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ORIGINAL ARTICLE

Agricultural drainage in Lithuania: a review of practices and environmental effects

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In Lithuania, artificial drainage is a common agricultural practice. The country remains one of the most extensively drained in the world. The total drained land area occupies 47% of the country's land area and 86% of the agricultural land area, of which 87% is tile-drained. Although the introduction of drainage has improved the quality of agricultural land, the benefits of drainage are associated with many changes in the local environment. Therefore, a review is presented of the results from various investigations and research studies conducted in Lithuania which have reported the historical and economic aspects of the development of agricultural drainage as well as its environmental effects on landscape structure, local hydrology and nutrient losses in the soil. Temporal changes in drainage run-off since the 1970s are also discussed. Furthermore, positive bidirectional effects of natural processes in and around open drain ditches on both environment and practice are highlighted which show the possibility of fostering them intentionally.

Keywords: agricultural drainage; drainage run-off; environmental effects; Lithuania; nutrient leaching

Introduction

Lithuania covers a total area of 65.3×10^3 km^2 and is situated along the south-eastern shore of the Baltic Sea (Figure 1). The country's climate is temperate, determined by the macro-processes in the atmosphere and local geographical factors. The spatial variations in the long-term annual averages of the main climatic characteristics are as follows: solar radiation 2298–3185 MJ m^{-2}; air temperature 6.1°C–8.0°C; precipitation 560–910 mm; and evapotranspiration 500–580 mm. There are 30,000 streams longer than 0.25 km. The average density of the stream network is 0.99 km km^{-2}. Run-off coefficient (defined as the ratio between average annual run-off and precipitation) is 0.32. Annual specific discharge (rate of discharge per unit of area) within the country varies from 5.0 to 12.0 L s^{-1} km^{-2} (Galvonaitė et al. 2013). The atmospheric supply of water, along with the rather plain topography and low permeability of prevailing glacial tills, has resulted in more than 33.7×10^3 km^2 of soils suffering from excess moisture (Aleknavičius 1989).

To deal with the excess moisture, drainage of agricultural land in Lithuania started at the end of the nineteenth century. According to Čeičys et al. (1970), by the end of Second World War, 487.2×10^3 ha of land had been drained (7.5% of the whole area of the country) and 19,437 km of ditches dug. By then, it was primarily shallow ditches which drained the agricultural land, with only a small area of about 12×10^3 ha drained by subsurface drainage. This situation continued until the 1960s, when the lands were mostly drained by open drains. The shallow 2–3 m wide ditches excavated 20–50 m apart removed the excess soil moisture. Their efficiency was low, but the method was cheap and the only available measure at that time.

The shallow drain ditches significantly enhanced the overall density of ditches per unit of drained area

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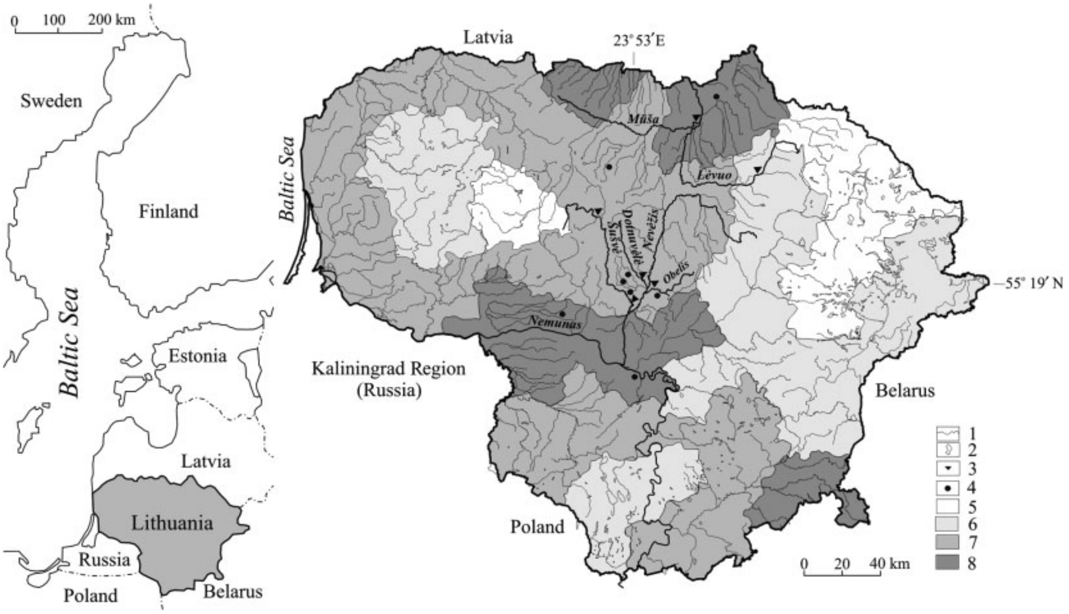

