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Quantification of nitrates leaching from grassland soils in winter using the Burns model

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Abstract: This paper presents the results of a study on the level of nitrate leaching from the 0–30 cm layer of grassland (GL) soil in the Lublin Voivodship during the winters of 2018/2019, 2019/2020 and 2020/2021. The amounts of leached nitrates were determined using the Burns model. For the calculations based on this model – directly and indirectly, the results determination of residual nitrate nitrogen, texture and organic matter in GL soils, obtained within the framework of agricultural monitoring of soils by the National Chemical and Agricultural Station (KSChR), and results of system meteorological measurements conducted by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) were used.

The analysed soil samples were taken from 39 permanent control and measurement grassland sites. The research discovered in particular that:
- the average leaching of nitrate nitrogen from GL mineral soil in the three analysed periods was 16.2 and 5.1 kg N·ha^{-1} from organic soil;
- on average, in autumn during the entire study period, 55.3% of NO_3-N leached from the 0–30 cm layer of GL mineral soil, and 27.3% from organic soil;
- among different agronomic categories of mineral soil, the highest leaching of NO_3-N was recorded from medium soil (17.4 kg N·ha^{-1}) and the lowest from heavy soil (11.5 kg N·ha^{-1});
- individually determined values of NO_3-N leaching from soil varied significantly from 0 to 68.5 kg N·ha^{-1} for mineral soil and from 0.1 to 23.65 kg N·ha^{-1} for organic soil.

Keywords: Burns model, grassland, mineral soil, nitrate leaching, nitrate nitrogen content, organic origin soil

INTRODUCTION

Nitrate leaching from agricultural soil is a major cause of groundwater quality deterioration worldwide (Rath *et al.*, 2021). Hence, regulations are being established (including, inter alia, action programmes) and various countermeasures are implemented to ensure that the amount of nitrates reaching aquifers does not result in excessive pollution (above permissible limit). An important part of measures taken to protect groundwater from nitrates of agricultural origin is its chemical monitoring. The monitoring is part of national and regional observation and research networks. It provides data necessary to identify water reservoirs sensitive to nitrate pollution and designate protection zones for these waters, as well as for monitoring the effectiveness of measures applied to reduce nitrogen leaching. However, results of direct measurements of nitrate concentration in groundwater as part of the monitoring system are not fully sufficient and appropriate for assessing the impact of agricultural activity on water pollution by the nutrient for the following reasons:
- changes in nitrate concentrations in water are often slow to respond to changes in agricultural practices (making it difficult to determine cause-and-effect relationship), and results of long-term monitored NO_3^- concentration are often influenced and distorted by weather events (Lord, Anthony and Goodlass, 2002);
- spatial and temporal resolution of data is relatively low (Wey *et al.*, 2021), which makes them useless or of little use in diagnosing the type and degree of threat from nitrates of

agricultural origin to water quality in a local intake; at the same time the high cost of water monitoring limit possibilities for its application in an extended form.

Therefore, in addition to results of groundwater nitrate pollution from macro-scale monitoring, there is a need to use other indicators of pressure by agricultural nitrogen. One of many indicators developed in recent decades is the amount of mineral nitrogen (N_{min}) accumulated in agricultural soil (AS) in autumn after crop harvest (Bockstaller *et al*., 2009; Buczko and Kuchenbuch, 2010). It is called residual soil mineral nitrogen (RN_{min}). A significant part of the nitrogen occurs in the form nitrates particularly susceptible to leaching from the soil profile in winter due to the reduction or cessation of its uptake by plant roots and the increased washing out by precipitation. Therefore, this indicator provides a rather high potential for assessing risk of nitrate losses from agricultural soil, mainly after and before the vegetation period (Wachendorf *et al*., 2004; Lu *et al*., 2019; Delin and Stenberg, 2021). The applicability of the indicator has been proved by various studies showing that autumn N_{min} in agricultural soil and nitrate concentrations in groundwater below the surface are correlated (Roelsma, 2002; Ruijter de *et al*., 2007; Schröder *et al*., 2010) (although strength of correlation between these factors is sometimes weak). As an indicator for potential nitrogen leaching to groundwater, RN_{min} is used, for example, in Germany, the Netherlands, France, the USA (Buczko and Kuchenbuch, 2010), and Canada (Drury *et al*., 2007). In the federal state of Baden-Württemberg, Germany, there are regulations that make direct payments dependent on the residual N_{min} content in their farm soil (Wey *et al*., 2021).

In autumn, the content of N_{min} in agricultural soil can be used directly to diagnose the risk of groundwater contamination by nitrate, although as indicated by the results of Wey *et al.* (2021), it should be regarded as a useful relative but not absolute indicator of nitrate leaching. The residual soil mineral nitrogen can also be indirectly used to assess groundwater nitrate risk by extracting the nitrate fraction and subsequently converting it into an indicator of potential nitrate loss through leaching outside the plant root zone. It should be emphasised that the content of nitrogen in nitrate form in the soil profile is one of the most important factors on which the amount of nitrates in the water percolating through it depends as stated White and Magesan (1991) (as cited in Maheswaran *et al.* (2022), p. 7). The possibility to determine the potential leaching of nitrate from agricultural soil based on tests of their residual NO_3-N content is provided by the model developed and verified by Burns (1976). In its mathematical form, it expresses nitrate leaching into the soil profile as a function of soil water capacity and the difference in precipitation and evapotranspiration, while assuming that there is an effective plant rooting depth beyond which all inorganic nitrogen in soil is equally available and below which it is completely unavailable to plants. The model is fairly simple and as it has been shown it can be used to calculate the level of nitrate loss due to leaching with satisfactory accuracy (Khanif, Cleemput van and Baert, 1984; Magesan, Scotter and White, 1999). According to Cameron and Wild (1982), this accuracy is at a practicable level. Burns model has become relevant and used in many studies on the transport of nitrate and other contaminants deep into the soil profile in various countries, including Belgium (Neve de and Hofman, 1998; Moreels *et al*., 2003; El-Sadek, 2014), Chile (Matus and Rodriguez, 1994; Salazar *et al*., 2014), Czech Republic (Haberle *et al*., 2009; Haberle *et al*., 2018), Denmark (Vogeler *et al*., 2022), France (Pervanchon *et al*., 2005; Chelil *et al*., 2022), Indonesia (Widowati, Neve de, 2016), and New Zealand (Kelliher *et al*., 2014; Cichota *et al*., 2016).

The multitude of studies and results developed using Burns model prove that it is a functional tool for determining the level of nitrate leaching from agricultural soil. In view of the above, and taking into account certain limitations of a realistic assessment of groundwater pollution by nitrates from agricultural sources on the basis of monitoring data, it seems that the model should find its practical application in connection with the implementation of the Nitrates Directive (Council Directive, 1991). Such application could contribute to further precise identification of places at particular risk of pollution with nitrates from agricultural areas and thus it can help to implement protection measures. Such measures would in turn be conducive to the achievement of the objectives set by the directive. Poland, where the Nitrates Directive applies to the whole country, can benefit greatly from the use of Burns model to quantify nitrates leached from agricultural soil. A system for monitoring the content of mineral nitrogen in soil can be established and run by the National Chemical and Agricultural Station (Pol. Krajowa Stacja Chemiczno-Rolnicza – KSChR) and its subordinate district stations on the basis of a research network comprising over 5,000 measurement and control points throughout the country. As part of the system, the content of nitrate nitrogen is determined based on samples of agricultural soil taken in autumn, including more than 1,000 samples of grassland (GL). The results can be used to determine the level of nitrate leaching from agricultural soil subject to extensive spatial and temporal patterns. The present study attempts to use such indicators in this particular way. The aim is to implement a pilot study using Burns model to determine the level of nitrate leaching from the 0–30 cm layer of GL soil in the Lublin Voivodship in three selected winter periods. This can be based on the autumn content of mineral nitrogen in the form of nitrates, monitoring of which is provided by chemical and agricultural stations. It can also be used to determine the usefulness of the model in studies on nitrate leaching from agricultural soil nationwide.

MATERIAL AND METHODS

DATA ORIGIN AND LOCATION OF SAMPLING SITES

The study uses results of laboratory tests on soil samples from the monitoring of mineral nitrogen in grassland by the KSChR and district chemical and agricultural stations, in cooperation with the Institute of Technology and Life Sciences – National Research Institute (Pol. Instytut Technologiczno-Przyrodniczy – Państwowy Instytut Badawczy – ITP-PIB). Moreover, the study uses measurement (analytical) data on soil from 39 control and measurement sites of grassland located in the Lublin Voivodship. Thirty of these sites were located on mineral soils and 9 on organic origin soils (Fig. 1).

Of the sites were located on mineral soils, 6 were located on very light soils containing ≤10% floatable fractions (FF), i.e. grains <0.02 mm in diameter, 12 on light soils (10 < FF ≤ 20%); 8 on medium soils (20 < FF ≤ 35%) and 4 on heavy soils (FF > 35%).

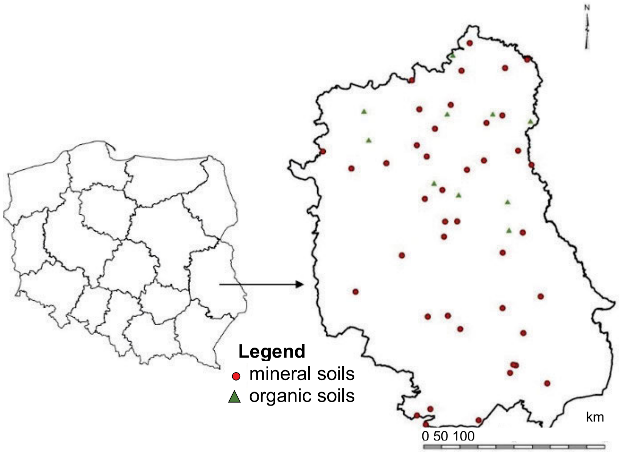

Fig. 1. Location of grassland soil sampling sites in Lublin Voivodship for laboratory analysis; source: Nawalany (2022), unpublished

The division into mineral and organic soil and the classification of mineral soil according to agronomic categories were made by the chemical-agricultural stations when setting up the test and measurement stations.

The nitrate leaching studies were implemented in November, December, January and February during winter periods: 2018/2019; 2019/2020; 2020/2021.

METHODOLOGY FOR LABORATORY ANALYSIS OF SOIL

As part of the monitoring, soil samples for laboratory analyses were taken from the topsoil layer of 30 cm, with a representative (composite) sample of approximately 100 g formed from 15–20 individual samples taken from an area of no more than 100 m^2 (Lipińska *et al.*, 2021). The soil samples were then subject to laboratory tests of granulometric composition, nitrate nitrogen content, and organic carbon content. The tests covered as follows:
- granulometric composition was determined by laser diffraction using Mastersizer 2000 by Malvern;
- content of nitrate nitrogen (V) (NO_3-N) in the samples was determined by flow colourimetry according to PN-R-04028:1997; the analytical procedure included the determination of the nitrate nitrogen content (V) (NO_3-N) in soil samples that were in the state with the current moisture content after thawing (before analysis, soil samples were stored at −18°C), after their extraction with a 1% solution of potassium sulphate (K_2SO_4) at the soil to solution ratio of 1:10; results for mineral forms of nitrogen were expressed in mg·kg^{-1} air-dry weight of soil;
- organic matter (OM) content in organic soils was determined in samples using the mass loss method after roasting at 550°C for 7 h (mass loss during roasting was taken as organic matter content) (IUNG, 1983); the percentage of organic matter was calculated as the ratio between the dry weight and constant weight before and after roasting;
- organic carbon content in mineral soils was determined using the Tiurin method; according to the method, chemical analyses included the oxidation of organic carbon in the soil sample using oxidant, potassium dichromate ($K_2Cr_2O_7$), in the presence of sulphuric acid (H_2SO_4) and, titration of the excess remaining in the oxidant solution with Mohr's salt ($Fe(NH_4)_2(SO_4)_26H_2O$); the organic carbon content was calculated based on the amount of potassium dichromate solution actually used; Tiurin method was applied to soil samples with an organic matter content of up to 15%, as above this value the method does not provide "reliable results, due to the difficulty to fully burn large amounts of organic carbon" (Fajer, 2014).

METHOD FOR DETERMINING NITRATE NITROGEN IN SOIL

The abundance of mineral nitrogen in the form of nitrate in soil was calculated using the following equation:

$$Z_{\mathrm{NO3-N}} = 0.1\ \mathrm{N}_{\mathrm{NO3-N}} \cdot y \cdot s \tag{1}$$

where: $Z_{\mathrm{NO3-N}}$ = nitrate nitrogen stocks in the soil layer 0–30 (kg·ha^{-1}); y = bulk density of soil (kg DM·dm^{-3}); $\mathrm{N}_{\mathrm{NO3-N}}$ = nitrate nitrogen content in soil layer of 0–30 (mg $\mathrm{N}_{\mathrm{NO3-N}}$·kg^{-1} DM); s = soil layer thickness (cm).

The bulk density of mineral soil was adopted as shown in Table 1. On the other hand, the density of organic soil was determined using the modified regression equation given in the article by Pietrzak (2015) with more precise parameters defined to seven decimal points. As the practical application of the model has shown, it is needed for the accuracy of calculations, especially in the presence of very high organic matter content. The calculation was as follows:

$$\begin{aligned} y = & -0.0000056\,OM^3 + 0.0010098\,OM^2 - 0.0623465\,OM + \\ & + 1.6346314 \\ & (R^2 = 0.9489;\ n = 186) \end{aligned} \tag{2}$$

where: OM = soil organic matter content (%).

Table 1. The bulk density of mineral soils depending on their agronomic category

Agronomic category of soils	The proportion of fine particles in diameter <0.02 mm (%)	Soil density (kg·dm^{-3})
Very light	≤10	1.533
Light	(10; 20>	1.500
Medium	(20; 35>	1.416
Heavy	>35	1.300

Source: own elaboration based on: Fotyma, Kęsik and Pietruch (2010).

Grassland samples and their laboratory tests (in our own accredited laboratories) were taken and performed by the district chemical and agricultural stations. Results were collected in a database run by KSChR. The compilation of the results was carried out at ITP-PIB Falenty on the basis of data provided by KSChR.

ESTIMATING POTENTIAL NITRATE LEACHING FROM GL SOIL DURING THE WINTER PERIOD

To determine the amount of nitrate leached from grassland soil, Burns equation (Burns, 1976; Burns, 1980) was used. This equation variant assumes that nitrate is uniformly distributed in soil during leaching and has the following form:

$$f \cong \left(\frac{P}{P+\theta_{FC}}\right)^{\frac{h}{2}} \tag{3}$$

where: f = share of nitrates leached below the soil layer of depth h; θ_{FC} = soil moisture corresponding to field water capacity ($cm^3 \cdot cm^{-3}$); P = cumulative amount of percolated water from the soil profile (cm); h = effective depth of plant root zone (cm).

Calculations assumed that the depth of the grassland community root layer h is 30 cm. This layer supports 90% of the root mass of grassland vegetation (Okruszko, 1988). The layer is the main source of nutrients, including nitrate ions.

The moisture in mineral soil corresponding to the field water capacity (suction force of 33 kPa) – $\theta_{FC\min}$ in %, was determined using the pedotransfer function (Tóth *et al.* (2015) as cited in Brand, Lilly and Smith (2020, p. 6):

$$\begin{aligned}\theta_{\mathrm{FC_{min}}} = 24.49 - 18.87\left(\frac{1}{1+\mathrm{C_{org}}}\right) + 0.4527(\mathrm{F_{clay}}) + 0.1535(\mathrm{F_{silt}}) + \\ + 0.1442(\mathrm{F_{silt}})\left(\frac{1}{1+\mathrm{C_{org}}}\right) - 0.00511(\mathrm{F_{silt}})(\mathrm{F_{clay}}) + \\ + 0.08676(\mathrm{F_{clay}})\left(\frac{1}{1+\mathrm{C_{org}}}\right)\end{aligned} \tag{4}$$

where: C_{org} = soil organic carbon content (%); F_{clay} = content of clay fraction, i.e., proportion of soil grains with $d \le 0.002$ mm (%) (d = soil grains diameter, mm); F_{silt} = content of silt fraction, i.e., proportion of soil grains with diameter >0.002 and ≤0.05 mm (%).

Organic soil moisture corresponding to the field water capacity (suction force of 33 kPa) – $\theta_{FC\mathrm{org}}$ (%), were determined from the regression equation:

$$\theta_{FC\mathrm{org}} = -33.107y + 67.542 \; (R^2 = 0.8869; n = 60) \tag{5}$$

This relationship was derived in-house based on a set of tests for bulk density and field water capacity of organic origin soil given by Jurczuk *et al.* (2004).

For the purpose of the calculations based on Burns model, the field water capacity results (%) were converted after dividing them by 100 and expressed in $cm^3 \cdot cm^{-3}$.

The cumulative amount of percolated water from the soil layer P was determined from the equation:

$$P = R - ETo \tag{6}$$

where: R = total precipitation (cm); ETo = reference evapotranspiration (cm).

The value of reference evapotranspiration was calculated using Penman–Monteith method with CROPWAT 8.0 (FAO, no date). This software was developed and is recommended by FAO (Food and Agriculture Organization). CROPWAT 8.0 requires the following data:
– minimum temperature (°C);
– maximum temperature (°C);
– sunshine duration (h);
– wind speed ($km \cdot day^{-1}$), 1 $m \cdot s^{-1}$ = 86.4 $km \cdot day^{-1}$;
– relative humidity (%);
– latitude, longitude and altitude.

The sets of climate data for CROPWAT and precipitation totals (R were generated based on the results of meteorological measurements by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) collected from 49 measurement stations located throughout Poland between November and February in 2018–2021 (IMGW-PIB, no date). These results of monthly mean values were subjected to spatial interpolation using Surfer 14.0 using the gridding process with reference to 39 selected control points of grassland soil in the Lublin Voivodship (with known geographical coordinates). This led to obtaining sets of climate data closely related to these points. The altitude at grassland soil monitoring points in the Lublin Voivodship was determined using Google Earth.

Based on complete results, proportions of nitrate leached during winter months (between November and February of the following year) were calculated from Burns equation and then monthly and winter leaching values were calculated using the following formulas:

$$W_{\mathrm{NO3-N\_11}} = Z_{\mathrm{NO3-N}} \cdot f_{11} \tag{7}$$

$$W_{\mathrm{NO3-N\_12}} = (Z_{\mathrm{NO3-N}} - W_{\mathrm{NO3-N\_11}}) \cdot f_{12} \tag{8}$$

$$W_{\mathrm{NO3-N\_1}} = (Z_{\mathrm{NO3-N}} - W_{\mathrm{NO3-N\_11}} - W_{\mathrm{NO3-N\_12}}) \cdot f_1 \tag{9}$$

$$W_{\mathrm{NO3-N\_2}} = (Z_{\mathrm{NO3-N}} - W_{\mathrm{NO3-N\_11}} - W_{\mathrm{NO3-N\_12}} - W_{\mathrm{NO3-N\_1}}) \cdot f_2 \tag{10}$$

$$W_{\mathrm{NO3-N}} = W_{\mathrm{NO3-N\_11}} + W_{\mathrm{NO3-N\_12}} + W_{\mathrm{NO3-N\_1}} + W_{\mathrm{NO3-N\_2}} \tag{11}$$

where: $W_{\mathrm{NO3\text{-}N\_11}}$, $W_{\mathrm{NO3\text{-}N\_12}}$, $W_{\mathrm{NO3\text{-}N\_1}}$, $W_{\mathrm{NO3\text{-}N\_2}}$ = amount of nitrate nitrogen displaced from the potential rooting zone of meadow vegetation in November, December, January and February, respectively (kg NO_3-N$\cdot ha^{-1}$); f_{11}, f_{12}, f_1, f_2 = nitrate leached below the meadow vegetation rooting zone in November, December, January and February, respectively.

The calculation of f_{11}, f_{12}, f_1, f_2 was based on cumulative amount of water greater than 0 percolated from the soil layer (P) only. The latter was determined for individual monitoring points and reflected quantitative precipitation over reference evapotranspiration. This is because it is assumed that nitrate leaching is possible when total precipitation exceeds evapotranspiration (Tonhauzer *et al.*, 2020). When evapotranspiration exceeds precipitation, leaching can occur to a small extent only (Cummings, 1978).

STATISTICAL METHODS FOR COMPILING RESEARCH RESULTS

The results were statistically processed. It included the following:
– values of descriptive statistics that were determined for sets of soil sample tests and selected indicators (parameters), using such measures as: number of data, arithmetic mean, coefficient of variation (CV), highest value (max), and lowest value (min);
– r-Pearson correlation analysis involving various factors associated with nitrate leaching.

RESULTS AND DISCUSSION

The granulometric composition analysis of the assessed mineral grassland soil from the Lublin Voivodship showed that they contained on average 40.0% of silt ($0.002 < d \le 0.05$ mm) and 2.7% of clay ($d \le 0.002$ mm) in the 0–30 cm layer (Fig. 2). Within each soil agronomic category, the average content of silt ranged from 29.6% in very light soil to 69.3% in heavy soil, and clay from

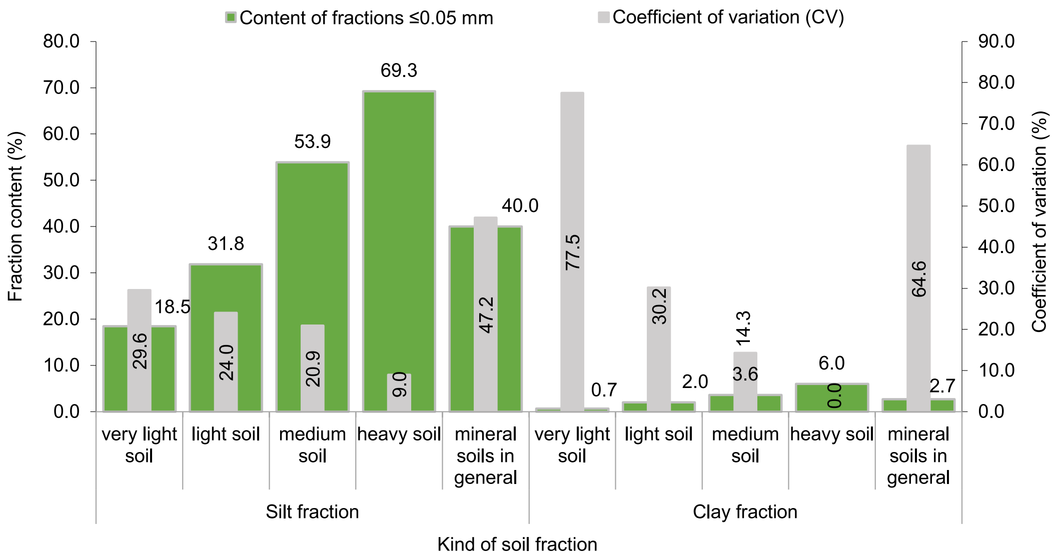

Fig. 2. Percentage content of silt and clay fraction in the fine earth particles of the studied soils, and its variability; source: own study based on KSChR data

0.7 to 6.0%, respectively. As a whole, the tested soils were characterised by a strong variation (>45%) in the proportion of silt and clay particles in them.

In the top 30 cm layer, the organic carbon ranged from 0.59 to 4.51% with an average of 1.77% (CV = 48%) – see Table 2.

