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Content of nitrates in drainage and groundwater from permanent pasture, grassland and arable crop rotation soil

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Sustainable land and nitrogen fertilisation management practices must be developed to secure viable agricultural production and reduce nitrate pollution of surface and groundwater. The study designed to explore nitrate concentration levels in drainage and groundwater as affected by land use type and N fertiliser levels was conducted at the Lithuanian Institute of Agriculture in 2001–2005 in an experimental site with 11 separate drainage systems.

Permanent pasture, managed without nitrogen fertilisers and with medium grazing intensity, was an effective means to maintain nitrate content in drainage and upper groundwater below the guideline value of 50 mg l^{-1} set by the EU Drinking Water Directive. Permanent grass leys established in an arable crop rotation and managed without nitrogen fertilisers after one year reduced the levels of nitrates to those of permanent pasture. In the arable soil of crop rotation the risk of exceeding the limit of 50 mg l^{-1} was considerable, irrespective of the level of N fertilisation. The algorithms and program worked out at the Lithuanian Institute of Agriculture enabled calculating N rates which were efficiently utilised to produce the yield, and no surplus of N balance in the crop rotation was created.

Key words: water quality, nitrogen, fertilisers, balances

INTRODUCTION

Nitrogen is an essential element for plant growth and the major limiting nutrient in Lithuanian soils. Application of nitrogen is required for economically viable plant production; however, leaching of fertiliser nitrate through the soil profile and into drainwater can contribute to eutrophication of streams and lakes and nitrate contamination of surface and groundwater resources. In order to prevent drinking water from nitrate contamination, in 1980 the EU adopted Drinking Water Directive which set the legally allowable maximum of 50 mg l^{-1} of nitrate in drinking water. The Nitrate Directive issued in 1991 requires member states to identify and designate as nitrate vulnerable zones all known areas of land where water drainage into natural water bodies could exceed the 50 mg l^{-1} limit for nitrate concentration. Studies of implementation of Nitrate Directive (EEC, 1991), directly targeting pollution by nitrates from agricultural sources, showed that member states were not fulfilling their obligations either in substance or in time (Goodchild, 1998). The directive, for the first time, require that farmers themselves take measures necessary to control water pollution by nitrates. Although strategies and legislature can help outlining the general direction and measures to be taken, they should be supplemented with rather detailed measures and guidance for farmers. Li-thuania, as a EU member, must implement Nitrate Directive by defining Nitrate Vulnerable Zones and encourage farmers to adopt more sustainable land management practices in order to reduce water pollution by nitrates. Water quality monitoring provides comprehensive qualitative information regarding water quality issues. Analysis of the regional distribution of nitrates in the rivers of the Nemunas River basin show that nitrate concentrations are higher in the basins of the rivers where the most fertile soils provide best conditions for agricultural production (Šileika et al., 2003). These results are in good agreement with the results of analyses performed using the MIKE BASIN model which shows that the highest loads, above 15 kg ha^{-1} of total nitrogen from non-point pollution, occur in Central and North Lithuania (Aplinkos..., 2005). Based on a study of the impacts of agrarian reform, it was suggested that the decreasing input of mineral and organic fertilisers will not automatically result in decreased nitrate nitrogen losses (Šileika et al., 2003). Insignificant changes of nitrogen

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concentration in riverside areas in the last fifteen years are reported (Povilaitis, 2006). Connection between the amount of nitrogen fertilisers and the level of nitrates in the soil and lysimetric water (40 cm deep) was found in 27-year of experiments with different fertilisation levels. Very high values of nitrates (up to 159 and 301 mg l^{-1}) were measured in the water from plots fertilized each year with N_{114} and N_{228} (Adomaitis et al., 2004). In experiments on lighter soils, mean nitrate concentrations in lysimetric water were 71 mg l^{-1}, if medium rates of fertilisers were applied, but increased up to 149 mg l^{-1}, if high rates of organic and mineral fertilisers were applied (Tripolskaja, 2005). However, other studies suggest that nitrogen surplus rather than the actually applied N rate is more relevant for water contamination with nitrates. In arable lands, about 25 percent of N surplus is leached to groundwater and tile water, while leaching of nitrates was almost twice as high from arable land than from grassland (Fraters et al., 2001). Studies of runoff from fields dominated by cereal and grass production on clay soil have shown that N leaching depends on N balance and the volume of total runoff or subsurface drainage. However, the high-est annual N leaching losses are not always caused by high N balances, but rather by poor management (Salo, Turtula, 2006). It is difficult to establish a straightforward relationship between nutrient management, surplus, losses and environmental impact, hence agronomic and environmental references or target values need to be established for different production systems, geographical areas and elements (Oborn, 2003). In Lithuania, water from shallow wells is used by one third of the population, and a rather large number of wells contain high nitrate concentrations (Kadūnas, 2001). Management of agricultural fields can be also of great importance as an indirect factor through the sources of shallow groundwater affecting drinking water quality. The information regarding the content of nitrates in drainage and especially in groundwater from agronomic experiments with a strict control of fertiliser and other management factors is scanty.

The aim of this study was to explore nitrate concentration levels in drainage and groundwater depending on land use type and N fertiliser levels in arable crop rotation soils in compliance with the limit set by the Drinking Water Directive.

MATERIALS AND METHODS

The study was conducted at the Lithuanian Institute of Agriculture in 2001–2005 in an experimental site with 11 separate drainage systems constructed in 1991 (Bučienė, 2003). The experimental site is situated a few hundred meters from the Dotnuvėlė River on a relatively flat area surrounded by a permanent pasture. The prevailing soil is Endocalcari-Epihypogleyic Cambisols (CMg-p-w-can), medium textured, with the following characteristics of the arable layer: pH_{KCl} 7.6–7.6, humus 2.0–2.2%, P_2O_5 119–200, K_2O 121–135 mg kg^{-1} of soil (A–L method).

Each drainage system contained two separate tile (5 cm in diameter) drains installed at a depth of 1.10–1.20 m parallel to the length of the plot and covered an area of 0.35 ha (32 m wide and 110 m long). Equipment for measuring drainage water discharge and a borehole (4 meters deep) for upper groundwater sampling and level measuring were installed in each drainage system. One system was occupied by a permanent pasture established in 1952, which during this study received no fertilisers and was grazed 4–5 times per season by 10 milk cows. One system had been used for arable crops since 1991. In 2001, it was sown with a mixture of red clover and timothy and converted to permanent grassland, which was cut two times per season and received no fertilisers. Nine systems were occupied by arable crops and each contained 4 equal fields with winter wheat, spring rape, spring barley and red clover (rotating in the enumerated order) arranged across the drainage tiles. Crops in three drainage systems (later referred to as systems without N) were managed without N fertilisers (according to the rules of organic farming, with some differences in plant protection and K fertilisation measures). Crops in the two systems (system with N for target yield) received the rates of N, P and K calculated within the fertiliser program (Švedas, Tarakanovas, 2001) for a target yield (125 kg ha^{-1} N for 7.5 t ha^{-1} of winter wheat, 100 kg ha^{-1} N for 6 t ha^{-1} of spring barley, 120 kg ha^{-1} N for 3 t ha^{-1} of spring rape and no nitrogen fertilisers applied for 3 t ha^{-1} DM red clover). Pesticides in this system were applied as recommended by LIA for a relatively good control of weeds, diseases and pests. Crops in four systems (system with reduced N) received by 35–40% lower rates of N, P, K (70 kg ha^{-1} N for winter wheat, 45 kg ha^{-1} N for spring barley, 80 kg ha^{-1} N for spring rape and no nitrogen fertilisers applied for red clover) and pesticides only for an essential control of pests. After the cereal and rape harvest, the straw was crushed, incorporated in soil and ploughed in at the end of September.

The discharge of drainage water was measured continuously and is presented here as daily means. Samples of drainage water were collected once per month when discharge occurred. The samples were collected directly from the incoming pipes. The level of groundwater was measured with one-week to two-month intervals, and water was sampled with intervals of 2–4 weeks depending on rainfall. All samples were analysed for NO_3 content (ISO-7890-3:1981).

The yield of crops was measured by harvesting six subplots (2.2 m wide, 20 long, total 44 m^2) in each crop field of a drainage system (24 plots per system). The total N content (by Kjeldahl) in the yield was measured in three samples from three subplots for each crop and each drainage system. A simplified balance (surplus) of N was calculated each year for a whole crop rotation in each drainage system by the formula $N_{surplus} = N_{fertiliser} - N_{harvest}$, where $N_{fertiliser}$ is N applied as a mineral fertiliser and $N_{harvest}$ is N removed from the field with grain or forage. Standard error of the mean was calculated using values from individual drainage systems, and the t test was used to separate the means among treatments.

During the study period, the climatic conditions were rather diverse. Precipitation and temperatures in 2001 and 2004 were close to normal. The years 2002 and 2003 were relatively dry because of higher temperatures and lower precipitation than average, except a higher precipitation in October 2002.

RESULTS

Diverse climatic conditions during the study period markedly affected the drainage and groundwater mode. The flow of drainage water was rather irregular, with large tile flows occurring in late autumn to spring, but with the main peaks at the end of February till the beginning of April and substantial quantitative differences among the years (Fig. 1). These results show a good correlation with the regularities reported for water runoff of Middle Lithuanian small rivers (Gaigalis, Šmitienė, 2004). During the years covered by our study, it was possible to sample drainage water only during discontinuous periods of different length in the autumn–spring period. After the very dry season of 2002, drainage water started to flow only in February 2003. The regularities described above were relevant for all drainage systems involved in the experiment. Some quantitative differences among the drainage systems probably were due to variation in soil properties and soil use rather than land use and fertiliser management.

Concentrations of nitrates in drainage water varied considerably over the study period as well as among land use types and individual drainage systems. The lowest concentrations of nitrates, in all cases below the drinking water guideline value of 50 mg l^{-1}, were measured in drainage water from permanent pasture (Fig. 2). Only in a few cases they exceeded the value of 25 mg l^{-1}, which according to the Nitrate Directive allows a lower intensity of freshwater monitoring. The concentration of nitrates in drainage water from the grassland was of the same level as in that from the pasture, except the autumn–spring period of 2001–2002 following the first year of the sowing of grasses. In the arable soil of crop rotation, the concentration of nitrates in drainage water was much higher than in the permanent pasture or grassland and in most cases exceeded the drinking water guideline value of 50 mg l^{-1}. The values above 100 mg l^{-1} were frequent, and the values above 150 mg l^{-1} were also found in a few cases. Actually, the maximum nitrate concentrations were on the same level, notwithstanding the level of N fertilisation.

The groundwater level was also greatly affected by climatic conditions and varied during the period of studies from 3.9 to 0.3 m (Fig. 3). After a very dry summer–autumn period in 2002, the groundwater level on 22 October 2002 dropped to the depth of 2.9–3.9 m. A similar situation occurred in 2003, with slightly lower values for groundwater level. Only in the autumn of 2004 groundwater restored to a more normal level. There were no regular significant differences between drainage systems differing in land use type or N fertilisation regarding the level of groundwater.

Because of the installation of boreholes used in our experiment, our study actually refers only to the upper, most recently formed groundwater occurring within 4 m from the soil surface, but unrecoverable by crops either directly or by capillary rise (Fraters et al., 2001). The concentration of nitrates in groundwater was obviously associated with the level of groundwater and recharging processes in the autumn–spring period. Measurements of nitrate content in autumn–spring following the season with precipitation close to normal (2001 and 2004) showed a rather large variation (Fig. 4). The average figures, however, are below 15 mg l^{-1} for grassland and pasture and below 50 mg l^{-1} for arable crop rotation. During the very dry period of 2002 when the groundwater level was very low, nitrate concentration was also very low. The next year (2003) was drier than normal and relatively low levels of nitrates (up to 16 mg l^{-1} for grassland and pasture and 36 mg l^{-1} for arable crop rotation

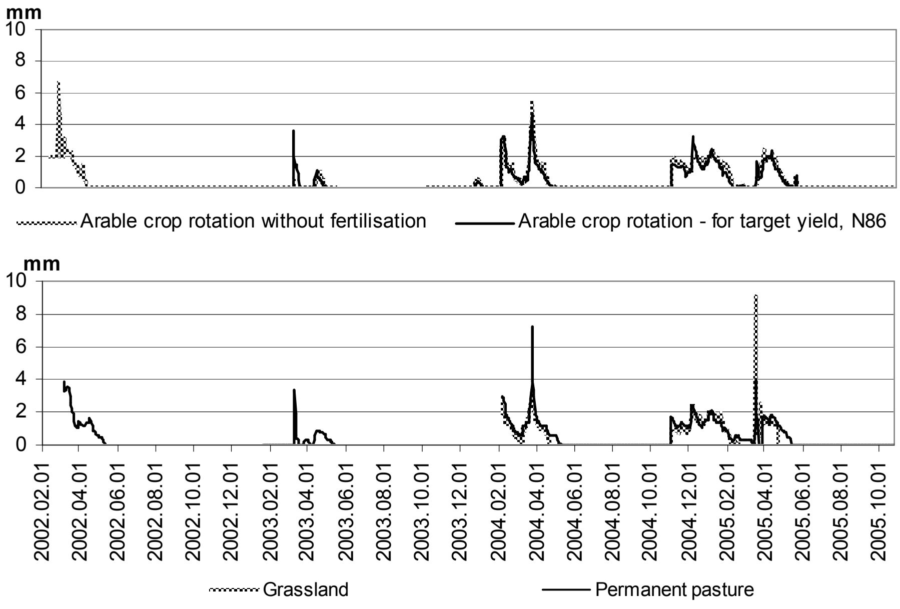


Fig. 1. Daily drainage water flow from arable crop rotation, grassland and pasture

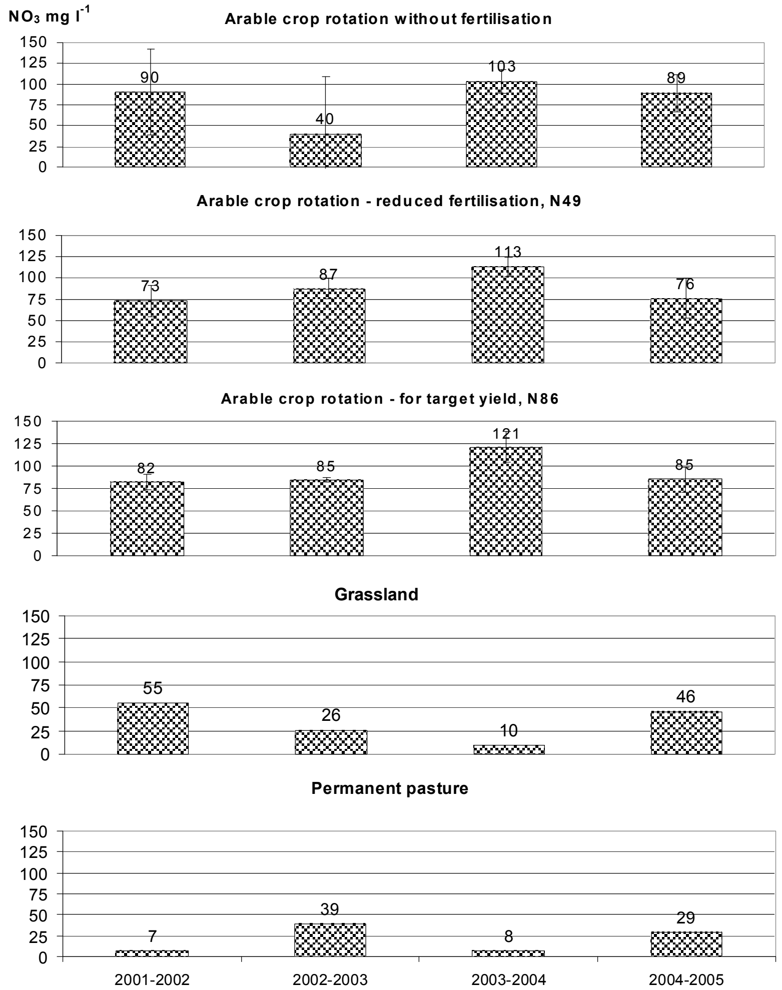
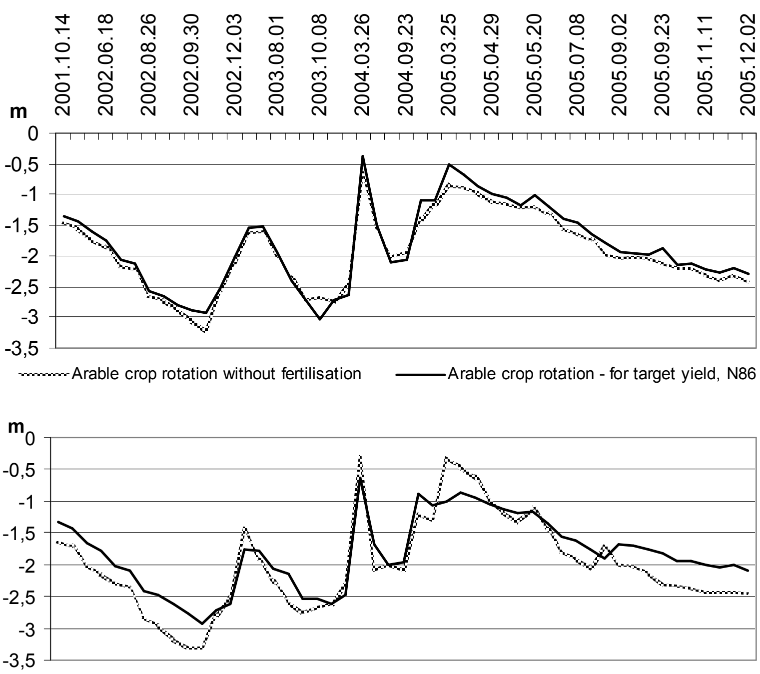


Fig. 2. Average nitrate concentrations in drainage water during autumn–spring period in arable crop rotation (under different levels of N fertilisation), grassland and pasture. Error bars are standard error



on average) were prevailing until the end of autumn. However, at the end of this period of two dry years, just at the moment when the groundwater level started to recover on 20 October 2003, the highest concentrations of nitrates were measured. The concentrations of nitrates were higher in arable crop rotations (58–82 mg l^{-1}) than in the grassland (69 mg l^{-1}) or in the permanent pasture (31 mg l^{-1}). The increase was short and measurements on 7 December 2003 showed again low levels (below 11 mg l^{-1}) of nitrates in all drainage systems. The second largest peak (27–75 mg l^{-1}) occurred in February–March 2005, with a longer period of increased values of nitrates in groundwater, which also coincided with the increasing level of groundwater. The actual yields of crops varied substantially, but a simplified farm-gate type nitrogen balance calculated as $N_{fertiliser} - N_{harvested}$ was negative in all years and systems (Fig. 5) and no surplus of N was produced.

DISCUSSION

During the study period, the concentrations of nitrates in groundwater were in most cases below the level of 50 mg l^{-1} and much lower than in drainage water. The lower concentration of nitrates in borehole water could be a combination of a longer travel time and higher denitrification losses (Fraters et al., 2001). This suggestion, considering the lower nitrate concentrations in drainage and groundwater in grassland and the higher concentrations in arable soils of crop rotation, is not straightforward. High levels of nitrates in groundwater in all cases coincided with the sharply increasing groundwater level, pointing out a rapid and discontinuous groundwater recharge with surface water as the main way of contamination with nitrates rather than smooth infiltration of water during the autumn–spring period. Irrespective of their use (for grazing or sown in crop rotation and used for forage), permanent grasses were an effective means of maintaining nitrate content in drainage and groundwater below the limit of 50 mg l^{-1} set up by the EU Nitrate Directive. Grasses in crop rotation can substantially reduce nitrogen leaching (Kutra, Aksomaitienė, 2003). Results of our experiments

Fig. 3. The lowest depth of groundwater in arable crop rotation, pasture and grassland