Figure 1. Map of Lithuania, showing the location of the studied rivers and drainage research sites mentioned in the analysis. (Symbols in the legend: 1 – rivers and streams; 2 – lakes; 3 – river water monitoring site; 4 – drainage water monitoring site; 5–8 – percentage distribution of drained agricultural area: 5 – below 65%; 6 – 65%–75%; 7 – 75%–85%; 8 – over 85%).

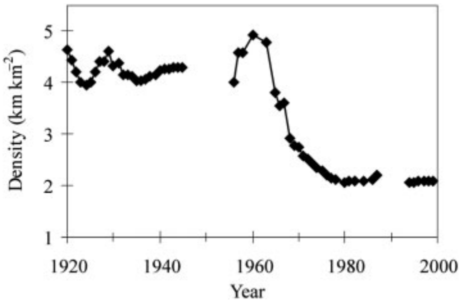

Figure 2. Overall ditch density in drained area (Povilaitis 2001).

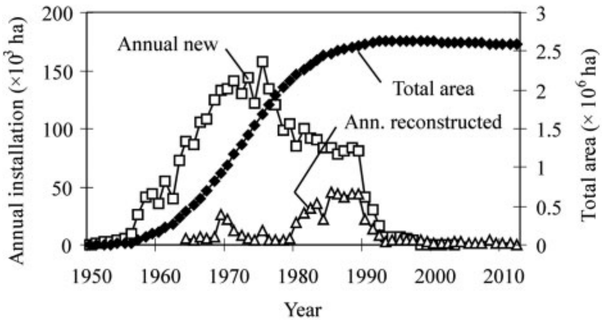

Figure 3. The dynamics of the installation of subsurface drainage systems (Povilaitis et al. 2011).

by an average of up to 4.0–4.5 km km^{-2} (Figure 2). The density of open drains began to decrease drastically when, in the sixth through ninth decades, the technology of tile pipe production was developed. This meant that the areas annually drained by means of subsurface drainage increased significantly. Surface drainage systems began to be replaced by subsurface drainage. The total area drained by subsurface drainage added up to 2620.5 × 10^3 ha, or about 72% of the total agricultural land area, and most drainage works were completed during this period.

Subsequently, the draining of land almost ceased (Figure 3). The density of open ditches dropped to about 2.1 km km^{-2}. These open ditches, totalling 63,400 km or 82.6% of the entire hydrographical network in Lithuania, are an integral part of every current drainage system. About 15% of them have been excavated along the edges of forests to protect farm fields from spring thaw waters. The remaining 85% of these open ditches, about 53,000 km, have been designed only to collect and divert the water from subsurface drainage systems. Most of these ditches, about 46,000 km (87%), are regulated natural streams of the first to the fourth order (Jablonskis 2001).

During the sixth through ninth decades, 1603.7 × 10^3 km of subsurface drainage lines were installed; some 270.3 × 10^3 km of these lines comprised subsurface drain collectors and the remaining ones, 1333.4 × 10^3 km, comprised lateral drains. The subsurface drainage in Lithuania was largely built by applying tile pipes. Diameters of the tile pipes ranged from 4.0 to 7.5 cm for lateral drains and from 7.5 to 25.0 cm for collectors. The diameters of drain collectors were even larger if the drainage system took in an extremely large area of several tens or hundreds of hectares. The pipes of these large drain collectors were made of concrete, ferro-concrete or asbestos. The drain spacing, depending primarily on soil texture and longitudinal gradient, ranged between 16 and 30 m and had a depth of 0.9–1.2 m. The drain line's longitudinal gradients were 0.004–0.01 $m \cdot m^{-1}$. Plastic (polythene) pipes have only been used since 1986. Currently, plastic pipes are the only pipes used for drainage purposes in Lithuania. Depending on local soil and climate conditions, the average annual specific subsurface drainage discharge in different parts of the country ranges from 4.0 to 6.0 $L\ s^{-1}\ km^{-2}$.

