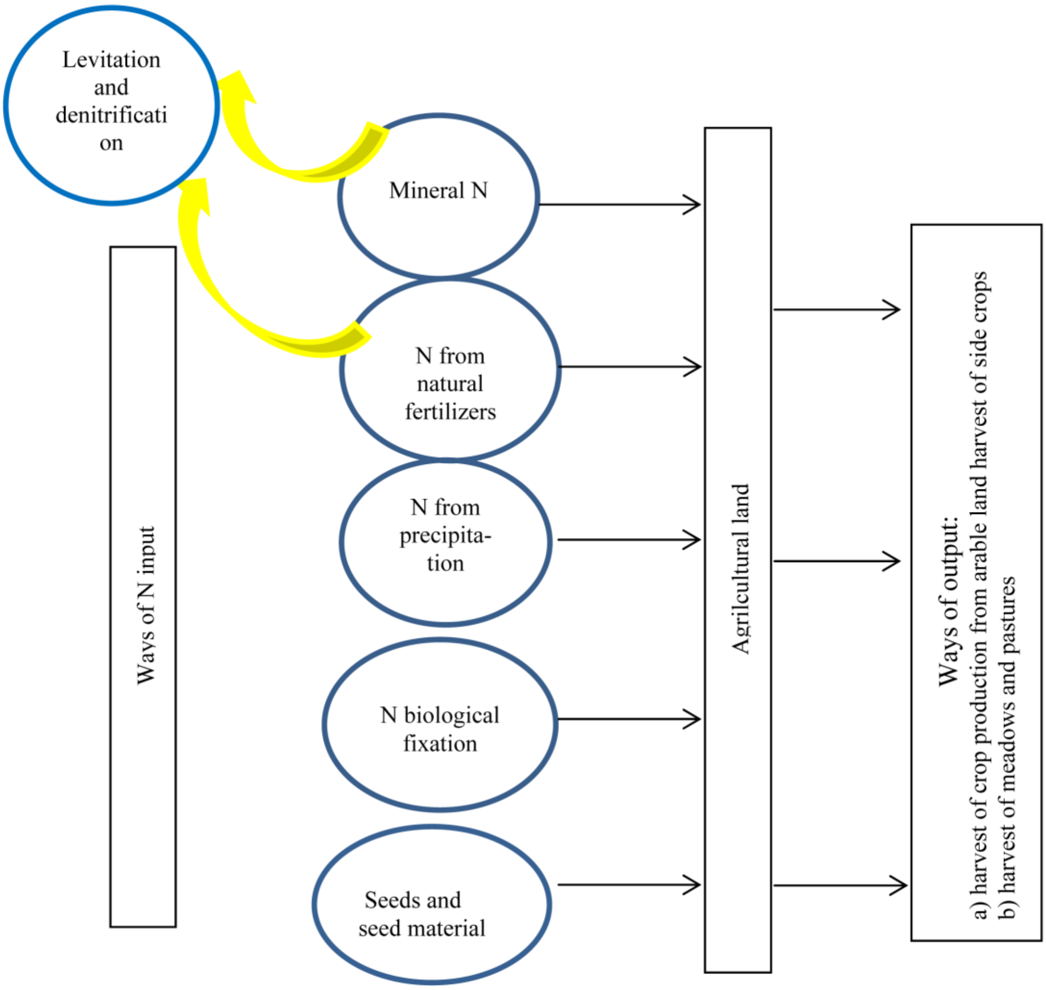


Fig. 1. Gross nitrogen balance in the European Union [kg N·ha^{-1} of AL] [23]
Rys. 1. Bilans azotu brutto w krajach Unii Europejskiej [kg·ha^{-1} UR] [23]



Source: own study / Źródło: opracowanie własne

Fig. 2. Gross nitrogen balance components
Rys. 2. Składniki bilansu azotu brutto

3. Nitrogen migration in soil

Nitrogen applied to the soil can be subjected to various transformations, and its leaching occurs even in the conditions of adequate fertilizer management. According to Krysztoforski [24], plants uptake is equal to 50% of the application of nitrogen, 5% is leached deep into the soil profile, about 20% - escapes into the atmosphere due to denitrification, and with regard to 25% there is a reasonable chance for its immobilization, which in time after mineralization can be available to plants. A confirmation of the above can be found in the results of the study [25], where it has been demonstrated by the example of long-term cultivation of maize on loamy soil, that denitrification and nitrogen incorporation into soil organic matter are to the greatest extent responsible for the depletion of unused nitrogen. The

NO_3-N content in soil, if not used by cultivated plants, may, however, be subject to leaching outside the zone that is accessible by roots, and this depends on, among others by soil type, manure fraction [26], ability of transport by water, e.g. with precipitation that infiltrates in the soils throughout the cultivation period [27]. Removal usually occurs in the autumn and early spring months when fertilizer application takes place [28]. Other studies [26] demonstrate low level of nitrate leaching that accompanied winter wheat cultivation (19–34 kg $N \cdot ha^{-1}$) after spring mineral and natural nitrogen fertilization, which is attributed to the use of nutrients by plants during their growth. However, a significant increase in nitrate leaching was recorded in the conditions when natural solid fertilizers were applied in the autumn (23–35% of cumulative N).