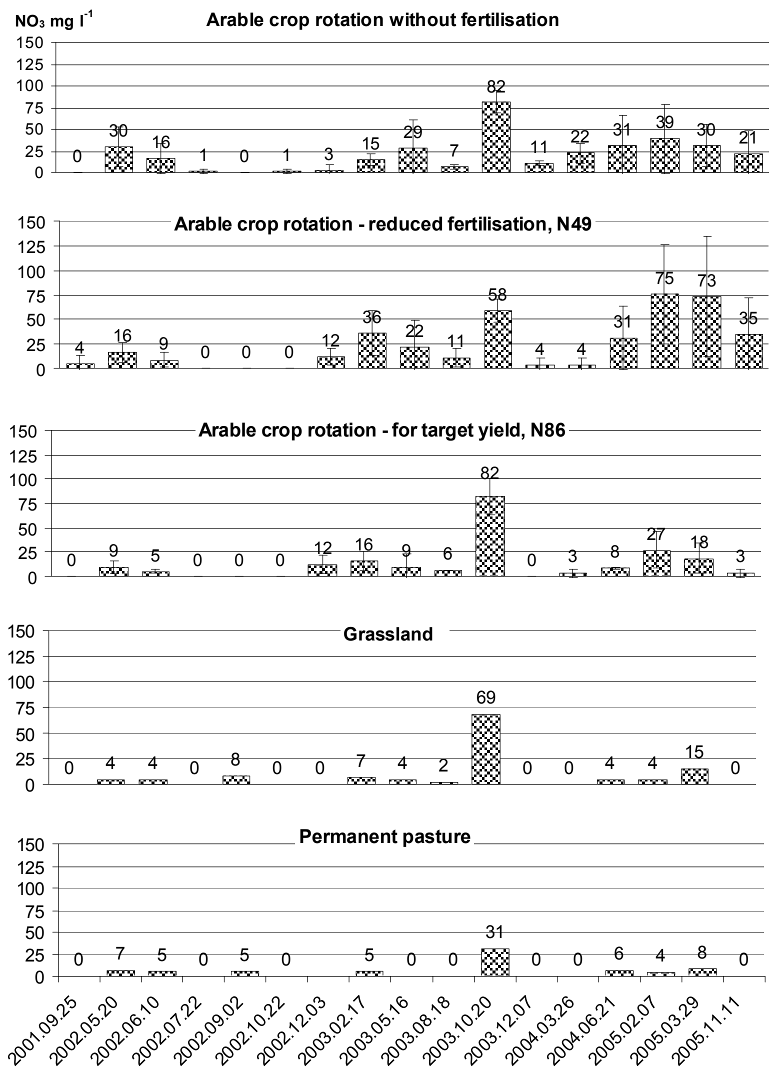


Fig. 4. Average groundwater nitrate concentration in arable land (under different levels of N fertilisation), grassland and pasture. Error bars are standard error

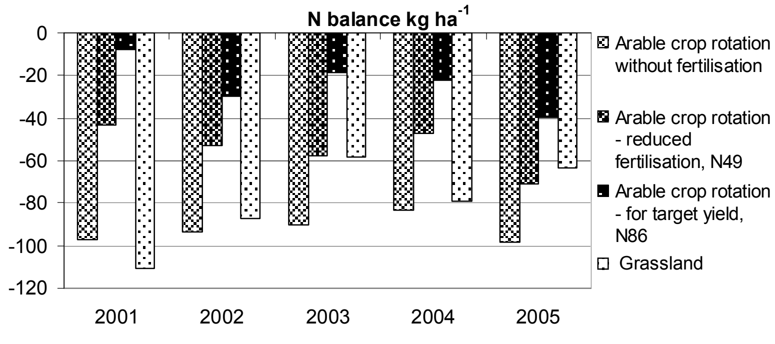


Fig. 5. Simplified nitrogen balance calculated as $N_{fertiliser} - N_{harvested}$ in arable land (under different levels of N fertilisation and grassland