Throughout the history of land drainage, the overall drained area (ditches plus tile drains) totalled 3021.4×10^3 ha, or 87% of the agricultural land area. Of the Baltic and Nordic countries, Lithuania, with a tile-drained area of 2620.5×10^3 ha, spearheaded the installation of subsurface drainage: in Latvia, about 1500×10^3 ha is tile-drained; in Estonia, 700×10^3 ha; in Sweden, 1200×10^3 ha; in Denmark, 1400×10^3 ha; and in Finland, 1000×10^3 ha (Povilaitis et al. 2011). Agricultural drainage has enabled radically improved soil cultivation and plant growth conditions. Therefore, in order to improve information about the drained land and its state since 1996, the GIS-based Land Reclamation Database, on a scale of 1:10,000, was generated in Lithuania (Povilaitis 2002). In some regions within the country, this digital information is available on a scale of 1:2000.

However, during the period of enhanced draining activity from 1955 to 1995, some questionable measures were taken. For example, nearly 50×10^3 ha of wetlands was destroyed. Also, in 1966, there were still 280,000 individual farmsteads surrounded by various elements of landscape: meadows and pastures, shrubs, fruit trees and kitchen gardens, etc. Unfortunately, such a large number of farmsteads 'impeded' drainage works, and more than 115,000 of those farmsteads were evicted into settlements until 1990 (Povilaitis 2001).

Furthermore, all abiotic and biotic varieties of the former stream channel conditions and their original riparian zones were destroyed when the streams were regulated. The regulated streams were straightened, deepened and trapezium-shaped with narrow (1 m width) grassy buffer strips. Drainage activities significantly changed the structure of the landscape: expanded fields were practical for farming but open to soil erosion and deflation. The landscape lost the patchiness and heterogeneity which, according to Forman (1995), ensured the landscape's resistance to disturbance.

In the 1990s, it was found that the accelerated and enhanced lessening of the water table by subsurface drains and the expansion of arable areas, as well as the regulation of streams and destruction of the riparian zones, had managed to cause some damage to rivers and soil cover (Pauliukevičius & Juodis 1987; Račinskas & Beliauskas 1987; Vaitkevičius 1989; Zalakevicius 2001). On the other hand, drainage systems in Lithuania are ageing. Their average lifetime is something over 40 years. This means that about 56% of subsurface drains and 76% of ditches are suffering from deterioration today. Intensive land drainage has also raised issues regarding its impact on local hydrology and water quality.

The purpose of this paper is to present a short review of the research findings on agricultural drainage in Lithuania, with specific reference to its effects on local hydrology, nutrient losses from soil and measures aimed at reducing negative impacts.

Results and discussion

Economic benefit of land drainage

Agricultural drainage installed for soil water control plays a major role in the development of plant and animal production in Lithuania. In 2013, the total asset value of drainage structures in the country was 2.67 billion Litas (1 Litas = 0.289 Euros; Reclaimed land 2014).

Land productivity in Lithuania is ranked by conventional points, which vary from 25 to over 50. Therefore, land drainage enables the country to grade upgrade land productivity, from 7.2 to 21.4 extra points (Figure 4a; Buivydaitė et al. 1999). Cambisols prevailing in the Middle Lithuanian Lowland are particularly fertile. This region is superior to other regions in the country. According to the analysis conducted at the Lithuanian Institute of Agrarian Economics (Agriculture in Lithuania 2000), marketable plant growing is profitable only in regions where agricultural land productivity exceeds the mean value of the whole country (i.e. 39.1 points). Depending on land productivity, the income from crop cultivation in different regions differs 3.5 times (calculated for 1 ha of agricultural land). Comparison of the income of farmers with rich and poor soils showed that they differ by 1.5 times (Figure 4b). Statistical analysis by Šaulys and Lukianas (2003) showed a strong dependence on the income of farms from crop cultivation on drained land.

Issues associated with the economic efficiency of land drainage in Lithuania were analysed by a number of investigators (Buožis & Bastienė 1998; Katkevičius et al. 1998; Bastienė & Gurklys 2007). It was determined that the economic benefit gained from drained agricultural land varies from none up