Besides, the types of crops and ratio of soil cover by vegetation form some of the important factors that regulate the migration of nitrogen deep into the soil, beyond the zone accessible to roots. The depth of the root structure, the rate at which the plant absorbs water, and with it nitrogen, are factors closely related to the type of plant cover. As demonstrated in one study [29], nitrogen leaching is lower on grasslands compared to croplands. When very small doses are supplied, the level of nitrogen leaching from croplands is much higher than on grasslands. This is probably due to the different characteristics in which nitrogen absorption occurs on these fields. On grasslands, however, there is a stronger increase in nitrogen removal at doses higher than 200 kg $N \cdot ha^{-1} \cdot year^{-1}$. However, at very high doses (above 800 kg $N \cdot ha^{-1} \cdot year^{-1}$), the type of crop will no longer play an important role in the leaching processes. Another experiment [30] also indicated that nitrogen doses of 285 and 400 $kg \cdot ha^{-1}$ were not fully absorbed by the plants, thus increasing the concentration of nitrates in the soils. This impact was also observed in periods without crops even after 2 to 3 years.

Limited nitrogen migration deeper into the soil profile has also been demonstrated in no-tillage plowing compared to traditional tillage [31]. In the study [32] it was concluded among others that nitrate leaching to a soil profiles of 30–60 and 60–90 cm was equal to, respectively: 48.6% and 47% lower in a no-tillage system compared to the case when using traditional tillage was employed.

On the one hand, the above examples indicate the multitude of factors that affect the leaching of nitrogen compounds. Even so, from the point of view of environmental protection and indications of possible measurable economic losses in a farm, it seems reasonable to analyze the actual course of nitrogen circulation in a soil after fertilization is applied. Actual tests can be supplemented by data derived with simulation results based on dedicated programs. They give the possibility of theoretical determination of the migration of nitrogen in a given farm, assuming various weather conditions, rates if fertilization, crops, procedures, etc. Of course, such analyses require a broad data apparatus and conduct research over a longer period of time, but they allow to determine the actual threats that are posed.

Test results using modeling with regard to nitrogen migration in soil and circulation nutrient are well documented. The study of Stalenga and Jończyk [33], applied the NDICEA simulation program for the organic system, and demonstrated high convergence of results with real measurements for the 0–30 cm soil profile. The program included both an account of the nitrogen balance (33 kg $N \cdot ha^{-1} \cdot year^{-1}$) and the loss of nitrogen resulting from its leaching (mean of 8 kg $N \cdot ha^{-1} \cdot year^{-1}$) and denitrification (average 17 kg $N \cdot ha^{-1} \cdot year^{-1}$).

A variety of reports include a statement that despite the fact that nitrogen forms an important component in plant production, its migration into the keeper soil profiles and into the environment (beyond the intended use) has many negative outcomes in terms of health and environment. At the same time, various systems that are applied to model the ways of nitrogen absorption and its leaching offer the understanding of the beneficial and adverse outcomes of the nitrogen use. The N-PIOT model applied as an example [34] has demonstrated that corn, soybean and wheat are capable of extracting the ratio equal to 86, 11 and about 3% of nitrogen supplied in the form of fertilizers, respectively. At the same time, the degree of leaching of N compounds into the environment (water and air) was the largest when maize was grown (approx. 22%), while N emission accompanying the cultivation of soybeans was approx. 10%, and around 4%. when wheat was grown. Other studies [35] indicate that, the constant intake of nitrogen fertilizers resulting from irrigation is probably responsible for the increase in nitrate concentration in groundwaters. Seasonal nitrogen removal rates were highest on sandy loams and the lowest on silty loams. In the model that was applied, the assessment of micro-irrigation to play to role of another fertilization stage was performed, as it was proven to be more effective in terms of both water consumption and nitrogen leaching. The CAPRI model [36] offers an example of an interesting approach to the issue of nitrogen migration. As a result of its application for the area in the European Union, it was directly demonstrated that the supply of total nitrogen, intensive agriculture and specialization in animal production turn out to be the principal factors responsible for the surplus pf nitrogen and the low efficiency of its use. A total of 27.8 tons $N \cdot year^{-1}$ is supplied to croplands in Europe. However, the plants were able to apply and return only 17.6 8 tons $N \cdot year^{-1}$ in the harvested crops. This means that approximately 10.1 tons of $N \cdot year^{-1}$ could be lost to the environment, leading to the absorption of nitrogen at a mean level of about 65%. On the basis of the assumption adopted by Krysztoforski [24] that about 5% of nitrogen can be leached to water, we get a figure of about 0.5 Mt $N \cdot year^{-1}$ that is carried with land waters. Using the CAPRI model, an estimation of the nitrogen budget was performed for the EU area, where each country is considered as a representative farm. The scope of this analysis was broad, however, it focused only on the results of the N balance at soil level, its excess for the EU was equal to an average of 55 kg $N \cdot ha^{-1} \cdot year^{-1}$, including such countries as the Netherlands and Malta.

4. Objective of this study

The amount of nitrogen that is carried with water beyond the topsoil profile forms the most difficult part of the overall estimations concerned with nitrogen balance. This amount depends on the moisture content of the soil, precipitation during the considered period, and on the moisture characteristics and water conductivity of soils. The plant growth is accompanied by uptake of nitrogen and this process continuously changes the soil structure. Nevertheless, the circulation of water in soils forms the basic mechanism that is responsible for leaching of nitrogen compounds outside the topsoil layer. A method that is used to determine the amount of nitrogen carried away from the soil can be based on the mathematical modeling of its migration in soil.