were partly predetermined by the moderate level of grazing intensity in permanent grassland and withdrawal of N fertilisers from the grassland during the study. Under conditions of a high density of livestock and especially in combination with a high level of nitrogen fertilisation, the concentrations of nitrates in drainage and groundwater from grassland can be high (Kylimar et al., in press). In the arable crop rotation, the risk of exceeding the limit of 50 mg l^{-1} was considerable; however, differences among the drainage systems with a different intensity of N fertilisation were insignificant. Nevertheless, a four-year average value shows an increasing tendency in nitrate concentration in relation to a high N fertilisation level: the concentration of nitrates in drainage water from a crop rotation which received 49 kg N ha^{-1} was by 7.5% and which received 86 kg N ha^{-1} by 11.8% higher than without N fertilisers. For groundwater, no connection with nitrogen fertilisation levels was found, either. Instead, some individual boreholes demonstrated distinctive levels of nitrates during the whole four-year period. This is not very surprising because it is well known that a number of factors such as subsurface hydrology may strongly influence surface runoff and nitrate fluxes from agricultural lands even when soil properties, yield distributions and climate are similar (Daughtry et al., 2001). The rates of N fertilisers for arable crops in the most intensive N application system were calculated according to the needs of targeted yield using the parameters worked out at LIA on the basis of experiments performed under local conditions, so nitrogen surplus even in the most intensive N system was not produced. If the value of 150–200 kg ha^{-1} N fixed by clover (Lapinskas, 1998) is included, a slight nitrogen surplus (up to 40 kg ha^{-1}) will appear only in a crop rotation with the most intensive level of N fertilisation. Thus, the potential for leaching of nitrates because of the surplus of nitrogen balance was rather low. N leaching was not possible to predict if good agricultural practice was maintained (Salo, Turtola, 2006), but the potential for nitrate leaching during winter, arising from mineralization of the soil humus when soils are bare or crop demand is low, in fertile soils is high. So the land use and management measures directed to reduce the levels of nitrates in drainage and groundwater below the drink-ing water guideline value of 50 mg l^{-1} must combine the shortening of periods with bare soil and balanced fertilisation required for target yield.

CONCLUSIONS

Permanent pasture managed without nitrogen fertilisers and with a medium grazing intensity was an effective object for securing nitrate content in drainage and upper groundwater below the quid line value of 50 mg l^{-1} set by the EU Drinking Water Directive. Permanent grass leys established in arable soils of crop rotation and managed without nitrogen fertilisers after one year reduced the levels of nitrates to those of permanent pasture. In arable crop rotation soils, the risk of exceeding the limit of 50 mg l^{-1} was considerable, irrespective of the level of N fertilisation. The algorithms and program worked out at the LIA were able to ensure the N rates that were efficiently used to produce yield and no surplus of N balance in crop rotation.

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NITRATŲ KIEKIS GRUNTINIAME IR DRENAŽO VANDENYJE IŠ ILGALAIKĖS GANYKLOS, DAUGIAMEČIO ŽOLYNO IR SĖJOMAINOS ARIAMOJE DIRVOJE

S a n t r a u k a

Tausojančios žemdirbystės ir azoto trąšų panaudojimo sistemos turi būti plėtojamos taip, kad užtikrintų konkurencingą augalininkystę ir sumažintų paviršinių ir gruntinių vandenų taršą nitratais. Lietuvos žemdirbystės institute 2001–2005 metais bandymų poligone, turinčiame 11 atskirų drenažo sistemų, vykdyti tyrimai siekiant ištirti žemės naudojimo būdo ir tręšimo azotu lygio įtaką nitratų koncentracijai drenažiniuose ir gruntiniuose vandenyse. Netręšiama azoto trąšomis ir ganoma vidutiniu intensyvumu daugiametė ganykla užtikrino mažesnį nei nustatytą Europos geriamo vandens direktyvoje nitratų lygį drenažo ir gruntiniame vandenyje iki 50 mg l^{-1}. Nuolatinis žolynas, pasėtas ariamoje žemėje ir netręšiamas azoto trąšomis, jau po vienerių metų sumažino nitratų koncentraciją iki daugiametės ganyklos lygio. Sėjomainoje ariamoje žemėje rizika viršyti 50 mg l^{-1} buvo ženkli ir nepriklausė nuo tręšimo azoto trąšomis lygio. Lietuvos žemdirbystės institute parengti algoritmai ir kompiuterinė programa leido numatyti tokias N normas, kad azotas efektyviai didino derlių ir azoto balanso pertekliaus sėjomainoje nesusidarė.

Raktažodžiai: vandens kokybė, azotas, tręšimas, balansas