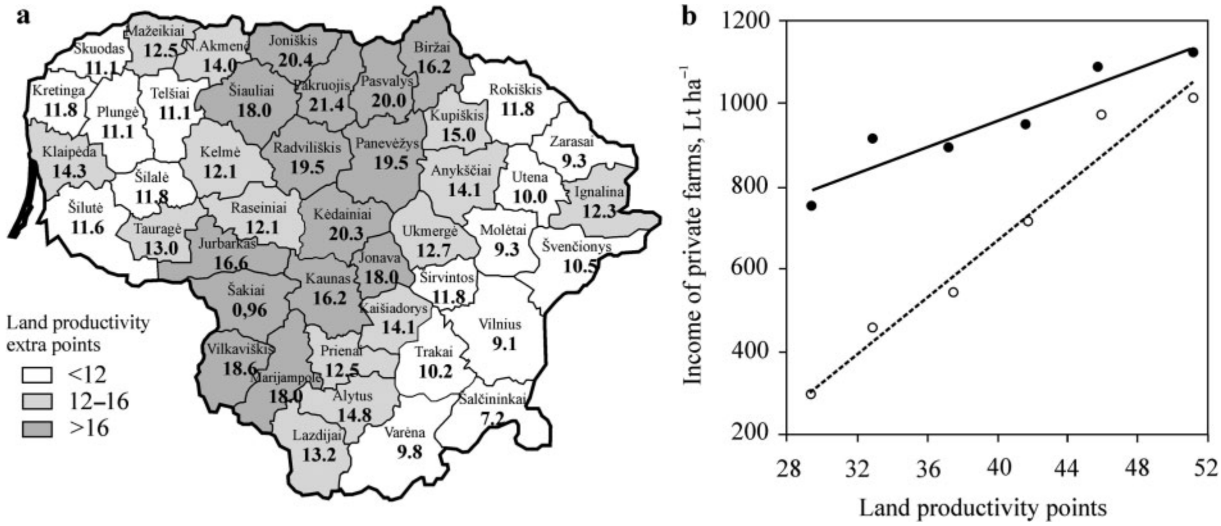

Figure 4. Land productivity extra points gained due to drainage in different Lithuanian administrative districts (a); and the relationship between common income (black dots) and the income from crop cultivation (hollow dots) against land productivity points (b).

to 413 Litas (120 Euros) for one productivity point. According to the dissimilarity of the profit gained from agricultural activity, the whole territory can be divided into four zones (Figure 5).

Currently, one of the most urgent problems in Lithuanian agriculture is the repair of land drainage systems. Because of the lack of financial resources, the state is unable to provide sufficient financing for the maintenance of such a large quantity of drainage structures. For this reason, some of them have been lost. Consequently, the area of inefficiently functioning subsurface drainage has significantly increased, up to 250,000 ha, or about 9.5% (Reclaimed land 2014). Legally, about 97% of open drains and 30% of subsurface drains remain under the ownership of the state, and ownership of subsurface drains with a pipe diameter of less than 12.5 cm was transferred to private landowners. Local municipalities are responsible for the maintenance of state-owned drainage systems.

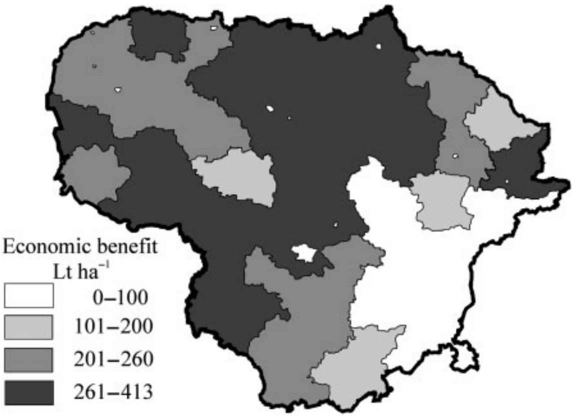

Figure 5. Zones of economic benefit due to land drainage.

Hydrological effect of land drainage

It is well-known that along with land-use changes the presence of drainage affects the general environment and to some extent the pattern of flow in streams. However, various hydrologic studies conducted in Lithuania (Lukianienė 1973; Macevičius & Lukianienė 1975; Marčėnas 1991; Dumbrauskas & Larsson 1993; Juozapaitis & Zelionkienė 1997; Dumbrauskas et al. 1998; Ruminaitė 2010) have produced very controversial results.

This has shown that the effects of agricultural drainage on downstream hydrology are still undetermined. Most hydrologic phenomena have high interannual variability. Therefore, changes in the amount of precipitation associated with cyclic weather patterns and the complexity of natural factors can mask the effects of land drainage (Hirsch et al. 1990; Robinson 1990; Baker et al. 2004; Matteau et al. 2009; Bormann 2010; Jay & Naik 2011). The cumulative impacts of natural factors and human-made alterations to the flow regime may go unnoticed because they often occur gradually. