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RESEARCH ARTICLE

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# Nitrogen migration in crop rotations differing in fertilisation

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## Abstract

Inappropriate use of nitrogen fertilisers is becoming a global problem; however, continuous fertilisation with N fertiliser ensures large and constant harvests. To evaluate the relationships of differently fertilised cultivated plant rotation with N metabolism in the agroecosystem the research was conducted between 2006 and 2013 at Lipliūnai, Lithuania, in fields with calcareous gley brown soil, *i.e. Endocalcari Endohypogleyic Cambisol* (*CMg-n-w-can*). The research area covered three drained plots where crop rotation of differently fertilised cereals and perennial grasses were applied. The greatest productivity was found in a higher fertilisation (TII, 843 kg N/ha) cereals crop rotation. With less fertilisation (TI, 540 kg N/ha) crop rotation productivity of cereals and perennial grasses (TIII, 218 kg N/ha) was 11-35% lower. The highest amount of mineral soil N (average 76 kg/ha) was found in TI. It was influenced by fertilisation ($r$=0.71) and crop productivity ($r$=0.39). TIII tended to reduce $N_{min}$ (12.1 mg/L) and $N_{total}$ (12.8 mg/L) concentrations in drainage water and leaching of these elements (7 and 8 kg/ha). $N_{min}$ and $N_{total}$ concentrations in the water depended on crop productivity respectively ($r$=0.48; $r$=0.36), quantity of mineral soil N ($r$=0.65; $r$=0.59), fertilisation ($r$=0.59; $r$=0.52), and N balance ($r$=0.26; $r$=0.35). Cereal crop rotation increased N leaching by 12-42%. The use of all crop rotations resulted in a negative N balance. Nitrogen balance depended on fertilisation with N fertiliser ($r$=0.55). The application of perennial grasses crop rotation in agricultural fields was the best environmental tool, reducing N migration to drainage.

**Additional key words:** drainage; leaching; nitrogen balance; yield.

**Abbreviations used:** a.m. (active matter); $r$ (pair correlation); $LSD_{05}$ (limit of reliable (95%) difference); $t_{fact.}$ (estimated Student's test statistic); $t_{theor.95\%}$ (Student's test value at 95% confidence level); $N_{min}$ (mineral nitrogen); $N_{total}$ (total nitrogen).

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## Introduction

Nitrogen is the main crop nutrition element that has some impact on its productivity (Oenema *et al.*, 2009). Continuous fertilisation with N fertiliser ensures large and constant harvests. Nitrogen excess in agricultural production has a negative impact on the environment (leached nitrates, evaporating ammonia and N oxide) (Ahlgren *et al.*, 2008). The abuse of N fertiliser is becoming a global problem and affects the environment in a number of ways: (1) human health problems caused by nitrates (Powlson *et al.*, 2008); (2) livestock health problems (Lundberg *et al.*, 2008); (3) surface water eutrophication (Smith & Schindler, 2009); (4) formation of nitrous acid, which is linked to acid rain (Menz & Seip, 2004); (5) depletion of the ozone layer in the atmosphere because of atmospheric nitrate oxides, which strengthen ultraviolet radiation (Savci, 2012; Rosenstock *et al.*, 2013); and (6) causes the global warming effect (Martinez-Blanco *et al.*, 2014; Payen *et al.*, 2015).

In terms of non-point source pollution, N constitutes 52 to 61% (Klaushal *et al.,* 2011). Agricultural pollution constitutes on average 30 to 35% of N leaching (Klaushal *et al.*, 2011). Due to particular agricultural operations in Lithuania, 36,000 tonnes of N per year reach the Baltic Sea waterborne load (Larsson & Granstedt, 2010). Previous research has shown that leaching of elements and compounds from the soil is essentially determined by the hydrothermal regime, the amount of these element in the soil and their fertilisation (Beeston *et al.,* 2010; Komonweeraket *et al.,* 2011). A higher rate of $N_{min}$ leaching occurs in humid years (Sogbedji *et al.,* 2001). Views on fertilisation systems constituting human influence on water quality are rather mixed in the scientific literature. While some authors claim that mineral fertilisation systems are more environmentally dangerous (Kokkora & Hann, 2007; Ulen *et al.,* 2012), others claim the opposite, that organic systems are more dangerous (Hossain *et al.*, 2007). Nonetheless, it is known that unproductive fertiliser losses and water pollution increase considerably through the irrational and unbalanced use of both mineral and organic fertiliser (Hongxu *et al.,* 2011; Hyytiäinen *et al.,* 2011). It was determined in Finland that the yield of crops increases substantially, while N leaching falls with balanced fertilisation with N carried out several times during the vegetation of crops (Salvioni *et al.,* 2011). As tests have shown, $NO_3$- N leaching from the soil can be reduced significantly by changing scattered fertilisation into local (Nakamura *et al.,* 2004).

Current knowledge suggests that the scale of leaching of chemical elements and compounds should be inversely proportional to the agroecosystem's total biomass synthesis. Cabrera *et al.* (2007) determined that a bigger biomass synthesis and dryer year limit N leaching by drainage and ground water. Securing a rich harvest (crop rotation with cover crops and continuously occupied soil, plants of high biological potential, balance and rational fertilisation and application of organic production) reduces the potential water pollution risk (Thorup-Kristensen *et al.*, 2012; Buckley & Carney, 2013).

The quality of water which filters though the soil and in the surface runoff depends on the changes that occur in the soil when a variety of crops is grown. The fact that around 67% of the leached N is from the soil has been known for a very long time (Ulen & Johansson, 2009). Research data on N migration and its compounds' dynamics in the soil in the agroecosystems affected by human activity is not substantial.

Based on statistical data, cereals crop areas have increased since 1991 in Lithuania and constitute 34.3 to 41.8% of the total crop area. Perennial and annual grass areas reduced from 46 to 41%. For many years, large areas of perennial grasses, which are used for a longer time without inclusion in crop rotations, are used to grow cereals successively. The farmer's decision to grow more of one or another kind of crop, as well as the general farming culture, is affected by economic interest. Such a one-sided approach can worsen the indicators of the agro landscape and become a potential non-point pollution source, even when other agrarian measures are used correctly and rationally.

On the basis of the data obtained, we have proposed the hypothesis that non-point source pollution of the agro-landscape is inversely proportional to the synthesis of total biomass of the ecosystem, and that all of the available means ensuring high crop productivity actually reduce the potential risk of water pollution. The novelty of this paper is the evaluation of the effect of crop rotations under different fertilisation levels on the environment. The aim of the research was to evaluate the relationship between crop rotations of different intensity and biological potential with the migration of N.

# Material and methods

## Site description

The experiment was performed in the Middle Lithuania lowland in the basin of Graisupis (area 16.6 km$^2$) and in the village of Lipliūnai (N 55°18′, E 23°51′). A subsurface drainage site was used for the investigations. Investigations were carried out from 2006 to 2013. The experimental site included three plots (Fig. 1).