In terms of mathematical formula, the circulation of water in soil is accounted for by the Richards equation [37, 38, 39], which is supplemented by an equation which captures the relation between soil suction pressure and moisture content, as well as a dependence applied to take into account the relation between the conductivity of unsaturated soil and its moisture content.

In this work, an attempt was made to model the variations in nitrogen stocks in croplands across the soil profile of 0–60 cm. The analysis was carried out with regard to three fields, characterized by various characteristics expressed by water conductivity. Various crops were cultivated in these fields, characterized by root systems specific to them and different fertilization programs were applied in them including various demand for water. An attempt at the determination of nitrogen fluxes that migrate deep into the soil profile with water was undertaken. In addition, the cumulative amount of nitrogen was calculated which was not absorbed by the plants and eventually penetrated into groundwater. The modeling of mineral nitrogen stocks across the soil profile of 0–60 cm was verified on the basis of laboratory data with soil tests. Additionally, the results obtained were referred to gross nitrogen balances calculated for the analyzed fields.

5. Materials and methods

The study and experiments concerned with the problem was performed for three examples of croplands with the following surface areas:

a) field A: 1.20 ha,
b) field B: 1.40 ha,
c) field C: 0.62 ha.

The analyzed fields are located in the Opolskie Voivodeship, in the village of Komorniki, Strzeleczki commune, Krapkowice district. The period of the investigations lasted from March 2014 to November 2015. Soil sampling for laboratory tests from each field was carried out four times in 2014 and three times in 2015. The soil samples were extracted across the soil profiles of 0–30 cm and 30–60 cm. For the purpose of soil nitrogen content analysis, the soil profile that was assumed was 0–60 cm. Soil laboratory tests were carried out at the District Chemical and Agricultural Station in Opole. The research included:

a) soil texture,
b) concentration of $N_{min.}$ across the profiles of 0–30 cm and 30–60 cm.

In addition, the retention curve and the conductivity curve of unsaturated soil were determined in the laboratory of the Institute of Agrophysics of the Polish Academy of Sciences in Lublin.

With the purpose of the comprehensive problem analysis, the following data was derived from the farms:

a) yields and crop N removal,
b) basic agrotechnical data, including: sowing and harvesting dates, doses and dates of nitrogen application and soil sampling dates for the purposes of the analysis,
c) data regarding precipitation.

The data in the Table 1 contains basic summary of information regarding the fields: area, textural classes of soils, types of crops, and their yields. On the other hand, Table 2 contains information on agrotechnical operations related to intake and leaching rates of nitrogen, including soil sampling data.

Table 1. General information on the analyzed fields
Tab. 1. Ogólne informacje dotyczące analizowanych pól

Field	Area [ha]	Soil textural classes	Crop		Yield [dt·ha^{-1}]	
			2014	2015	2014	2015
A	1.20	silty loam	maize (grain)	winter wheat	125	70
B	1.40	sandy loam	cereal-legume mixture	winter rape	35	30
C	0.62	sandy loam	cereal-legume mixture	cereal mix	35	33

Source: own study / Źródło: opracowanie własne

Table 2. Basic agrotechnical data for fields A, B, C and dates of soil sampling
Tab. 2. Podstawowe dane agrotechniczne dla pól A, B, C oraz terminy poboru próbek glebowych

Date of activity	Field A		Field B		Field C	
	Activity	N [kg·ha^{-1}]	Activity	N [kg·ha^{-1}]	Activity	N [kg·ha^{-1}]
06.03.2014	SS		SS		SS	
07.03.2014					M/S 35 t·ha^{-1}	69.3
08.03.2014			AP			
10.03.2014	AP					
11.03.2014			$N_{min.}$	64	AP	
12.03.2014					$N_{min.}$	64
14.03.2014			CS		CS	
22.04.2014	CS					
22.04.2014	$N_{min.}$	134				
09.05.2014			$N_{min.}$	2,3	$N_{min.}$	2.3
12.06.2014	SS		SS		SS	
14.07.2014			H			
28.07.2014					H	
12.08.2014	SS		SS		SS	
25.08.2014			Nmin.	15		

Cont. Table 2 / *Tab. 2. cd*

26.08.2014			CS			
24.09.2014					AS	
27.10.2014	H					
31.10.2014	SS		SS		SS	
31.10.2014	M/S 20m^3·ha^{-1}	64				
05.11.2014	CS					
05.11.2014	$N_{min.}$	10				
23.02.2015	SS		SS		SS	
02.03.2015			$N_{min.}$	52		
07.03.2015	$N_{min.}$	44.2			M/S 20 t·ha^{-1}	39.6
07.03.2015					AP	
21.03.2015			$N_{min.}$	64		
24.03.2015	$N_{min.}$	34.4				
28.03.2015					CS	
28.03.2015					$N_{min.}$	38.8
17.04.2015			$N_{min.}$	48		
26.04.2015			$N_{min.}$	1.84		
15.05.2015	$N_{min.}$	41.6				
18.05.2015	$N_{min.}$	2.3				
30.06.2015	SS		SS		SS	
21.07.2015			H			
29.07.2015	H					
31.07.2015					H	
14.08.2015			AS		AS	
09.09.2015	SS		SS		SS	

Notes : SS – soil sampling; $N_{min.}$ – mineral N fertilization; M/S – manure or slurry fertilization; AP – aftercrop ploughing, AS – aftercrop sowing, CS – crop sowing; H – harvesting

Source: own study / Źródło: opracowanie własne

The amount of precipitation in the analyzed period was relatively low. According to the meteorological data by Central Statistical Office, in 2014 the average rainfall was 594 mm [40] for the Opolskie Voivodeship and in 2015 it was only 358 mm [41]. Precipitation on the investigated fields in the analyzed period was equal to a total of 704 mm. The period covered by the analysis was therefore quite specific. A small, local amount of precipitation and a long period of drought, in particular in 2015, resulted in different courses of variation in the nitrogen content in the soils. Gross nitrogen balance for ABC fields was determined using the reports and the norms referred to therein [21, 24, 42, 43].