Table 2. Descriptive statistics of organic carbon/organic matter content in grassland soils in the 0–30 cm layer

A measure of statistics	Organic carbon content (%)					
	mineral soils					organic origin soils
	very light	light	me-dium	heavy	total	
$\bar{x}$	1.36	1.87	1.65	2.33	1.77	45.08
CV	33.8	62.0	29.7	24.9	48.0	60.4
max.	1.95	4.51	2.23	3.12	4.51	81.55
min.	0.88	0.59	0.96	1.74	0.59	6.50

Explanations: $\bar{x}$= arithmetic mean, CV = coefficient of variation, max. = maximum value, min. = minimum value.
Source: own study.

Among different categories of mineral soil, the highest amount of C_{org} was found in heavy soil (2.33%) and the lowest in very light soil (1.36%). In organic origin soil, the average organic matter content in the profile up to 30 cm below the ground surface was 45.08% (CV = 60.4%). The average content of organic carbon in the analysed mineral soils of UZ was lower than the average content of this component in this type of soils throughout Poland (its level is 2.44%) (Pietrzak and Hołaj-Krzak, 2022). In relation to organic soil, there was an inverse relationship. The content of C_{org} in mineral soil was statistically significantly correlated with the proportion of silt (r-Pearson = 0.3680; p < 0.01) and clay (r-Pearson = 0.2682; p < 0.05) – which is a generally observed regularity for soils under similar climatic conditions (Li *et al.*, 2022).

The field water capacity (θ_{FC}) of the mineral soils in whole was 0.26 $cm^3 \cdot cm^{-3}$ on average – see Table 3. The value of this parameter depended on the agronomic category of soil and increased from very light soil (include sands) to heavy soil (consisting mainly in clay and loam), from 0.21 to 0.33 $cm^3 \cdot cm^{-3}$. These results reflect the key importance of soil texture in shaping soil water retention (Geroy *et al.*, 2021). The field water capacity of organic origin soil was at 0.50 $cm^3 \cdot cm^{-3}$ and was almost half higher than in mineral soil. Sets of calculated results for this indicator varied from 0.18 to 0.34 $cm^3 \cdot cm^{-3}$ for mineral soil and from 0.25 to 0.60 $cm^3 \cdot cm^{-3}$ for organic soil. These were relatively homogeneous (with low variability). Obtained results of calculations of field water capacity for mineral soils were between the empirically determined values of this parameter (at a suction pressure of 33kPa) for soil texture classes ranging from sand to clay, which were respectively 0.091 and 0.396 $cm^3 \cdot cm^{-3}$ (Rawls, Brakensiek and Saxtonn, 1982). The high field water holding capacity of organic soil was due to the high proportion of organic matter in the soil. This soil component is characterised by a high

Table 3. Descriptive statistics of field water capacity of grassland soils in 0–30 cm layer

A measure of statistics	Soil moisture content at field capacity (θ_{FC}) when the water potential in the soil is at −33 kPa					
	mineral soils					organic soils
	very light	light	me-dium	heavy	total	
$\bar{x}$($cm^3 \cdot cm^{-3}$)	0.21	0.24	0.29	0.33	0.26	0.50
CV (%)	7.13	12.56	9.78	2.48	18.42	24.75
max. ($cm^3 \cdot cm^{-3}$)	0.23	0.30	0.33	0.34	0.34	0.60
min. ($cm^3 \cdot cm^{-3}$)	0.18	0.19	0.25	0.32	0.18	0.25

Explanations as under Table 2.
Source: own study.

capacity to retain and store water (Walczak *et al*., 2002), and belongs, besides granulometric composition, to the key factors shaping water retention of soil (Manns, Parkin and Martin, 2016; Plošek *et al*., 2017).

In 2018–2020, the total of residual nitrate nitrogen (NO_3-N) in the 0–30 cm layer of GL mineral soil was 5.1–8.8 mg N·kg^{-1} (on average 7.1 mg N·kg^{-1}), and in organic soil 13.6–32.4 mg N·kg^{-1} (on average 22.0 mg N·kg^{-1}) – see Table S1. Among mineral soil types, the highest NO_3-N content was recorded in medium category soil (on average 8.8 mg N·kg^{-1}) and the lowest in very light soil (on average 5.1 mg N·kg^{-1}). The contents of nitrate nitrogen remaining from autumn varied considerably between the study periods. In this respect, in 2020, the average N-NO_3 content in mineral soil was 1.6 and 1.9 times higher comparing to its average content in 2018 and 2019, respectively. In the case of organic origin soil, the ratio of the value above mentioned indicator in the third study period compared to the first and second periods was 1.5 and 0.6, and between the second and first periods the ratio was even 2.4. In this context, it should be emphasised that fluctuations in mineral nitrogen, including nitrate nitrogen, occurring from month to month and from year to year in the topsoil of agriculturally used land are a typical phenomenon (in contrast to changes in their total N content) and depend on the balance of processes that lead to the accumulation and release of N_{min} (Jarvis and Barraclough, 1991; Lord *et al*., 2007).

The average nitrate nitrogen stock in the discussed period amounted at 30.7 kg N·ha^{-1} in mineral soils and 23.7 kg N·ha^{-1} in organic origin soil. In the different time intervals, the ratios of nitrate nitrogen stock in this soils were at a similar level to indicated above proportions characterising changes in the content of this component. Changes in the residual NO_3-N stocks had a strong impact on the formation of nitrate leaching. This is demonstrated by a study conducted by Wachendorf *et al.* (2004), which shows that N_{min} stocks in grassland soils stored at the end of the growing season are strongly (R^2 = 0.74) positively correlated with nitrate losses from these soils.

Within isolated categories of mineral soil, a particularly large variation in the quantity of NO_3-N occurred between autumn periods of 2020 and 2019 for medium soil. It was close to 11.9 mg NO_3-N·kg^{-1} DM and 50.5 kg·ha^{-1} GL. The variability of NO_3-N content determination in the mineral soil during the periods ranged from 85.7–100.0%, and in organic soil from 81.5–128.6%. The differentiation of these results varied from strong to very strong. The variation in the abundance index for the two soil types was strong. The content of nitrate nitrogen (NO_3-N) and its stocks in the 0–30 cm layer of GL mineral soils were not statistically significant and not related to the content of organic carbon and silt and clay. This is consistent with the results of research on the relationships between the mentioned factors for GL soils in the whole Poland (Pietrzak and Urbaniak, 2023). In organic soil, the content of nitrate nitrogen was significantly correlated with the content of organic matter (*r*-Pearson = 0.5842; $p < 0.01$). In contrast, the NO_3-N stock the soil was not related to organic matter content.

The precipitation and the reference evapotranspiration during the winter periods ranged from 11.95 to 16.20 cm and from 6.71 to 8.74 cm, respectively – see Table 4. The distribution of precipitation and evapotranspiration was uneven in each winter period. In the same months of each winter period, the indicators varied. During the winter period of 2018/2019, evaporation outweighed precipitation in November and February.

Over the three winter periods, the average nitrate nitrogen leaching from the 0–30 cm layer of GL soil determined using Burns model was 16.2 kg N·ha^{-1} for mineral soil and 5.1 kg N·ha^{-1} for organic soil – see Table S2. The level of nitrate leaching from organic origin soil was low and from mineral soils was medium-low following the classification proposed by Eriksen *et al.* (2015). According to it, the level of nitrate leaching is low when it is <10 kg N·ha^{-1}, medium–low when it is between 10–20 kg N·ha^{-1}, and medium and high when it occurs in the ranges of 25–50 kg N·ha^{-1} and >50 kg N·ha^{-1}, respectively.

The average (weighted) leaching of NO_3-N from all mineral and organic soils examined was at 13.6 kg N·ha^{-1}. If we consider this value of NO_3-N leaching representative for all GL soil in the Lublin Voivodship, which have an area of 225,861 ha (GUS, 2020), it can be calculated that, as a result of nitrate leaching from their top 30–cm soil, more than 3,080.7 Mg N leached in individual winter periods.

Taking into account individual winter periods, the average leached NO_3-N varied between 14.1 and 19.3 kg N·ha^{-1} for mineral soil taken together, and between 3.9 and 7.0 kg N·ha^{-1} for organic soil. Among mineral soil, the highest NO_3-N leaching over the three winter periods was recorded from medium agronomic soil, and the lowest from of heavy soil. An average of 17.4 kg N·ha^{-1} leached from the former soil category and 11.5 kg N·ha^{-1} from the latter. Within the individual soil categories, there were significant differences in nitrate nitrogen leaching in particular research periods, e.g. in 2019/2020, only 4.6 kg N·ha^{-1} leached from medium soil, while in 2020/2021 as much as 25.9 kg N·ha^{-1}.

The leaching of NO_3-N from GL soils considered in relative terms, as the ratio of NO_3-N leached from the soil to its autumn NO_3-N stock throughout the analysed time interval was at 52.8% (45.6–61.0%) for mineral soils taken as a whole, and at 21.5% (13.6–43.8%) for organic soils. Among the different categories of mineral soils, the largest percentage of autumn NO_3-N accumulated in them was leached from very light soils. It amounted 66.4% (58.5–73.8%) and was 1.2, 1.4 and 1.8 times higher than the proportion of leached residual NO_3-N from light, medium and heavy soils, respectively. These relationships correspond well with existing knowledge, that soil texture for the reason that it affects the soil's hydraulic properties (include infiltration and water retention) (Li, Chang and Salifu, 2014), has a direct impact on nitrate leaching. Fine-textured (clayey) soils have a higher nitrate-retention capacity than coarse-textured (sandy) soils (Gaines and Gaines, 1994), due to the fact that they have smaller pores. Hence, per unit of water leaching from the soil profile significantly more nitrate is removed from sandy soils than from clay soils (Domnariu *et al*., 2020).

The distribution of calculated NO_3-N leaching, grouped within ranges of 5 kg NO_3-N·ha^{-1}, was different for both types of soil – see Figure 3. As regards mineral soil, the most frequent sets of results occurred in leaching classes ≤5 kg N·ha^{-1} and from 5 to 10 and from 10 to 15 kg N·ha^{-1} inclusive. Shares of these results in the specified classes were 22.2, 20.0 and 18.9%, respectively. On the other hand, the values of N-NO_3 leaching rates determined for organic soils in the vast majority – 70.4%, were not greater than 5 kg N-NO_3·ha^{-1}.

Table 4. Average precipitation and reference evapotranspiration at all monitoring points, in the analysed periods

Period	Month	Total precipitation (*R*)			Reference evapotranspiration (*ETo*)			*R* – *ETo*		
		$\bar{x}$(cm)	*CV* (%)	min.–max. (cm)	$\bar{x}$(cm)	*CV* (%)	min.–max. (cm)	$\bar{x}$(cm)	*CV* (%)	min.–max. (cm)
2018/2019	November	1.12	14.1	0.80–1.45	1.54	4.3	1.40–1.70	–0.42	–39.1	–0.70–(–0.02)
	December	6.76	18.3	4.24–7.95	1.03	9.3	0.88–1.22	5.73	23.2	3.04–7.05
	January	3.52	13.6	2.43–4.07	1.10	2.8	1.05–1.20	2.42	20.1	1.33–3.02
	February	1.27	14.5	0.80–1.67	2.25	7.5	1.99–2.67	–0.98	–18.1	–1.27–(–0.51)
	Σ for period	13.65	–	–	4.93	–	–	6.75	–	–
2019/2020	November	4.16	16.7	2.99–5.31	1.86	8.6	1.70–2.25	2.30	26.6	1.22–3.42
	December	4.31	15.7	3.51–5.82	1.69	15.4	1.39–2.21	2.61	17.4	2.01–3.61
	January	2.68	8.4	2.09–2.97	1.43	19.7	1.04–1.99	1.25	38.1	0.13–1.83
	February	5.05	11.0	3.76–5.99	2.47	11.1	2.08–3.02	2.58	16.8	1.67–3.20
	Σ for period	16.20	–	–	7.46	–	–	8.74	–	–
2020/2021	November	1.61	13.1	1.18–2.25	1.59	8.3	1.40–1.83	0.02	–[1)]	–0.41–0.85
	December	3.13	16.0	2.28–4.28	1.12	5.7	0.97–1.26	2.01	23.8	1.09–3.10
	January	4.52	5.1	4.07–4.98	1.06	17.8	0.79–1.42	3.47	9.7	2.75–4.14
	February	2.69	21.3	1.89–4.17	1.48	9.0	1.27–1.73	1.22	39.6	0.43–2.44
	Σ for period	11.95	–	–	5.24	–	–	6.71	–	–

[1)] The coefficient of variation (*CV*) for the *R*–*ETo* difference occurring in November in the 2020/2021 period has not been determined, as the calculation of the value of this parameter should be performed if all numbers in the distribution have the same sign (it should be noted in this regard that *CV* values can also be negative) (Pélabon *et al.*, 2020). The coefficient of variation is not an appropriate measure of the state of dispersion for variables that have positive and negative values, or whose mean values are close to zero (Santos and Dias, 2021).
Explanations: as in Table 2.
Source: own study.

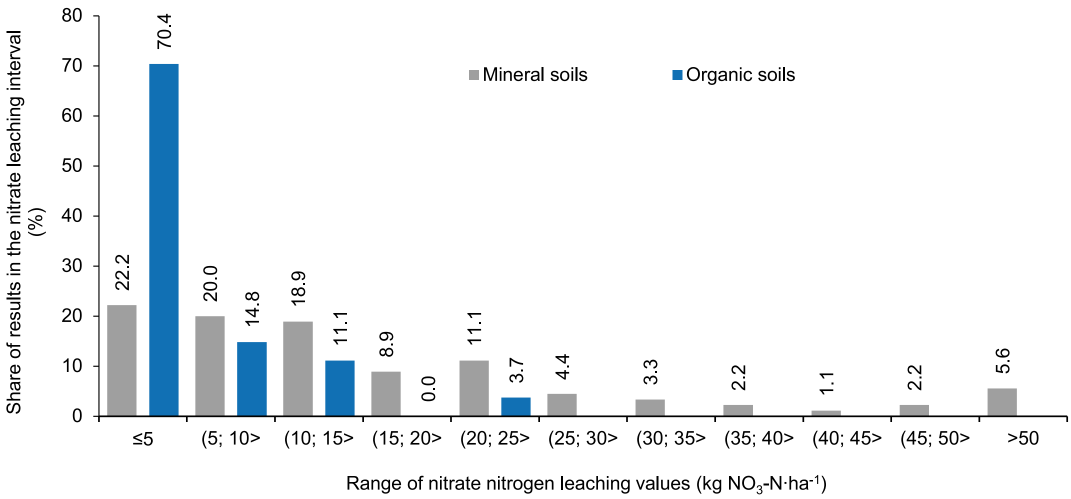

Fig 3. Distribution of NO_3-N leaching rates from grassland soils; source: own study based on KSChR data

No statistically significant relationship was found between the nitrate nitrogen leached for each winter period at specific monitoring points, except for its occurrence between the leaching from organic soil in the 2018/2019 and 2020/2021 (*r*-Pearson = 0.7805; $p < 0.05$). The level of NO_3-N leaching from soil over the entire research period for individual soil monitoring points was highly heterogeneous. In points located on mineral soil, NO_3-N leaching varied from 0.0 to 68.5 kg N·ha^{-1} and in points located on organic soil from 0.1 to 23.6 kg N·ha^{-1} – Table S2. Large variations in the amount of nitrate leaching from soil on meadows and pastures have also been shown previously by other authors based on experimental studies. For example:

- Decau, Simon and Jacquet (2004), on the basis of lysimeter studies, found that NO_3-N leaching losses from GL soils during winter may range from 2 to 50 kg N·ha^{-1}, depending on the level of nitrogen fertilisation, doses of cattle manure and the timing of its application;
- in a study in which plastic mini lysimeters (with an area of 0.0706 m^2 and a depth of 30 cm filled with clay sand) were used, leaching of nitrates below the top 30 cm layer of UZ soils

of 3–26.3 kg N·ha^{-1} was observed in the growing season and 2.8–1.8 N·ha^{-1} in non-growing season (Tampere *et al*., 2015); in both these periods, the leaching of nitrates was affected by the type of fertilisers used;
- experimental work carried out using suction cups to determine nitrates in soil solution showed that from 17 to 60 kg NO_3-N·ha^{-1} can leach from the pasture soil in a year depending on the age of the sward (at constant sward composition and nitrogen fertilisation of 300 kg N·ha^{-1}) (Eriksen and Vinther, 2002);
- based on the results of another experiment, in which the method of ceramic cups was used, it was determined that the losses of nitrates from soils of permanent grasslands used for mowing amount to only 2.1 ±0.3 kg·kg NO_3-N·ha^{-1} (Smit *et al*., 2021);
- in studies, carried out using continuous (flow proportional) soil leachate sampling, annual NO_3-N leaching rates from pasture soil were 3.7–14.6 kg NO_3-N·ha^{-1} when the soil was not fertilised with nitrogen, and 6.2–22.0 and 4.3–37.6 when different types of nitrogen fertiliser, namely urea and ammonium nitrate, were applied to it at the same rates (200 kg N·ha^{-1}) (Eckard *et al*., 2004).

Comparing the results presented above with our own results obtained using the Burns model, it can be stated that this is within similar value limits. As for the large variation in nitrate leaching losses from GL soils shown by various methods, it is a natural consequence of the fact that these are determined by many different factors, variable in time and space – such as those mentioned earlier, as well as others, for example, caused by drought stress (Klaus *et al*., 2020).

On the background of the discussed results of studies from the literature on nitrate leaching of UZ soils, it can be noted that the instrumental methods used within the framework of these studies (e.g., based on the use of lysimeters, or ceramic porous cups) are generally suitable for use at the micro-scale (e.g., with regard to relatively small agricultural parcels, or experimental plots). In contrast, these are not suitable for use at the macroscale (at the catchment, regional or national level), but also at the farm level, for financial and logistical reasons. The investigation of nitrate leaching on significant and large agricultural areas is possible primarily through mathematical models. Many such models have been developed, but in most cases they are too complex, which limits its applicability (Pervanchon *et al*., 2005). One of the few models that qualify for use under practical conditions is the Burns model (Neve de and Hofman, 1998). On the basis of the research work carried out, it can be stated that it is a solution of high utility (simple calculation procedure, relatively high ease of obtaining input data for the model). Taking this into account, and with reference to the assessments expressed in the literature (by various authors) that the results obtained on the basis of the Burns model are characterised by a fairly good accuracy, it can be concluded that it is a good tool for conducting utilitarian research on nitrate leaching from GL soils.

CONCLUSIONS

Based on the study using Burns model of nitrate leaching from the 0–30 cm layer of GL soil in the three four-month winter periods in the Lublin Voivodship, the following findings have been determined in particular:

1) in individual winter periods, nitrate nitrogen leaching from GL mineral soil ranged from 14.1 to 19.3 kg N·ha^{-1} and from organic soil from 3.9 to 7.0 kg N·ha^{-1};
2) between 48.9 and 58.8% the NO_3-N reserves present in autumn leached from GL mineral soil and between 19.9 and 5% from organic soil during the winter period;
3) the average nitrate loss over the entire study period was 16.2 kg N·ha^{-1} for mineral soil and 5.1 kg N·ha^{-1} for organic soil, and these losses in relation to autumn NO_3-N reserves in the aforementioned soil types were 3 and 27.3% respectively;
4) the total NO_3-N leaching from GL soil across the voivodship during one winter period was 3,080.7 Mg of N;
5) over the three periods, the average NO_3-N leaching from mineral soil classified into agronomic categories of very light, light, medium and heavy reached 6, 17.2, 17.4, and 11.5 kg N·ha^{-1}, respectively;
6) individually determined NO_3-N leaching from GL soil in the three periods varied from 0 to 68.5 kg N·ha^{-1} for mineral soil and from 0.1 to 23.6 kg N·ha^{-1} for organic soil; the results in the different winter periods were not correlated with each other except for one case related to organic soil and periods of 2018/2019 and 2020/2021.

The data provide some indication of the amount of nitrate leaching and the risk of groundwater contamination in areas occupied by GL, especially those situated in the Lublin region. In particular, they show that the level of nitrate loss from the GL topsoil in successive winter periods may vary considerably from one location to another, as well as their spatial range. Thus, they indirectly prove that the NO_3-N leaching from GL soil should be interpreted on the basis of test results obtained over several observation periods. In practical terms, the results provide new opportunities for assessing risks to groundwater due to nitrate leaching from GL soil. In conjunction with groundwater monitoring results for nitrate, and other related results, they may be useful from the point of view of water conservation measures in the region.

In general, the results of the study indicate that the application of Burns model to quantify nitrates leached from grassland soil, based on the autumn content of mineral nitrogen in the form of nitrate, is possible at the macroscale. This involves results of mineral nitrogen monitoring in soil by KSChR and the monitoring of meteorological conditions by IMGW-PIB. However, in order to be useful for the calculations with the above-mentioned model, many of monitoring results first need to be processed into suitable input data. Hence, additional tools, such as the mathematical functions for calculating field water capacity, and Surfer 14.0 and CROPWAT 8.0, are necessary. Therefore, the systematic practical monitoring of residual nitrogen in agricultural soil by KSChR would be helpful to assess the risk of nitrate loss and agricultural pressure on water quality at the national level. This would be conducive to water quality preservation and, in particular, would help to achieve the objectives set by the Nitrates Directive.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at https://www.jwld.pl/files/Supplementary_material_Pietrzak.pdf

REFERENCES

Bockstaller, C. *et al.* (2009) "Comparison of methods to assess the sustainability of agricultural systems. A review," *Agronomy for Sustainable Development*, 29(1), pp. 223–235. Available at: https://doi.org/10.1051/agro:2008058.

Brand, A., Lilly, A. and Smith, J. (2020) "A simple approach to modelling the soil water budget in cool temperate mineral topsoils," *Environmental Modelling and Software*, 127, 104700. Available at: https://doi.org/10.1016/j.envsoft.2020.104700.

Buczko, U. and Kuchenbuch, R.O. (2010) "Environmental indicators to assess the risk of diffuse nitrogen losses from agriculture," *Environmental Management*, 45(5), pp. 1201–1222. Available at: https://doi.org/10.1007/s00267-010-9448-8.

Burns, I.G. (1976) "Equations to predict the leaching of nitrate uniformly incorporated to a known depth or uniformly distributed throughout a soil profile," *The Journal of Agricultural Science*, 86(2), pp. 305–313. Available at: https://doi.org/10.1017/s0021859600054769.

Burns, I.G. (1980) "A simple model for predicting the effects of winter leaching of residual nitrate on the nitrogen fertilizer need of spring crops," *The Journal of Soil Science*, 31, pp. 187–202. Available at: https://doi.org/10.1111/j.1365-2389.1980.tb02075.x.

Cameron, K.C. and Wild, A. (1982) "Prediction of solute leaching under field conditions: an appraisal of three methods," *The Journal of Soil Science*, 33(4), pp. 659–669. Available at: https://doi.org/10.1111/j.1365-2389.1982.tb01797.x.

Chelil, S. *et al.* (2022) "NIT-DRAIN model to simulate nitrate concentrations and leaching in a tile-drained agricultural field," *Agricultural Water Management*, 271, 107798. Available at: https://doi.org/10.1016/j.agwat.2022.107798.

Cichota, R. *et al.* (2016) "Effects of irrigation intensity on preferential solute transport in a stony soil," *New Zealand Journal of Agricultural Research*, 59(2), pp. 141–155. Available at: https://doi.org/10.1080/00288233.2016.1155631.

Council Directive (1991) "Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources," *Official Journal*, L 375.

Cummings, T.R. (1978) *Agricultural land use and water quality in the upper St. Joseph River basin, Michigan.* Michigan, U.S.: Geological Survey Water-Resources Investigations Open-file Report 78-950. Available at: https://doi.org/10.3133/ofr78950.

Decau, M.L., Simon, J.D. and Jacquet, A. (2004) "Nitrate leaching under grassland as affected by mineral nitrogen fertilization and cattle urine," *Journal of Environmental Quality*, 33(2), pp. 637–644. Available at: https://doi.org/10.2134/jeq2004.6370.

Delin, S. and Stenberg, M. (2021) "Effects on nitrate leaching of the timing of cattle slurry application to leys," *Soil Use and Management*, 37(3), pp. 436–448. Available at: https://doi.org/10.1111/sum.12595.

Domnariu, H. *et al.* (2020) "Influence of soil-texture on nitrate leaching from small-scale lysimeters toward groundwater in various environments," *Carpathian Journal of Earth and Environmental Sciences*, 15(2), pp. 301–310. Available at: https://doi.org/10.26471/cjees/2020/015/130.

Drury, C.F. *et al.* (2007) "Residual soil nitrogen indicator for agricultural land in Canada," *Canadian Journal of Soil Science*, 87(Special Issue), pp. 167–177. Available at: https://doi.org/10.4141/s06-064.

Eckard, R. *et al.* (2004) "Nitrate leaching from temperate perennial pastures grazed by dairy cows in south-eastern Australia," *Australian Journal of Agricultural Research*, 55(9), 911. Available at: https://doi.org/10.1071/ar04042.

El-Sadek, A. (2014) "Stochastic approach to assess a nitrate process-factor in soil water," *Ain Shams Engineering Journal*, 5(2), pp. 315–320. Available at: https://doi.org/10.1016/j.asej.2013.10.006.

Eriksen, J. *et al.* (2015) "Nitrate leaching and residual effect in dairy crop rotations with grass–clover leys as influenced by sward age, grazing, cutting and fertilizer regimes," *Agriculture, Ecosystems & Environment*, 212, pp. 75–84. Available at: https://doi.org/10.1016/j.agee.2015.07.001.

Eriksen, J. and Vinther, F.P. (2002) "Nitrate leaching in grazed grasslands of different composition and age," in *Multi-Function Grasslands: Quality Forages, Animal Products and Landscapes," Proceedings of the 19th General Meeting of the European Grassland Federation, La Rochelle, France, 27–30 May 2002*, pp. 682–683. Available at: https://orgprints.org/id/eprint/160/ (Accessed: March 16, 2023).

Fajer, M. (2014) *Przewodnik do ćwiczeń z gleboznawstwa dla studentów I roku geografii [A guide to soil science exercises for first-year geography students]*. Katowice: Wydawnictwo Uniwersytetu Śląskiego.

FAO (no date) *CropWat*. Rome: Food and Agriculture Organization of the United Nations. Available at: https://www.fao.org/land-water/databases-and-software/cropwat/en/ (Accessed: March 16, 2023).

Fotyma, M., Kęsik, K. and Pietruch, C. (2010) "Azot mineralny w glebach jako wskaźnik potrzeb nawozowych roślin i stanu czystości wód glebowo-gruntowych [Mineral nitrogen in soils as an indicator of the fertilization needs of plants and the cleanliness of soil and groundwater]," *Nawozy i Nawożenie (Fertilizers and Fertilizaton)*, 38, pp. 5–80.

Gaines, T.P. and Gaines, S.T. (1994) "Soil texture effect on nitrate leaching in soil percolates," *Communications in Soil Science and Plant Analysis*, 25(13–14), pp. 2561–2570. Available at: https://doi.org/10.1080/00103629409369207.

Geroy, I. *et al.* (2011) "Aspect influences on soil water retention and storage," *Hydrological Processes*, 25(25), pp. 3836–3842. Available at: https://doi.org/10.1002/hyp.8281.

GUS (2020) *Użytkowanie gruntów i powierzchnia zasiewów w 2019 roku [Land use and sown area in 2019]*. Warszawa: Główny Urząd Statystyczny. Available at: (Accessed: March 16, 2023).

Haberle, J. *et al.* (2009) "The changes of soil mineral nitrogen observed on farms between autumn and spring and modelled with a simple leaching equation," *Soil and Water Research*, 4(4), pp. 159–167. Available at: https://doi.org/10.17221/7/2009-swr.

Haberle, J. *et al.* (2018) "Distribution of mineral nitrogen in soil in relation to risk of nitrate leaching in farms with irrigated vegetables and early potatoes," *Journal of Horticultural Research*, 26(2), pp. 47–54. Available at: https://doi.org/10.2478/johr-2018-0015.

IMGW-PIB (no date) *Dane publiczne IMGW-PIB [Public data IMGW-PIB]*. Warszawa: Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy. Available at: https://danepubliczne.imgw.pl/ (Accessed: March 16, 2023).

IUNG (1983) *Metody badań laboratoryjnych w stacjach chemiczno-rolniczych. Cz. IV. Badania gleb, ziem i podłoży spod warzyw i kwiatów oraz części wskaźnikowych roślin w celach diagnostycznych [Laboratory test methods in chemical and agricultural stations. Part IV. Research of soils, ground and substrates under vegetables and flowers as well as indicator parts of plants for diagnostic purposes]*. Puławy: Instytut Uprawy, Nawożenia i Gleboznawstwa.

Jarvis, S.C. and Barraclough, D. (1991) "Variation in mineral nitrogen under grazed grassland swards," *Plant and Soil*, 138(2), pp. 177–188. Available at: https://doi.org/10.1007/bf00012244.

Jurczuk, S. *et al.* (2004) *Nawadnianie podsiąkowe jako podstawa zwiększenia retencji wodnej małych dolin rzecznych [Underseepage irrigation as a basis for increasing the water retention of small river valleys]*. Falenty: Wydawnictwo IMUZ.

Kelliher, F.M. *et al.* (2014) "Effect of temperature on dicyandiamide (DCD) longevity in pastoral soils under field conditions," *Agriculture, Ecosystems & Environment*, 186, pp. 201–204. Available at: https://doi.org/10.1016/j.agee.2014.01.026.

Khanif, Y.M., Cleemput van, O. and Baert, L. (1984) "Evaluation of the Burns model for nitrate movement in wet sandy soils," *The Journal of Soil Science*, 35(4), pp. 511–518. Available at: https://doi.org/10.1111/j.1365-2389.1984.tb00608.x.

Klaus, V.H. *et al.* (2020) "Drought boosts risk of nitrate leaching from grassland fertilisation," *Science of The Total Environment*, 726, 137877. Available at: https://doi.org/10.1016/j.scitotenv.2020.137877.

Li, H. *et al.* (2022) "Soil texture controls added organic matter mineralization by regulating soil moisture—evidence from a field experiment in a maritime climate," *Geoderma*, 410, 115690. Available at: https://doi.org/10.1016/j.geoderma.2021.115690.

Lipińska, H. *et al.* (2021) "Quantification and comparison of ecosystem services of grasslands versus another fodder crop (maize) based on mineral nitrogen content in the 60–90 cm soil layer," *Agronomy Science*, 76(4), pp. 63–78. Available at: https://doi.org/10.24326/as.2021.4.5.

Li, X., Chang, S.X. and Salifu, K.F. (2014) "Soil texture and layering effects on water and salt dynamics in the presence of a water table: A review," *Environmental Reviews*, 22(1), pp. 41–50. Available at: https://doi.org/10.1139/er-2013-0035.

Lord, E. *et al.* (2007) "Investigating the effectiveness of NVZ Action Programme measures: Development of a strategy for England," *Report for Defra project*, NIT18. Available at: https://www.researchgate.net/publication/242550191_Investigating_the_effectiveness_of_NVZ_Action_Programme_measures_Development_of_a_strategy_for (Accessed: March 16, 2023).

Lord, E.I., Anthony, S.G. and Goodlass, G. (2002) "Agricultural nitrogen balance and water quality in the UK," *Soil Use and Management*, 18(4), pp. 363–369. Available at: https://doi.org/10.1111/j.1475-2743.2002.tb00253.x.