The soil in the site is non-acid *Endocalcari - Endohypogleyic Cambisol* (*CMg-n-w-can*) sandy light loam and sandy loam on sandy loam and sandy light loam (Liekis, 2001). According to the size distribution of soil particles, the research soil is rather homogenous.

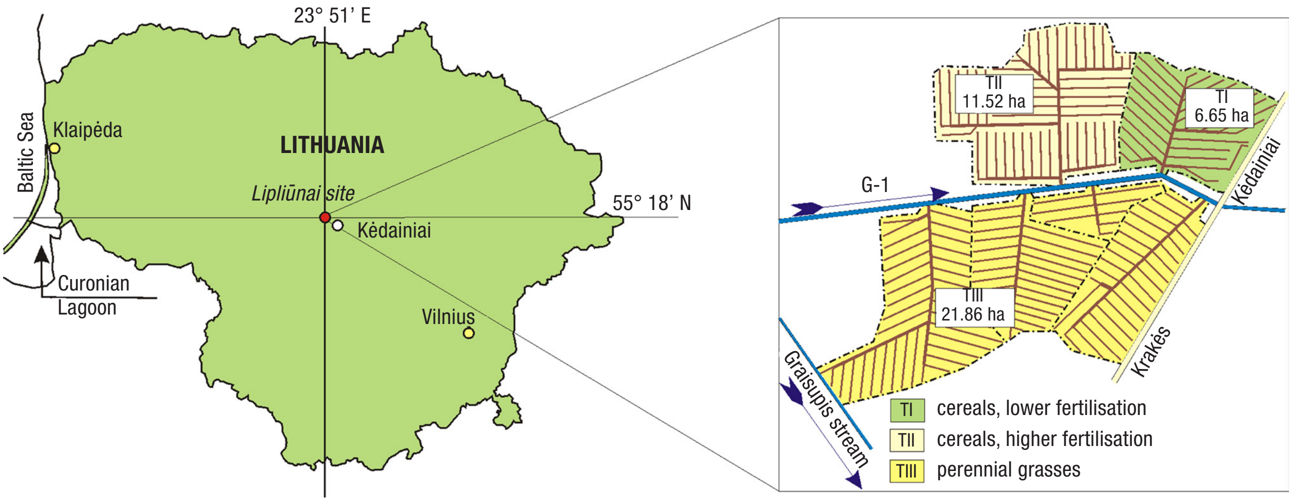


**Figure 1.** Geographical location and experimental layout of the Lipliūnai site.

The arable layer of TI and TII is sandy light loam. Its composition in deeper layers lightens until sandy loam. The soil in TIII is slightly lighter (Table 1). In the upper (0-20 cm) soil layer, the soil was average and high in humus (1.79-4.32 %). Agrochemical data analysis showed that differences in chemical elements of the soil among the treatments at the beginning of the research were not significant, except TIII, where we determined that N ($t_{fact.}$=2.82>$t_{theor.95\%}$=2.3) and humus ($t_{fact.}$=2.47>$t_{theor.95\%}$=2.3) were significantly lower than in TI. However, as we projected to use the perennial grass crop rotation in TIII, where perennial grasses fix N uses legume bacteria, we decided to start the research.

Meteorological conditions are described using the data of the Dotnuva meteorological station, which is 8 km away from the study area.

## Experimental design

In each of these plots, a field crop rotation with different fertilisations using mineral fertilisers was used. This was a production experiment; therefore, in different years at the beginning of the experiment, the amount of fertiliser used depended on the financial state of the farm. The following crops were grown: sugarbeet (*Beta vulgaris* L. var. *sacharifera*) 'Belmonte', spring barley (*Hordeum vulgare* L.) 'Ūla', winter wheat (*Triticum aestivum* Host) 'Portal', perennial grass red clover (*Trifolium pratense* L.) 'Liepsna' + feeding timothy (*Phleum pratense* L.) 'Gintaras II', summer wheat (*Triticum aestivum* L.) 'Nandu' and winter rape (*Brassica napus* L.) 'Valesca'. The long-term field experiment in Lipliūnai consisted of three crop rotations with 75, 87.5 and 50% proportions of cereals (Table 2).

Only mineral fertilisers were applied to crop fields. Nitrogen fertiliser (as well as phosphorus and potassium) was applied in the spring. The fertilisation schedule is presented in Table 2. The N fertiliser used was ammonium nitrate ($NH_4NO_3$). A dispersed fertilisation method was adopted, using a suspended fertiliser spreader "Amazone". The scattered fertiliser amount in higher or lower fertilisation fields was determined by academic recommendations and the financial position of the production farm.

**Table 1.** Soil properties in different layers before the start of the research

| Treatments | Depth (cm) | Soil bulk density (g/cm³) | Sand | Silt | Clay | $N_{total}$ | Humus |
|---|---|---|---|---|---|---|---|
| | | | (%) | | | | |
| TI | 0-24 | 1.53 ± 0.011 | 66.2 ± 3.31 | 23.8 ± 0.71 | 10.0 ± 0.25 | 0.29 ± 0.036 | 4.32 ± 0.62 |
| | 24-55 | 1.43 ± 0.013 | 54.7 ± 1.64 | 31.8 ± 1.11 | 13.5 ± 0.41 | 0.25 ± 0.041 | 3.32 ± 0.54 |
| | 55-91 | 1.47 ± 0.015 | 73.0 ± 1.83 | 21.0 ± 0.95 | 6.0 ± 0.24 | 0.021 ± 0.004 | 0.42 ± 0.31 |
| TII | 0-24 | 1.77 ± 0.014 | 57.0 ± 2.28 | 31.5 ± 1.58 | 11.5 ± 0.58 | 0.23 ± 0.003 | 3.42 ± 0.56 |
| | 24-55 | 1.71 ± 0.012 | 58.6 ± 1.17 | 33.9 ± 0.68 | 7.5 ± 0.19 | 0.14 ± 0.001 | 2.32 ± 0.64 |
| | 55-91 | 1.74 ± 0.016 | 70.1 ± 2.45 | 21.9 ± 0.77 | 7.9 ± 0.12 | 0.03 ± 0.001 | 0.45 ± 0.26 |
| TIII | 0-24 | 1.91 ± 0.018 | 59.6 ± 2.38 | 32.3 ± 1.45 | 8.1 ± 0.28 | 0.09 ± 0.001 | 1.79 ± 0.45 |
| | 24-55 | 1.83 ± 0.016 | 67.4 ± 1.35 | 20.4 ± 1.02 | 12.2 ± 0.49 | 0.07 ± 0.003 | 1.11 ± 0.51 |
| | 55-91 | 1.98 ± 0.014 | 74.0 ± 2.96 | 18.7 ± 0.75 | 7.3 ± 0.37 | 0.03 ± 0.0015 | 0.34 ± 0.23 |

**Table 2.** Field crop rotations (Rot) with proportions of 75, 87.5 and 50% of cereals and its N fertilisation (Fert, kg/ha a.m.) and crop yield (t/ha, dry matter)

| Years | TI-75% | | | TII-87.5% | | | TIII-50% | | |
|---|---|---|---|---|---|---|---|---|---|
| | Rot[1] | Fert | Yield | Rot[1] | Fert | Yield | Rot[1] | Fert | Yield |
| 2006 | SB | $N_{54}$ | 2.4 ± 0.79 | SB | $N_{84}$ | 4.25 ± 0.80 | B | $N_{32}$ | 10.4 ± 0.89 |
| 2007 | WR | $N_{24}$ | 1.85 ± 0.63 | B | $N_{32}$ | 10.3 ± 0.87 | SW | $N_{16}$ | 3.6 ± 0.54 |
| 2008 | WW | $N_{59}$ | 4.7 ± 0.41 | SW | $N_{103}$ | 5.2 ± 0.44 | PG | $N_0$ | 9.6 ± 0.71 |
| 2009 | SW | $N_{63}$ | 3.6 ± 0.42 | SB | $N_{103}$ | 4.4 ± 0.52 | PG | $N_0$ | 13.0 ± 0.96 |
| 2010 | SB | $N_{80}$ | 2.5 ± 0.43 | WW | $N_{115}$ | 4.2 ± 0.89 | PG | $N_0$ | 3.7 ± 0.36 |
| 2011 | WW | $N_{90}$ | 3.1 ± 0.49 | WW | $N_{140}$ | 5.1 ± 0.74 | SW | $N_{80}$ | 3.5 ± 0.36 |
| 2012 | WW | $N_{90}$ | 7.0 ± 0.96 | WW | $N_{140}$ | 8.3 ± 0.99 | SW | $N_{80}$ | 6.5 ± 0.58 |
| 2013 | WR | $N_{80}$ | 1.8 ± 0.36 | WW | $N_{126}$ | 7.2 ± 1.05 | PG | $N_{10}$ | 10.9 ± 0.72 |
| Total fertilisations | | $N_{540}$ | | | $N_{843}$ | | | $N_{218}$ | |

[1] B, sugar beet; SB, spring barley; SW, spring wheat; WR, winter rape; WW, winter wheat; PG, perennial grasses.

### Soil, plant and water analyses

Before starting the research, there were two soil profiles dug out in each of the treatments, and their soil genetic horizons were determined as well as samples from each of the layer were taken to determine physical and agrochemical characteristics from 0-24, 24-55 and 55-91 cm depth. The size distribution of soil particles (or soil texture) was determined by the Fere triangle method (Liekis, 2001), and soil density by the weight method in intact structure samples (Vadiunina & Korcagina, 1986). In order to determine the agrochemical soil characteristic, samples were taken in the autumn, after the harvest. Each year, in order to determine the agrochemical properties of the soil, samples were taken in autumn after harvest. Soil samples were collected using a drill up to 60 cm depth at every 20 cm. In TI and TII there were 15 boreholes drilled, while in TIII there were 20 boreholes. In each experiment treatment there were 3 collective samples created, which were analysed in the laboratory.

The soil pH was determined potentiometrically in a soil suspension in 1 M KCl (ISO 10390:2005); the humus content was determined by the method of Tyurin (1937); the $N_{total}$ was determined by Kjeldahl's procedure (ISO 11261:1995); available $P_2O_5$ and $K_2O$ were determined by the AL method (soil:solution ratio – 1:20, 0.1 M ammonium lactate + 0.4 N acetic acid, pH 3.74, 2 h shaking) (Egner *et al.*, 1960); and $N_{min}$ amount ($NH_4^+$-N + $NO_3^-$-N) contained in the soil was measured from the extraction of 0.2 M KCl using a flow injection analyser (FIA star 5012, AN 551, ASN 65-31-84, and ASN 50-01-84) (ISO/TS 14256-1:2003).

The yield was harvested mechanically and crop samples were taken from all replications. The cereals and grasses crop yield was harvested mechanically. The yield of row crops was determined manually. The stacionary area of the test fields of crops and grass was 30 m$^2$, row crops covered an area of 45 m$^2$. Crop harvest was determined by 6 replications in TI and TII, and by 8 in TIII. The main and secondary production of crops were weighed separately. The samples of the main and secondary production of yield were taken at the same time. Twenty different plants of sugar beet were taken in each test field (in a diagonal way). Leaves were sampled taking 2 kg of leaf mass. During the crop harvest time 3 kg of grain and 2 kg of straw were taken from each test field. Grass samples were taken during the grass haymaking time when a certain amount of grass was removed from 10 (in TI and TII) to 15 (in TIII) places in each test field. The amount of dry matter was determined in all samples used for yield production by drying at 105°C and reweighing to constant weight. Total crop yield energy was calculated using equivalents, which were multiplied with dry matter yield (Jankauskas *et al.*, 2000). $N_{total}$ in crop yield was determined after burning with sulphuric acid (ISO 5983-1:2005/Cor. 1:2008).

Drainage water discharge was measured by a volumetric method at every three days. Daily drainage was calculated by linear interpolation. Samples of drainage water were taken every 10 days. Monthly $N_{min}$ and $N_{total}$ leaching was calculated having multiplied the average monthly nutrient concentration by the monthly drainage value. N concentration in water was determined colorimetrically, $NH_4^+$ by the gas diffusion method (ISO 11732:2005), $N_{total}$ was determined after organic matter mineralisation with potassium persulphate and $NO_3^-$ by the cadmium reduction method (ISO 13395:1996).

### Data analysis

The data were processed by statistical methods. Disperse analysis and correlation and regression methods were applied (Shibusawa & Hache, 2009). The statistical significance of the data was computed by a multiple-way analysis of variance (ANOVA). In addition, the LSD multiple range test was used, the means of which differed significantly using a significance level of 0.01 and 0.05%. Student's test statistic was used to determine the reliability of differences between treatments.

## Results

Data show that perennial grasses and sugar beets produced the biggest yield (3.7-10.9 and 10.3-10.4 t/ha of dry material respectively). In all years, the higher fertilisation (843 N kg/ha) cereal crop rotation yield was determined to be larger than in the lower fertilisation (540 N kg/ha) cereal crop rotation (Table 2).

As different types of crops were grown in the research field, in order to determine which crop rotation field was the most productive, each of the yields of dry material amount was converted to GJ/ha and cumulative curves were drawn. After eight years of research, the biggest productivity was found in crop rotation of cereal with higher fertilisation, which accumulated 1483 GJ/ha of total energy harvest (Fig. 2).

Less fertilised cereal crop rotation productivity was 35% lower, and it was the lowest in the research range (966 GJ/ha). Perennial grass crop rotation productivity was 11% lower than the higher fertilised cereal crop rotation and constituted 1318 GJ/ha. With respect to humus and N, the soil of the site was not very homo-

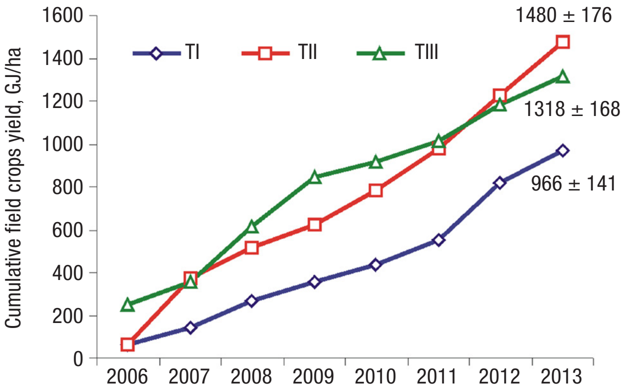


**Figure 2.** The influence of field crop rotations differing in intensity on cumulative field crops yield.

geneous, as the variation coefficients of these indicators were 17 and 14, respectively. At the end of the research the highest humus reserves were found in the field, where perennial grasses crop rotation was applied (4.11%) (Fig. 3). A slightly lower soil humus is obtained by applying higher fertilisation cereal crop rotation (3.7%), while the lowest is obtained using a lower fertilisation cereal crop rotation (2.94%). The data analysis revealed that the effect of different crop rotations on humus accumulation was significant: between TI and TII $t_{fact.}$=|–5.07|>$t_{theor.95\%}$=2.11, between TI and TIII $t_{fact.}$=|–8.02|>$t_{theor.95\%}$=2.11, and between TII and TIII $t_{fact.}$=|–2.28|>$t_{theor.95\%}$=2.11. An increasing tendency in $N_{total}$ accumulation in the soil was determined when using different fertilisation rates in the crop rotations (–0.25%, in TIII, –0.23% in TII, and –0.19% in TI). However, the differences between the treatments were not significant, between TI and TII $t_{fact.}$=|–0.96|<$t_{theor.95\%}$=2.11; between TI and TIII – $t_{fact.}$=|–1.53|<$t_{theor.95\%}$=2.11; and between TII and TIII - $t_{fact.}$=|–0.53|<$t_{theor.95\%}$=2.11.

The most stable $N_{min}$ concentration and accumulated amount were in TII, where variation coefficients of this element were 22% and 18%, respectively. With TI and TIII, $N_{min}$ concentration and accumulated amount in the soil varied more (from –41 to 35% and from 51 to 57%, respectively; Table 3). The average perennial data for $N_{min}$ concentration and accumulated amount in the soil are also rather uneven. The data show that in TI $N_{min}$ concentration and its accumulation in the soil was lower than in TII, however, this difference was not statistically significant ($t_{fact.}$=|–0.94|<$t_{theor.95\%}$=2.14 and $t_{fact.}$=|–0.79|<$t_{theor.95\%}$=2.20, respectively). Statistically significant differences between $N_{min}$ concentration and

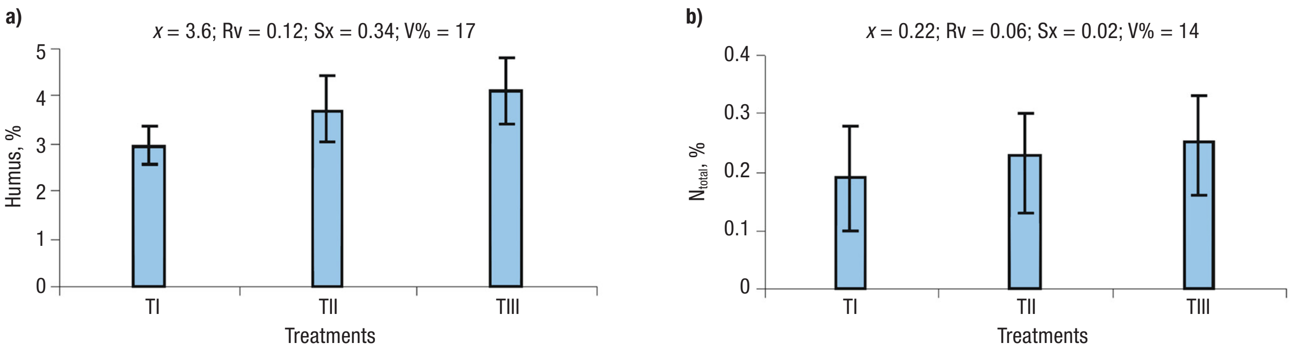


**Figure 3.** Variation in humus content (a) and total nitrogen (b) in the top layer (0-20 cm). *x* (arithmetical mean); Rv (amplitude of variation); Sx (error of average); V% (variation's coefficient).

**Table 3.** The impact of different crop rotations on $N_{min}$ concentration (mg/kg) and $N_{min}$ amount (kg/ha) in the soil (0-60 cm)

| Year | TI | | TII | | TIII | |
|---|---|---|---|---|---|---|
| | (mg/kg) | (kg/ha) | (mg/kg) | (kg/ha) | (mg/kg) | (kg/ha) |
| 2006 | 7.5 | 77.5 | 9.7 | 95.5 | 4.1 | 87.5 |
| 2007 | 2.0 | 35.7 | 7.8 | 64.3 | 3.1 | 41.7 |
| 2008 | 8.2 | 90.8 | 9.5 | 85.6 | 4.1 | 44.2 |
| 2009 | 8.3 | 82.2 | 5.2 | 76.4 | 0.91 | 27.6 |
| 2010 | 5.0 | 49 | 6.2 | 61.8 | 2.7 | 26.4 |
| 2011 | 10.7 | 105 | 8.2 | 81 | 6.4 | 65 |
| 2012 | 5.8 | 54 | 6.0 | 57.6 | 1.9 | 13.6 |
| 2013 | 5.0 | 54.9 | 8.3 | 88.4 | 2.8 | 30.0 |
| Average | 6.6 ± 0.94 | 69 ± 8.4 | 7.6 ± 0.60 | 76 ± 4.9 | 3.3 ± 0.58 | 42 ± 8.5 |
| *V%* | *41* | *35* | *22* | *18* | *51* | *57* |

For $N_{min}$ concentration, $LSD_{05}$=2.10; for $N_{min}$ amount, $LSD_{05}$=21.1. V%, variation's coefficient.

its accumulation in the soil were found in TI and TIII and in TII and TIII ($t_{fact.}$=2.98>$t_{theor.95\%}$=2.14 and $t_{fact.}$=2.23>$t_{theor.95\%}$=2.14; and $t_{fact.}$=5.27>$t_{theor.95\%}$=2.14 and $t_{fact.}$=3.52>$t_{theor.95\%}$=2.14, respectively).

$N_{min}$ concentration and its accumulated amount in the soil in higher and lower fertilisation cereal crop rotations were not statistically significant, even though the amount of this element in a lower fertilisation cereal crop rotation was determined to be lower, 13 and 9% up to 6.6 mg/kg and 69 kg/ha, respectively. The lowest $N_{min}$ concentration and its accumulated amount in the soil had the most productive perennial grasses crop rotation, and these indicators reached 3.3 mg/kg and 42 kg/ha, respectively. Correlation analysis results showed that $N_{min}$ amount was closely related to fertilisation. Also, its amount in the soil had a tendency to fall when the yield was high (Fig. 4).

A weak reverse linear was determined between $N_{min}$ amount in the soil and crop productivity. Increasing field crop productivity reduces the amount of $N_{min}$ in the soil, whereas increasing field crop fertilisation by N fertiliser increases the amount of $N_{min}$ in the soil. Field crop productivity determined the fluctuation of $N_{min}$ quantity by around 15%, and fertilisation by around 55%.

Precipitation dispersion was uneven during the research period, and it had effect on the formation of drainage (Table 4). It can be seen from the results that four of the years were dry (2006, 2008, 2011, and 2013), when precipitation was 80, 97, 97, and 91%, respectively, of the climate normals; 2007, 2009, 2010, and 2012 were damp years, because precipitation was 113, 125, 122, and 123%, respectively, of the climate normals. During almost the entire research period, the average air temperature was higher than the climate normals, except in 2010, when it corresponded to it.

Drainage quantity depended on the precipitation level and changed according to the direct linear pattern, as a higher level of precipitation increased the drainage.

According to the research data, on average during 8 years in a more productive, higher fertilisation cereal (TII: 55 ± 23 mm) and grass crop rotation there was a falling tendency in drainage determined, while in the least productive and lower fertilisation cereal (TI: 71 ± 29 mm) crop rotation there was an increasing tendency observed.

Even though drainage was 29% higher in TI and 25% higher in TIII than in TII, the differences between these treatments were not significant: between TI and TII, $t_{fact.}$=1.20<$t_{theor.95\%}$=2.14; between TI and TIII, $t_{fact.}$=0.12<$t_{theor.95\%}$=2.14; and between TII and TIII, $t_{fact.}$=–0.98<$t_{theor.95\%}$=2.14.

Drainage essentially depended on precipitation ($r$=0.68; $t_{fact.}$=4.31>$t_{theor.95\%}$=2.15). More intensively grown, larger biological potential crops, which use greater amounts of water, reduce not only soil humidity, but also drainage ($r$=0.43); $t_{fact.}$=2.23>$t_{theor.95\%}$=2.15)

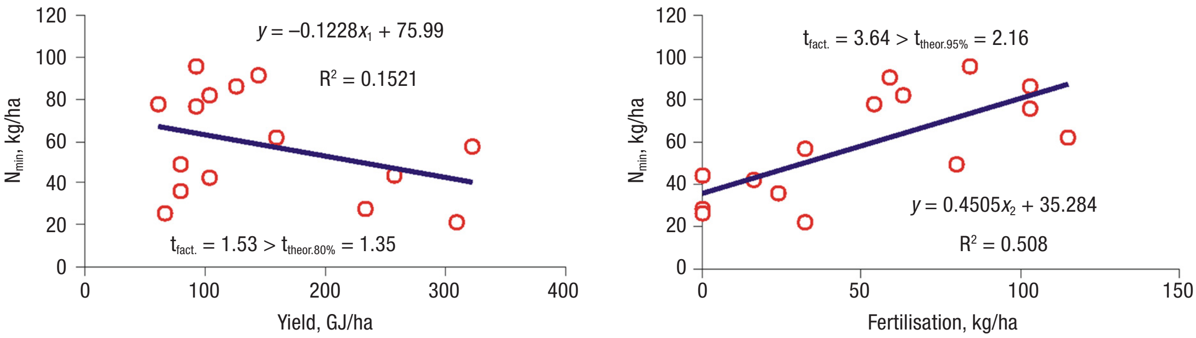


**Figure 4.** Dependence of mineral nitrogen amount in soil kg/ha ($y$) (0–60 cm) on crop yield GJ/ha ($x_1$) and nitrogen fertilisation kg/ha a.m. ($x_2$).

**Table 4.** Meteorological conditions and drainage of the study periods

| Indices | Year | | | | | | | | Perennial indices |
|---|---|---|---|---|---|---|---|---|---|
| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | |
| Precipitation, mm | 469 | 668 | 574 | 736 | 722 | 574 | 723 | 538 | 590[a] |
| Air temperature, °C | + 7.7 | + 8.0 | + 8.5 | + 7.2 | + 6.2 | + 7.9 | + 6.7 | + 7.5 | + 6.2[a] |
| Drainage, mm | 32 | 101 | 51 | 69 | 102 | 52 | 70 | 45 | 103[b] |

[a] Average rainfall and weather temperature climate normals during the 30 year period 1961-1990 (Korkutis, 1991; Alosevičienė, 1992).
[b] Average drainage in mid Lithuanian climate zone during the 29 year period 1962-1990 (Juozapaitis *et al.*, 1995).

(Fig. 5). In TIII, $N_{min}$ and $N_{total}$ concentrations were found to be 12.1 and 12.8 mg/L, respectively, in drainage water (Table 5).

Using a lower fertilised cereal crop rotation (TI) meant that $N_{min}$ and $N_{total}$ concentrations had a tendency to increase by 13 and 24% to 13.7 and 15.9 mg/L, respectively. An increasing tendency was also determined for $N_{min}$ and $N_{total}$ concentrations in drainage water in TII (15.6 and 18.5 mg/L). According to correlation and regression data analysis (Table 6), N concentration in water was determined by a number of factors.

Thus, as the field crops‘ productivity increased, N concentration in the drainage water changes according to the parabolic pattern and it was at its lowest when the field crops‘ productivity was 150-170 GJ/ha. When a higher productivity is achieved by fertilising field crops, both $N_{min}$ and $N_{total}$ concentrations in the drainage water increase. The relationship between soil $N_{min}$ and fertilisation by $N_{min}$ fertiliser with N concentration in drainage water can be expressed by this function: $y = a - b / x$ (Fig. 6); as soil $N_{min}$ as well as fertilisation with N fertiliser increases, the concentration of both N forms in drainage water increases.

The relationship of annual and cumulative N balance with N concentration in drainage water is of a direct linear nature and, as N balance increases, the concentration of both N forms in drainage water increases. Direct linear consistency means that $N_{min}$ concentration in drainage water increases as the soil N and humus increase. Due to the impact of field occupation coefficient N concentration in drainage water reduces.

Research data of leaching of N compounds by drainage showed (Table 5), that both $N_{min}$ and $N_{total}$ leaching had a downward trend when using grass crop rotation (7.0 and 8.0 kg/ha respectively).

An increasing tendency was found for N leaching in lower fertilised cereal crop rotation conditions (12 and 13%) and in higher fertilised cereals crop rotation conditions, 10.0 kg $N_{min}$/ha and 11.5 kg $N_{total}$/ha, respectively. Correlation and regression data analysis has shown that both $N_{min}$ and $N_{total}$ leaching is related to the productivity of agroecosystem and factors affecting it (Fig. 6). Crop fertilisation with mineral fertiliser had a very big effect on $N_{min}$ leaching ($r$=0.78), while it had only average effect on $N_{total}$ leaching ($r$=0.65). The yield affected $N_{min}$ leaching on average ($r$=0.57), while $N_{total}$ was weakly affected ($r$=0.46); however, it was statistically significant.

Nitrogen leaching through the drainage relationship between the fertilisation of an agroecosystem with mineral fertiliser and its productivity is parabolic. Fertilisation with N fertiliser until 66-71 kg/ha a.m. does not increase N leaching losses. Increasing the harvest by fertilisation leads to the increase in N leaching. The

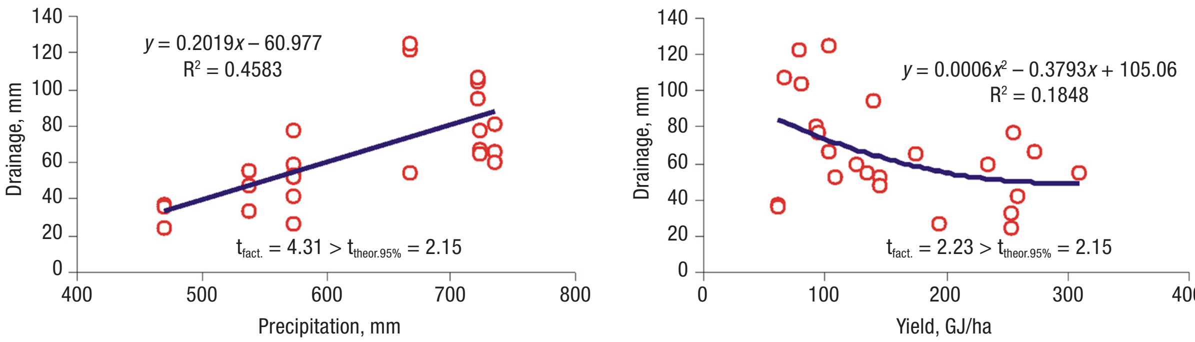


**Figure 5.** Drainage dependency on precipitation and crop yield.

**Table 5.** Different crop rotation impact on average yearly N concentration in drainage water and leaching (arithmetical mean ± average error)

| Treatments | $N_{min}$ | $N_{total}$ | $N_{min}$ | $N_{total}$ |
|---|---|---|---|---|
| | (mg/L) | | (kg/ha) | |
| TI | 13.7 ± 1.67 | 15.9 ± 3.72 | 8.7 ± 5.3 | 9.3 ± 5.1 |
| TII | 15.6 ± 0.69 | 18.5 ± 1.97 | 10.0 ± 4.3 | 11.5 ± 7.6 |
| TIII | 12.1 ± 2.29 | 12.8 ± 3.30 | 7.0 ± 2.2 | 8.0 ± 2.7 |
| $LSD_{05}$ | *4.8* | *8.7* | *11.7* | *15.5* |

$N_{min}$ concentration and leaching differences between treatments are reliable with 75% and 70% probability respectively, while $N_{total}$ concentration and leaching differences are reliable with 90% probability.

**Table 6.** The dependence of $N_{min}$ ($y_1$) and $N_{total}$ ($y_2$) concentrations (mg/L) in drainage water on environmental factors ($x$)

| Indices | Regression equation | Coefficient | Probability, % |
|---|---|---|---|
| Harvest, GJ/ha | $y_1 = 17.48 - 0.102x + 0.0003x^2$ | 0.48 | 96 |
| | $y_2 = 24.18 - 0.151x + 0.0005x^2$ | 0.36 | 93 |
| Mineral soil nitrogen, kg/ha (0–60 cm) | $y_1 = 20.82 - 279.48/x$ | 0.65 | 99 |
| | $y_2 = 27.69 - 441.64/x$ | 0.59 | 99 |
| Fertilisation, kg N/ha a.m. | $y_1 = 16.64 + 0.00055/x$ | 0.59 | 99 |
| | $y_2 = 21.08 - 0.00086/x$ | 0.52 | 90 |
| N balance, kg/ha | $y_1 = 16.26 + 0.0104x$ | 0.26 | 81 |
| | $y_2 = 21.06 + 0.0248x$ | 0.35 | 91 |
| Cumulative N balance, kg/ha | $y_1 = 17.61 + 0.012x$ | 0.71 | 99 |
| | $y_2 = 2.67 + 0.019x$ | 0.65 | 99 |
| Coefficient of N balance compensation by fertiliser, % | $y_1 = 16.64 - 0.00055/x$ | 0.59 | 99 |
| | $y_2 = 21.08 - 0.00086/x$ | 0.52 | 90 |
| Soil nitrogen, % | $y_1 = -1.78 + 70.95x$ | 0.56 | 99 |
| Soil humus, % | $y_2 = 1.87 + 3.588x$ | 0.54 | 98 |
| Coefficient of field occupation | $y_1 = 7.29 + 17.86x - 16.024x^2$ | 0.30 | 83 |
| | $y_2 = 621.78 - 11.119x$ | 0.40 | 95 |

lowest $N_{min}$ leaching losses were found when productivity reached 213 GJ/ha, whereas the lowest $N_{total}$ leaching losses were when productivity reached 212 GJ/ha. The relationship between $N_{min}$ and $N_{total}$ leaching by drainage with the balance of agroecosystem can be expressed by the formula $y = a - b / x$. As N balance changes from –300 to –20 kg N/ha, $N_{min}$ and $N_{total}$ leaching barely increases. It increases more significantly when the N balance becomes zero and positive. The relationship of $N_{min}$ leaching (kg/ha) with soil N % ($x_1$) and humus % ($x_2$) is as follows:

$$y = -6.98 + 101.52x_1;\ r = 0.35 \quad [1]$$

$$y = -2.40 + 5.383x_2;\ r = 0.35 \quad [2]$$

The usage of all crop rotations did not ensure a positive N balance in the agroecosystem. The lowest deficit of N was gained with the higher fertilised ce-

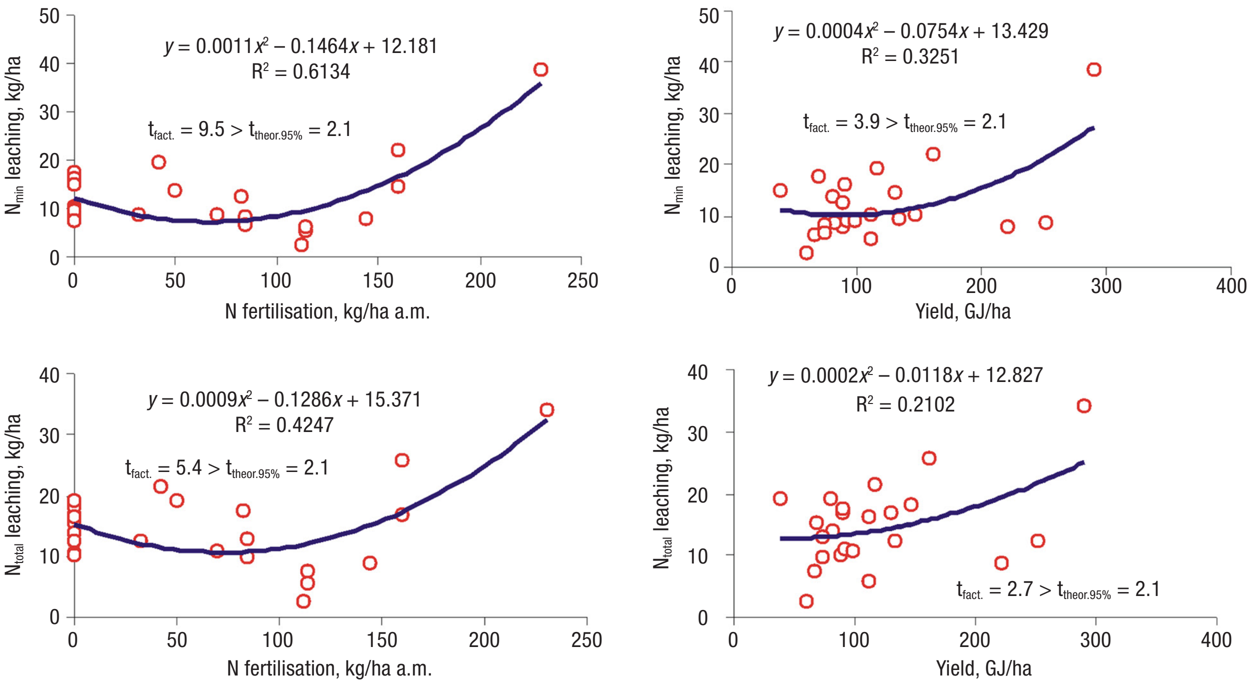


**Figure 6.** Mineral ($N_{min}$) and total ($N_{total}$) leaching by drainage dependent on fertilisation with N fertiliser and the obtainable harvest.

real crop rotation (–14 ± 48.1 kg N/ha/yr). Under less fertilised cereal crop rotation conditions, the N balance deficit increased by 2.2 times and reached -31±56.7 kg N/ha/yr. It was found to be the highest with perennial grass crop rotation (–100 ± 37.4 kg N/ha/yr). Significant N balance differences were found between TI and TIII as well as between TII and TIII ($t_{fact.}$=2.60>$t_{theor.95\%}$=2.11 and $t_{fact.}$=3.02>$t_{theor.95\%}$=2.07, respectively). Nitrogen balance was not statistically significant between TI and TII ($t_{fact.}$=–1.27<$t_{theor.95\%}$=2.07).

An average annual N balance over the eight research years was estimated, excluding N fixation with legume crops and denitrification losses in the soil, as we did not have the tools to record these indicators. An average correlation was determined between fertilisation with N fertiliser (*x*) and N balance (*y*):

$$y = 0.293x + 80.847;\ r=0.55;\quad t_{fact.}=3.08>t_{theor.95\%}=2.07 \qquad [3]$$

According to average data, in order to create 1 GJ energy, TIII outstood due to high costs (23.5). Slightly lower costs were reported using TII (18.1), while the lowest costs were using TI (13.9). This is related to the productivity of field crops (dry matter), expressed as GJ/ha. Costs to create vegetative produce include fertiliser, fertilisation, field crops' agricultural engineering, pesticides, etc. estimated as GJ/ha. $LSD_{05}$ of named indicators reached 7.6 GJ/ha.

## Discussion

During the 2006-2013 period, we were analysing several research questions, such as how $N_{min}$ affects the yield, how fertilisation affects $N_{min}$ in the soil, the effect of different crop rotations on the annual N balance, and the differences in mineral and $N_{total}$ concentrations in drainage water with fertilisation, as well as how they depend on the soil.

The study showed that a higher fertilised cereal crop rotation had the highest cumulative productivity (1483 GJ/ha), while cereals with less fertilisation and grass crop rotations had a productivity which tended to be lower by 11 to 35%, respectively, suggesting that the crop yield depends on fertilisation rate. Similar results were found by Křen *et al.* (2014), who analysed spring barley yields applying different N fertilisation rates. The yield increase was determined to be higher using N rate from 0 kg N/ha to 45 kg N/ha, rather than the rate from 45 kg N/ha to 90 kg N/ha. Grover *et al.* (2009) claimed that crop rotation is a prerequisite for a large crop yield, especially when legume crops are included in the rotation. However, the cultivation of corn monoculture produced the same yield as the crop rotation (Grover *et al.*, 2009). Babuliková (2014) contributed to the findings using wheat in the crop rotation. It was found that in order to obtain the highest wheat yield the best N rate was 96-168 kg N/ha. There was a small difference by fertilising with a rate of 150-200 kg N/ha; however, by increasing the N rate to 240 kg N/ha, the grain yield and N effectiveness dropped. In addition to this, a long-term research revealed that crop rotation and different fertilisation had only a slight effect on yield and soil fertility parameters (Cuvardic *et al.*, 2004). On the other hand, according to Coulter *et al.* (2011), a high yield in the "extended crop rotations for corn and soybean" can be obtained, even by reducing the fertilisation rates. Additionally, Øgaard (2014) found that excessive fertilisation with N leads to a fall in crop yields, an increase in N losses, and the formation of high N surplus.

In general, the results suggest that higher fertilisation increases mineral N concentration and accumulated amount in the soil. This is evident from our research, which showed that the highest mineral N concentration and accumulated amount in the soil was found in the higher fertilisation cereal crop rotation (respectively 7.6 mg/kg and 76 kg/ha), while the lowest amounts and concentrations were found in the grass crop rotation (3.3 mg/kg and 42 kg/ha), with values that were 57 and 45%, respectively, lower than for the higher fertilised cereal crop rotation. Similar results were found by Cuvardic *et al.* (2004), who observed an increasing trend in soil N (from 0.32 to 0.36%). Additionally, our research showed an increase in humus (4.11%) in perennial grasses crop rotation (Fig. 3). Other researchers found that using N-fixing legumes and red clover increase mineral N concentrations in the soil and might even accumulate the amount of 200 kg/ha of biological N for further crop rotation (Lapinskas, 1998; Riedell *et al.*, 2009). In addition, Röing *et al.* (2005) claimed that 50% more N mineralises in crop rotations with ley rather than in crop rotations where only cereals are grown. According to Sonneveld & Bouma (2003), on old pastures, reducing N application levels can lower the probability of exceeding the environmental threshold for nitrate by up 20%, whilst hardly affecting N uptake. Köhler *et al.* (2006), in sand soils, showed that nitrate leaching depended on N fertilisation and different crop rotations as well as mineralisation from soil organic matter. Catch crops were the most efficient way to reduce the $NO_3^-$ concentrations in the groundwater recharge of sandy soils. These results suggest that the $N_{min}$ concentrations in the soil depend not only on the fertilisation rate, but also on the type of crop rotation.

We found that the application of all crop rotations generally resulted in a negative N balance. However, the use of different cereals crop rotations showed a lower N balance deficit (–31 and –14 kg N/ha), while the grass crop rotation resulted in a negative N balance, which increased by 3.2 and 7.1 times and reached -100 kg N/ha. According to Kutra & Aksomaitiene (2003), the most negative N balance (-426 kg N/ha) was found in the perennial grass fields; the most positive balance (+ 174 kg N/ha) was in fields with sugar beets rotation.

The results from a number of countries show that the main environmental problem related to agriculture is N leaching. According to Arregui & Quemada (2006), the amount of leached N highly depends on the amount of it found in drainage and soil before planting crops. When N balance is positive, there is a high possibility that N concentrations in drainage water will be above the maximum allowable values. When N balance is negative, its concentrations are determined to be low. Crop rotation where perennial grasses are grown is regarded to be the best in terms of the impact to the environment, as $N_{total}$ concentrations in drainage water were determined to be the lowest (12.8 mg/L) and not to exceed the required environmental regulations (VZ, 2011). This was also observed in our research, as the $N_{min}$ and $N_{total}$ leaching had a tendency to fall in grass crop rotation (7.0 and 8.0 kg/ha, respectively), while in cereal crop rotations with lower and higher fertilisation there was an increasing tendency in N leaching (by 13 to 42%) observed. Additionally, Kutra & Aksomaitiene (2003) showed that in fields where cereals were dominating, N surplus was + 74 kg N/ha. Weber & Kubiniok (2013) also found that in the soils sown with perennial grasses, chemical elements' leaching losses were lower than in cereals. Thus, due to the fact that grass crop rotations reduce N concentrations in the soil, they also reduce the risk of it leaching into the drainage water. However, there are more factors that affect N leaching, as fertilization rate not higher than plant need and minimized soil tillage systems (Kutra *et al.*, 2006).

Lysimetric research revealed that nitrate concentrations in lysimeter water were highly dependent on fertilisation rates. Moreover, according to a 30-year research work (Adomaitis *et al.*, 2008), by fertilising crop rotation plants (winter wheat, sugar beet, spring barley, annual grasses and perennial grasses), using the fertilisation rates 112 and 224 kg N/ha, the nitrate concentrations observed in lysimeter water at a depth of 0-80 cm were 112.1 and 187.2 mg/L, respectively. Tripolskaja & Verbylienė (2014) determined that by fertilising with N fertiliser (on average 120 kg/ha), compared to unfertilised soil, the average nitrate concentration in lysimeter water was increased by 37.5 to 54.3%. However drainage, due to more dense and more exuberant crops, which reduce precipitation filtration, fell during the year on average by 13.7-16.2%. This is also supported by our research results, which showed that larger biological potential crops reduced drainage by 23% compared to lower biological potential crops. Tiemeyer *et al.* (2006) determined that N concentrations in drainage water were increasing by increasing flow rates, high loss rates always occurred at high flow rates, and higher loss rates are to be expected in wetter years. This was also confirmed by our research: when the precipitation level was higher, the drainage was also higher. Drainage essentially depended on meteorological conditions. Previous research showed that agroecosystem´s hidrological regime is determined not only by natural, but also by human farming activity factors (the crops grown, the farming level). More intensively grown, higher biological potential crops use up more water and thus reduce not only the soil moisture but also drainage (Aksomaitienė *et al.*, 2002). The problematic nature of the research is that the majority of results were obtained from small drainage sites or even by lysimetric research methods. To determine similar patterns by performing tests in large drainage systems is also difficult, not only because of their large amortisation effect (Cornelese *et al.*, 2001), but also because of the research background promiscuity (soil cover variegation, ground water stratification depth, etc.); however, under some circumstances, patterns remain (Sileika & Guzys, 2003).

Both $N_{min}$ and $N_{total}$ leaching by drainage, due to the crop productivity and their fertilisation with N fertiliser, change according to $y = a - bx / cx^2$. The smallest N leaching losses were obtained by fertilising 66-71 kg N/ha and crop productivity of 212 GJ/ha. Furthermore, $N_{min}$ and $N_{total}$ concentration in drainage water depended on crop rotation, its productivity and the factors determining productivity. Both $N_{min}$ and $N_{total}$ concentration in drainage water had a tendency to fall in grass crop rotation (12.1 and 12.8 mg/L respectively). The use of cereal crop rotations with higher and lower fertilisation increased $N_{min}$ concentration by 13 and 29%, while total N by 24 and 44%. According to Adomaitis *et al.* (2008), a larger amount of nitrates is leached when annual crops are grown, compared with perennial grasses. Regular grass sown in arable land and not fertilised with N reduced nitrate concentration to the level of perennial pasture in just one year. The risk of exceeding the maximum allowable limit of nitrates in crop rotation in arable land was significant and did not depend on the level of fertilisation with N (Mašauskas *et al.*, 2006).

Moreover, Beaudoin *et al.* (2005), determined that nitrate concentrations change subject to the year, crops and soil type; in a deep loamy soil, concentrations fluctuated between 31 mg/L and 92 mg/L in shallow sand. Correa *et al.* (2005) and Tonitto *et al.* (2006)

observed that the biggest leaching losses occurred in the bare, fallow soil. The lowest concentrations were determined in crop rotation with sugar beet/wheat (38 mg/L), whereas the highest concentrations were found in the pea/wheat crop rotation (66 mg/L) (Beaudoin *et al.*, 2005). Kutra *et al.* (2006), found that the majority of N was leached from row crops (22.4 kg/ha), slightly less from cereal fields (16.6-18.9 kg/ha) and least of all from grasslands (10.5 kg/ha). On the contrary, Bohm *et al.* (2009) showed that legume crop cultivation can considerably increase $N_{min}$ concentration in the soil solution and leaching as well.

The data imply that the amount of $N_{min}$ in the soil is a very labile indicator. Loosening during the mineralisation period and spreading during fertilisation ensure that $N_{min}$ is quickly used up by crops. The longer the crop vegetation period and the greater their biological potential, the stronger this preventative effect (Kutra *et al.*, 2006; Askegaard *et al.*, 2011; Doltra *et al.*, 2011).

Finally, as the data collected by many researchers show, the advanced agricultural technologies and efficient application (not the rates) of mineral fertilisers are among the essential preconditions for reduced non-point source water pollution with N (Goulding *et al.*, 2000; Sileika & Guzys, 2003).

The obtained results showed that the application of perennial grasses crop rotation in agricultural fields was the best environmental tool, reducing N migration to drainage. By fertilising with other treatments using higher N rates, mineral N accummulation in the soil increased, stimulating a higher yield and reducing N leaching by drainage. By fertilising with higher N rates than it is neccesary for plants, both mineral and total N leaching to drainage had a tendency to increase.

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