The analysis of nitrogen transport in soil applies the mathematical model based on the Richards equation, equation of flow continuity for soil solution and additional formulae that are applied to relate other physical quantities. The analyzed issue is treated as one-dimensional and non-stationary. On the basis of these assumptions, the Richards equation takes the form (2):

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left(K(\theta)\frac{\partial h_S(\theta)}{\partial z}\right)-\frac{\partial K(\theta)}{\partial z}-S(\theta) \quad (2)$$

and the flow continuity equation takes the form (3):

$$\frac{\partial\rho}{\partial t}=\frac{\partial\left(D_d\,\frac{\partial\rho}{\partial x}\right)}{\partial z}-\frac{\partial(\rho\nu)}{\partial z}+q \quad (3)$$

In this formula, θ represents the soil moisture defined as a volumetric water content in a given volume of soil, $K(\theta)$ denotes the hydraulic conductivity of unsaturated soils. The value h_s represents the suction pressure of soil, and $S(\theta)$ represents the source term. ρ gives the nitrogen density per unit of soil solution, D_d forms the dispersion-diffusion coefficient that accounts for diffusion and hydrodynamic dispersion relative to the flow velocity. The quantity ν, in the equation denotes the mean velocity of the particle flux containing nitrogen, $\rho\nu$ forms the Darcy's flux [39].The relations between soil moisture content and conductivity $K(\theta)$ as well as suction pressure $h_s(\theta)$ are represented by polynomial expressions, which were developed on the basis of the results of experiments involving soil samples.

The sources term q in equation (3) gives an account of the supply of nitrogen into the soil with mineral and organic fertilizers, nitrogen from the decomposition of organic matter (ploughed catch crops, dead plant roots), intake of nitrogen from the air with precipitation and nitrogen uptake by plants.

The water uptake of plants is relative to on the size of the root mass growth and its distribution in the soil, as well as the soil moisture content [39]. The weight of the roots and its distribution over time are relative to the type of the cultivated plants and its development.

The source term in equation (2) is expressed by the formula (4) in which Tp represents the potential transpiration per unit of root mass, $\gamma(\theta)$ denotes a coefficient that expressed the dependence of water uptake and the soil moisture content. This approach is very similar to the one applied in [44] where a reference was made to the study by Feddes et al. [45], the γ coefficient depends on the soil suction pressure, and β coefficient gives the linear increase of the root mass throughout the vegetation period

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

The structure of the roots in the soil is not taken into account, as an assumption is made regarding the gradual growth of root structure deeper into the soil. It has been assumed that the growth of the root structure occurs linearly with the increase of green mass of cultivated plants. For the case of winter crops, it is assumed that this increase occurs mainly in the spring. It was also assumed that the uptake of water by plant roots increases as their mass increases.

Equations in the mathematical model were solved using finite difference method [39, 46, 47] using the original script developed in the algorithmic lg-FORTRAN. It was proven the finite difference method can be effectively applied to solve numerous mathematical-physics problems, including fluid movements in porous media.

6. Results and analysis

6.1. Gross nitrogen balance

The results giving the gross nitrogen balance in fields A, B, C, for the years 2014 and 2015 demonstrates the existence of considerable surplus of nitrogen for fields B and C (Table 3). For field A, there was a slight deficit of nitrogen supply in the year 2014.

From the data in Table 3, we can see that a significant surplus in the nitrogen balance in 2015 occurred for field B (81.3 kg·ha^{-1}) and in 2014 for field C (93.5 kg·ha^{-1}). On the basis of the analysis of the total nitrogen balance for the analyzed period from March 2014 to November 2015, we can conclude about the occurrence of surplus nitrogen intake to the fields, equal to 48.5 kg·ha^{-1} for field A, 122 kg·ha^{-1} for field B and 163 kg·ha^{-1} for field C. Some of this nitrogen is absorbed in various layers of soil, and some is leached with water beyond the soil profile that is accessible to plants. This amount of mineral nitrogen loss is estimated in various manners. Some reports suggest that this range is from 5-9% of unbalanced nitrogen. Due to the fact that the leached nitrogen forms a significant hazard to the environment, the mathematical model of nitrogen migration was applied to estimate the changes in N_{min} value in the 0–60 cm profile in the analyzed fields, and the nitrogen flux migrating into the soil and the total amount of leached nitrogen were determined in the analyzed period.

6.2. Nitrogen migration in soil

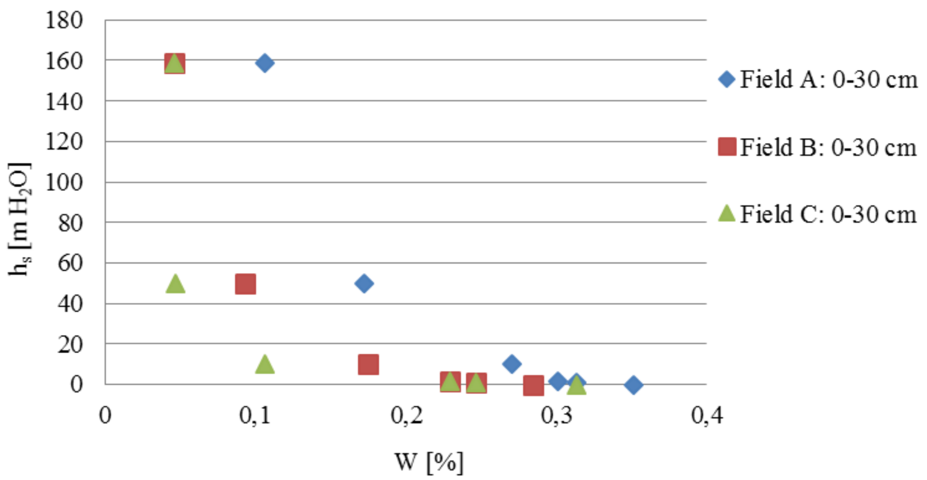
The migration of nitrogen in the soil is largely relative to the physical properties of a given soil, its moisture saturation, and the incidence and value of precipitation. Throughout the vegetation season, the uptake of water and mineral nitrogen by plants is of equal importance. Figs. 3 and 4 show suction pressure as a function of moisture content and the relation between unsaturated water conductivity and suction pressure for the analyzed soils.

We can conclude that the physical characteristics of the analyzed soils are distinctly different. In the conditions marked by a similar moisture content, the soil suction pressure is generally higher in the soil in field A than for soils B and C. As a consequence, the hydraulic conductivity of soil in field A in the unsaturated state is two times lower than for soils B and C. Also with regard to saturated hydraulic conductivity, Soil A demonstrates four times smaller conductivity than soil B and twenty times smaller than soil in field C. The test results presented in Figs. 3 and 4 relate to the 0–30 cm soil profile. The 30–60 cm soil profile has similar characteristics.

Table 3. Gross nitrogen balance results [kg N·ha^{-1}] for fields A, B, C in 2014 and 2015
Tab. 3. Wyniki bilansu azotu brutto [kg N·ha^{-1}] dla pól A, B, C w 2014 i 2015 r.

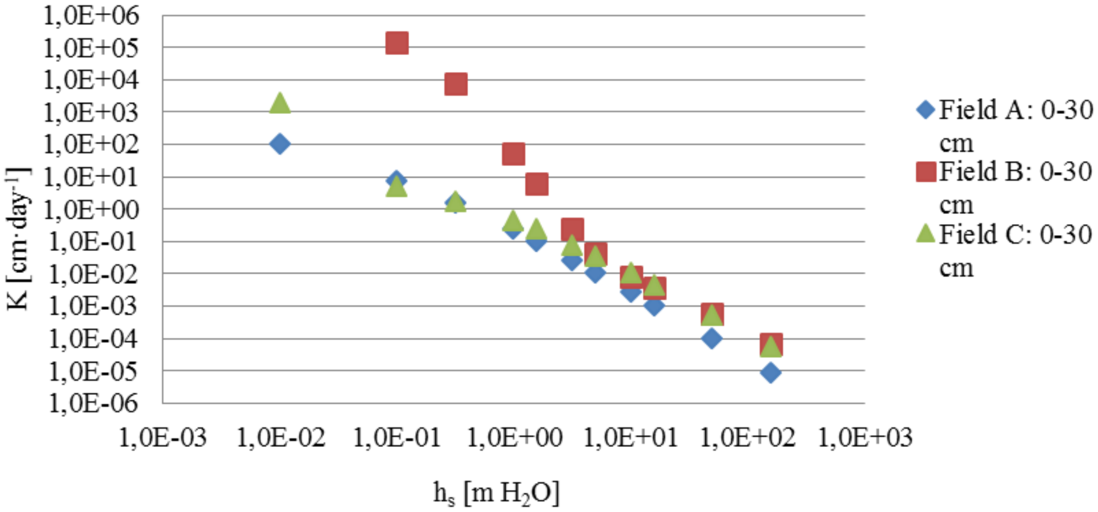
A		B		C	
2014	2015	2014	2015	2014	2015
Nitrogen supplied from all sources					
271	231.5	145.7	240.3	198.5	154.5
Nitrogen uptake with main and secondary crops					
275	179	105	159	105	85.0
Balance N result					
-4	52.5	40.7	81.3	93.5	69.5
Total balance for the analyzed period from March 2014 to November 2015					
48.5		122		163	

Source: own study / Źródło: opracowanie własne



Source: own study / Źródło: opracowanie własne

Fig. 3. Relation between suction pressure and soils moisture content in fields A, B, C
Rys. 3. Zależność między ciśnieniem ssącym a wilgotnością gleby na polach A, B, C

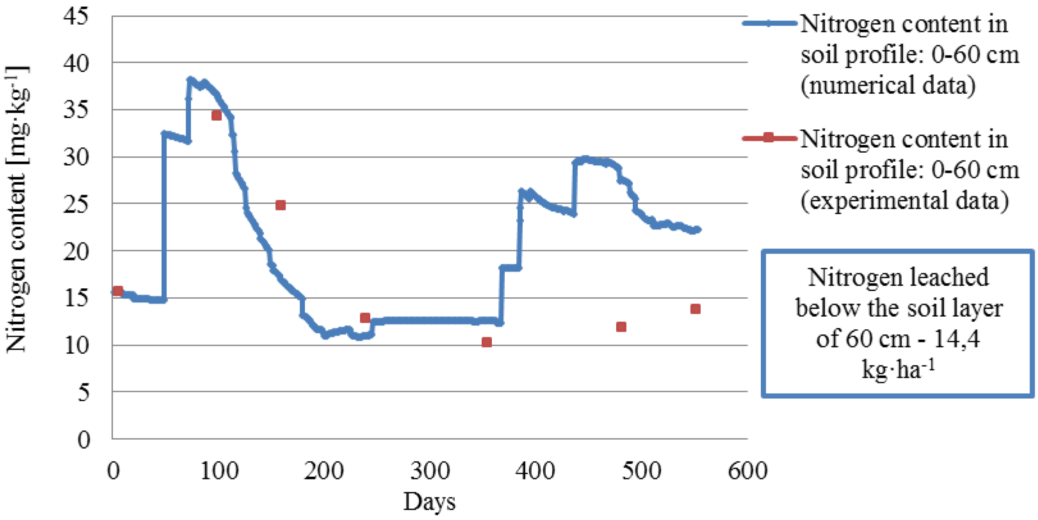


Source: own study / Źródło: opracowanie własne

Fig. 4. Relation between hydraulic soil conductivity and soil suction pressure in fields A, B, C

Rys. 4. Zależność między przewodnością hydrauliczną a ciśnieniem ssącym gleby na polach A, B, C

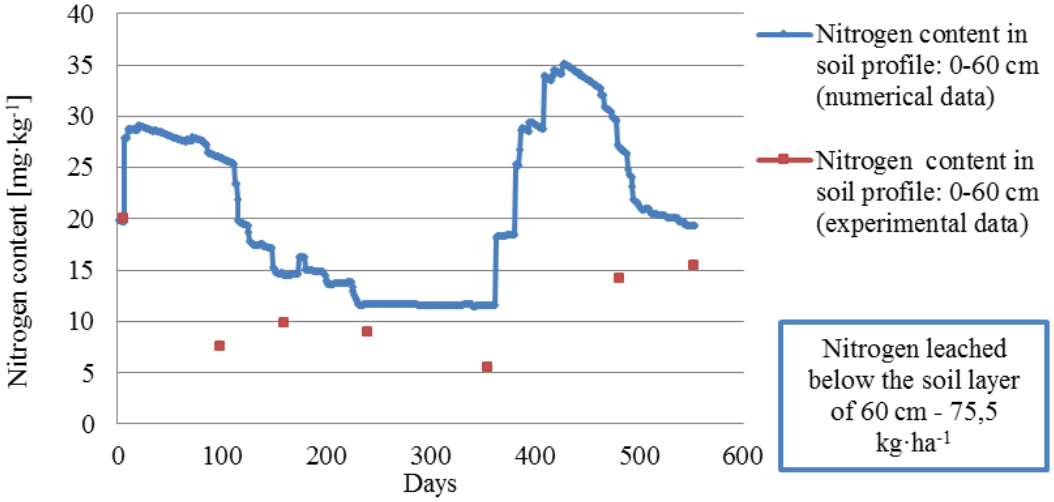
Figs. 5, 6 and 7 present the nitrogen concentrations in the 0–60 cm soil profiles in the investigated period. The calculations take into account the initial nitrogen concentrations in the 0–30 cm, 30–60 cm soil profiles as well as the results with regard to the profile under 60 cm gained from soil sampling results. Agrotechnical operations and crop characteristics presented in Table 2 are also taken into account. The calculations also involve detailed data on precipitation in the investigated period. The figures also include laboratory data regarding the values of $N_{min.}$ A conclusion regarding qualitative compliance of the calculated values with laboratory data from soil tests can be made. The biggest differences are related to periods in which there were large fluctuations in $N_{min.}$ content over short periods of time in the soils, that are attributed to fertilization or intense precipitation. Over such periods, changes in nitrogen concentration occur within a few or dozen days, which is not fully taken into account in the calculation procedures. Such results can also be attributable to locally increased water content in soils, the effect of root structure on the soil environment, ploughing aftercrops or other considerations that are difficult to account for in calculation procedures. We can see that in the case of field B, nitrogen migration deeper into the soil profile occurs faster than in the case of the soil in field A. This is primarily due to the greater hydraulic conductivity of soil in field B. The following Figs. 5, 6 and 7 also demonstrate the total amount of nitrogen leached from the 0–60 cm soil profile in the analyzed time period of. It is equal to 14.4 kg ha^{-1} for field A, 75.5 kg ha^{-1} and 91.4 kg ha^{-1} for fields B and C, respectively.