Lu, J. *et al.* (2019) "Accumulation and leaching of nitrate in soils in wheat-maize production in China," *Agricultural Water Management*, 212, pp. 407–415. Available at: https://doi.org/10.1016/j.agwat.2018.08.039.

Magesan, G.N., Scotter, D.R. and White, R. (1999) "The utility of Burns's equation to describe solute movement through soil under various boundary and initial conditions," *European Journal of Soil Science*, 50(4), pp. 649–656. Available at: https://doi.org/10.1046/j.1365-2389.1999.00262.x.

Maheswaran, S. *et al.* (2022) "Effects of sheep grazing systems on water quality with a focus on nitrate leaching," *Agriculture*, 12(6), 758. Available at: https://doi.org/10.3390/agriculture12060758.

Manns, H.R., Parkin, G. and Martin, R.C. (2016) "Evidence of a union between organic carbon and water content in soil," *Canadian Journal of Soil Science*, 96(3), pp. 305–316. https://doi.org/10.1139/cjss-2015-0084.

Matus, F. and Rodríguez, J. (1994) "A simple model for estimating the contribution of nitrogen mineralization to the nitrogen supply of crops from a stabilized pool of soil organic matter and recent organic input," *Plant and Soil*, 162(2), pp. 259–271. Available at: https://doi.org/10.1007/bf01347713.

Moreels, E. *et al.* (2003) "Simulating nitrate leaching in bare fallow soils: A model comparison," *Nutrient Cycling in Agroecosystems*, 67(2), pp. 137–144. Available at: https://doi.org/10.1023/a:1025526802717.

Neve de, S. and Hofman, G. (1998) "N mineralization and nitrate leaching from vegetable crop residues under field conditions: A model evaluation," *Soil Biology & Biochemistry*, 30(14), pp. 2067–2075. Available at: https://doi.org/10.1016/s0038-0717(98)00082-0.

Okruszko, H. (1988) "Zasady podziału gleb hydrogenicznych na rodzaje oraz łączenia rodzajów w kompleksy [Taxonomy of hydrogenic soils and joining them into soils complexes]," *Roczniki Gleboznawcze – Soil Science Annual*, 39(1) pp. 127–152.

Pélabon, C. *et al.* (2020) "On the use of the coefficient of variation to quantify and compare trait variation," *Evolution Letters*, 4(3), pp. 180–188. Available at: https://doi.org/10.1002/evl3.171.

Pervanchon, F. *et al.* (2005) "A novel indicator of environmental risks due to nitrogen management on grasslands," *Agriculture, Ecosystems & Environment*, 105(1–2), pp. 1–16. Available at: https://doi.org/10.1016/j.agee.2004.06.001.

Pietrzak, S. (2015) "Kształtowanie się stanu ilościowego azotu mineralnego w glebach organicznych pod użytkami zielonymi w Polsce [Formation of the quantitative state of mineral nitrogen in organic soils under grasslands in Poland]," *Woda-Środowisko-Obszary Wiejskie*, 15(2(50)), pp. 87–96.

Pietrzak, S. and Hołaj-Krzak, J. (2022) "The content and stock of organic carbon in the soils of grasslands in Poland and the possibility of increasing its sequestration," *Journal of Water and Land Development*, 54, pp. 68–76. Available at: https://doi.org/10.24425/jwld.2022.141556.

Pietrzak, S. and Urbaniak, M. (2023) "The relationship between the granulometric composition of grassland soils and their content of mineral nitrogen and organic carbon," *Journal of Water and Land Development*, 57, pp. 69–77. Available at: https://doi.org/10.24425/jwld.2023.145337.

Plošek, L. *et al.* (2017) "Leaching of mineral nitrogen in the soil influenced by addition of compost and N-mineral fertilizer," *Acta Agriculturae Scandinavica Section B-soil and Plant Science*, 67(7), pp. 607–614. Available at: https://doi.org/10.1080/09064710.2017.1322632.

Rath, S. *et al.* (2021) "Quantifying nitrate leaching to groundwater from a corn-peanut rotation under a variety of irrigation and nutrient management practices in the Suwannee River Basin, Florida," *Agricultural Water Management*, 246, 106634. Available at: https://doi.org/10.1016/j.agwat.2020.106634.

Rawls, W.J., Brakensiek, D.L. and Saxtonn, K.E. (1982) "Estimation of soil water properties," *Transactions of the ASAE*, 25(5), pp. 1316–1320. Available at: https://doi.org/10.13031/2013.33720.

Roelsma, J. (2002) "Nitrate leaching versus residual soil mineral nitrogen," in H.F.M. ten Berge (ed.). *A review of potential indicators for nitrate loss from cropping and farming systems in the Netherlands*. Wageningen: Wageningen University & Research pp. 105–118.

Ruijter de, F.J. *et al.* (2007) "Nitrate in upper groundwater on farms under tillage as affected by fertilizer use, soil type and groundwater table," *Nutrient Cycling in Agroecosystems*, 77(2), pp. 155–167. Available at: https://doi.org/10.1007/s10705-006-9051-9.

Salazar, O. *et al.* (2014) "Monitoring of nitrate leaching during flush flooding events in a coarse-textured floodplain soil," *Agricultural Water Management*, 146, pp. 218–227. Available at: https://doi.org/10.1016/j.agwat.2014.08.014.

Santos, C. and Dias, C. (2021) "Note on the coefficient of variation properties," *Brazilian Electron Journal of Mathematics*, 2, pp. 1–12. Available at: https://doi.org/10.14393/BEJOM-v2-n4-2021-58062.

Schröder, J.J. *et al.* (2010) "Nitrate leaching from cut grassland as affected by the substitution of slurry with nitrogen mineral fertilizer on two soil types," *Grass and Forage Science*, 65(1), pp. 49–57. Available at: https://doi.org/10.1111/j.1365-2494.2009.00719.x.

Smit, H.P.J. *et al.* (2021) "Very low nitrogen leaching in grazed ley-arable-systems in northwest Europe," *Agronomy*, 11(11), 2155. Available at: https://doi.org/10.3390/agronomy11112155.

Tampere, M. *et al.* (2015) "The effect of fertilizer and N application rate on nitrogen and potassium leaching in cut grassland," *Zemdirbyste-Agriculture*, 102(4), pp. 381–388. Available at: https://doi.org/10.13080/z-a.2015.102.048.

Tonhauzer, K. *et al.* (2020) "Estimation of N_2O emissions from agricultural soils and determination of nitrogen leakage," *Atmosphere*, 11(6), 552. Available at: https://doi.org/10.3390/atmos11060552.

Vogeler, I. *et al.* (2020) "Marginal nitrate leaching around the recommended nitrogen fertilizer rate in winter cereals," *Soil Use and Management*, 38(1), pp. 503–514. Available at: https://doi.org/10.1111/sum.12673.

Wachendorf, M. *et al.* (2004) "Performance and environmental effects of forage production on sandy soils. II. Impact of defoliation system and nitrogen input on nitrate leaching losses," *Grass and Forage Science*, 59(3), 307. Available at: https://doi.org/10.1111/j.1365-2494.2004.00430.x.

Walczak, R., Rovdan, E. and Witkowska-Walczak, B. (2002) "Water retention characteristics of peat and sand mixtures," *International Agrophysics*, 16(2), pp. 161–165. Available at: http://www.old.international-agrophysics.org/artykuly/international_agrophysics/IntAgr_2002_16_2_161.pdf (Accessed: May 12, 2023).

Wey, H. *et al.* (2021) "Field-scale monitoring of nitrate leaching in agriculture: Assessment of three methods," *Environmental Monitoring and Assessment*, 194, 4. Available at: https://doi.org/10.1007/s10661-021-09605-x.

Widowati, L.R. and Neve de, S. (2017) "Nitrogen dynamics and nitrate leaching in intensive vegetable rotations in highlands of Central Java, Indonesia," *Journal of Tropical Soils* 21(2), pp. 67–78. Available at: https://doi.org/10.5400/jts.2016.v21i2.67-78.