Source: own study / Źródło: opracowanie własne

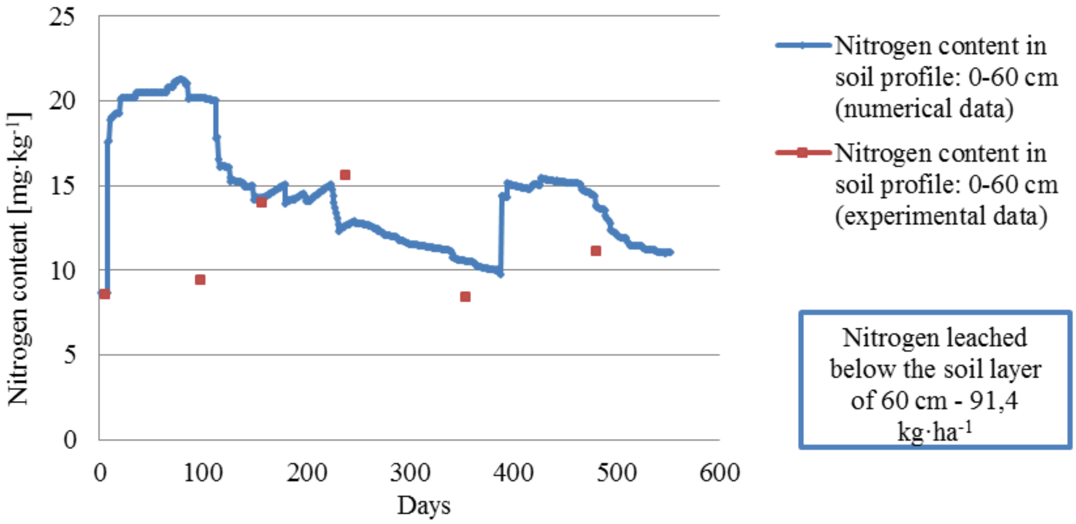
Fig. 5. Mean $N_{min.}$ content in the 0–60 cm soil profile for soil in A field

Rys. 5. Średnia zawartość $N_{min.}$ w glebie na głębokości profilu 0–60 cm na polu A



Source: own study / Źródło: opracowanie własne

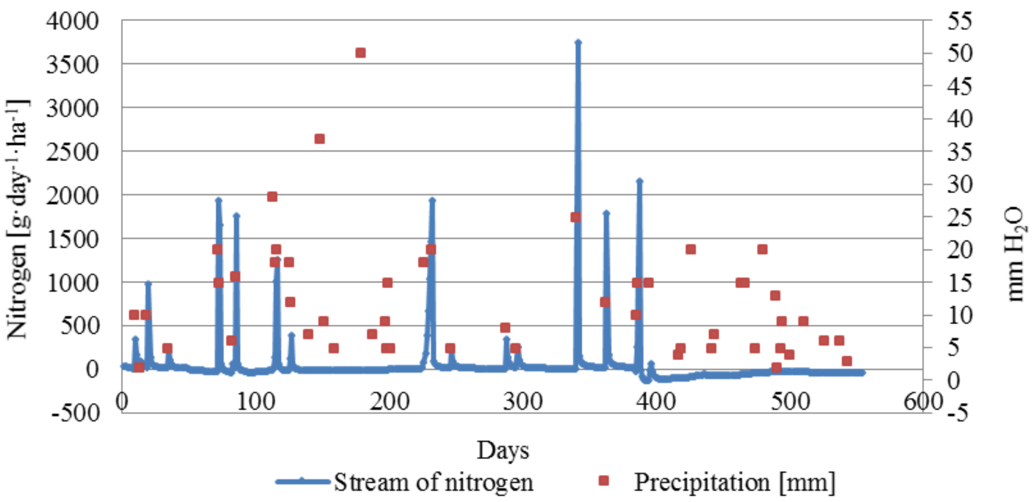
Fig. 6. Mean $N_{min.}$ content in the 0–60 cm soil profile for soil in B field
Rys. 6. Średnia zawartość $N_{min.}$ w glebie na głębokości profilu 0–60 cm na polu B



Source: own study / Źródło: opracowanie własne

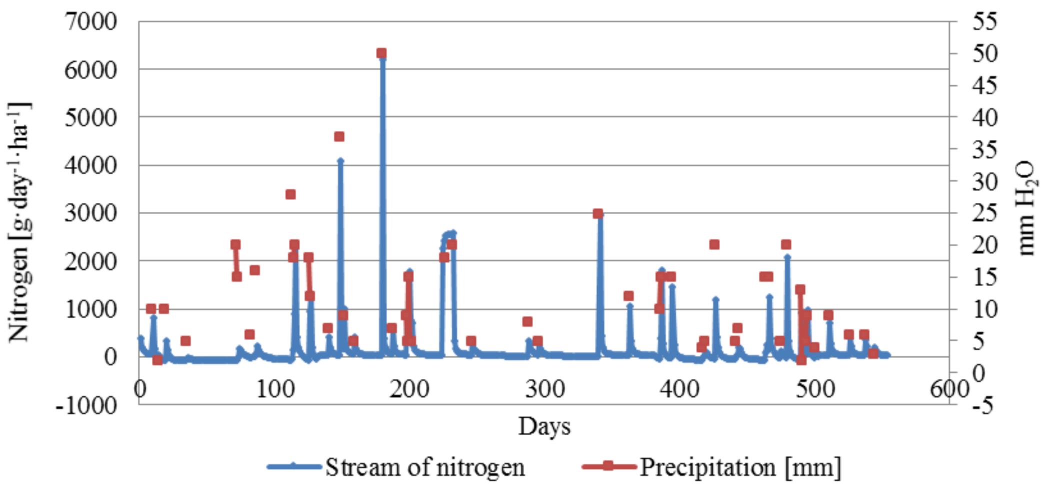
Fig. 7. Mean $N_{min.}$ concentration in 0–60 cm soil profile for soil in C field
Rys. 7. Średnia zawartość $N_{min.}$ w glebie na głębokości profilu 0–60 cm na polu C

Figs. 8, 9 and 10 contain numerically calculated nitrogen fluxes migrating deep into the soil in the soil profile of 60 cm in g·(ha·day)$^{-1}$. These figures also contain details of precipitation expressed in mm H_2O on the specific dates. We can see that this flux takes on values in the range of a dozen or several dozen g·(ha·day)$^{-1}$. Periodically, it can also assume negative values, when the suction pressure of the soil from which the plants absorb water causes the rise of water from deeper layers. In the conditions of higher rainfall, this flux can increase its instantaneous value up to several thousand g (h·day)$^{-1}$. This value is relative to the precipitation rate, hydraulic conductivity of the soil and the current concentration of mineral nitrogen as a function of soil depth, especially in this case in the soil profile of 40–60 cm. The effect of these factors can be perceived on the basis of the comparison between fields A and B (Figs. 8 and 9). In the case of field A, over the period from 150 to 200 days and after 450 days of the experiment, the analyzed nitrogen flux input plays an insignificant role despite the occurrence of rainfall. This is due to the lower hydraulic conductivity of the soil and, above all, to the low concentration of $N_{min.}$ in this period in the soil profile of 40–60 cm. However, the case is different for soils in field B. In the analyzed case, each larger instance of precipitation was associated with virtually more nitrogen leaching deeper into the soil. It resulted from the much greater conductivity of the sol as well as the period and greater amount of mineral nitrogen supply. The cumulative amount of nitrogen that was leached from the soils, both in the case of soils in fields B and C, demonstrates that for soils with such physical properties, organic fertilization offering a gradual release of mineral nitrogen offers a more beneficial option.



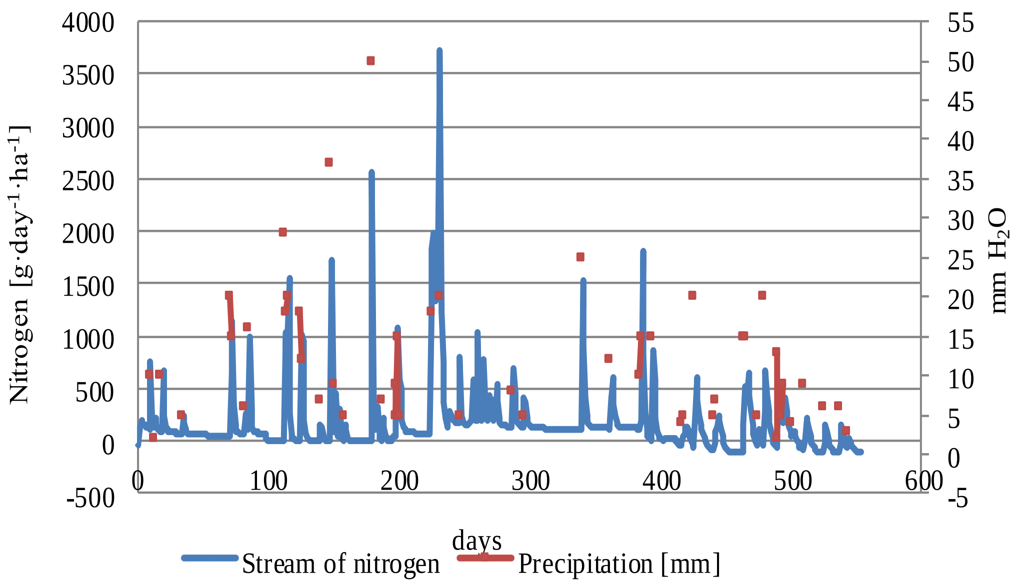
Source: own study / Źródło: opracowanie własne

Fig. 8. Stream of $N_{min.}$ in soil at a depth of 60 cm and precipitation on specific dates (field A)
Rys. 8. Strumień $N_{min.}$ w glebie na głębokości 60 cm i opady (pole A)



Source: own study / Źródło: opracowanie własne

Fig. 9. Stream of $N_{min.}$ in soil at a depth of 60 cm and precipitation on specific dates (field B)
Rys. 9. Strumień $N_{min.}$ w glebie na głębokości 60 cm i opady (pole B)



Source: own study / Źródło: opracowanie własne

Fig. 10. Stream of $N_{min.}$ in soil at a depth of 60 cm and precipitation on specific dates (field C)
Rys. 10. Strumień $N_{min.}$ w glebie na głębokości 60 cm i opady (pole C)

7. Conclusions

- In the case of the analyzed fields, production of crops and the procedures that were applied lead to various levels of nitrogen imbalance. In each case, we have to do with nitrogen surplus; however, it was much larger on soils in fields B (122 kg) and C (162 kg).
- The calculations demonstrate that the developed mathematical model and calculation algorithm can assist in the assessment of the concentration of mineral nitrogen in soils and its variations over time.
- Numerical calculations demonstrated that a significant proportion of the overall excess nitrogen can be leached with water outside the layer of the soil that is accessible to plants. In the analyzed cases, this amount was 14.4 kg for soils in field A, 75.5 kg for soils in field B and 91.4 kg for field C.
- The leaching of nitrogen is relative to the soil structure, as well as to the amount and intensity of precipitation and the concentrations of nitrogen in the soils, which in turn result from the fertilization and cultivation procedures.
- When sandy soils are subjected to extensive program of mineral fertilization, they are particularly susceptible to leaching of nitrogen. In this case, a level of monitoring should be applied to assist in planning agrotechnical procedures.

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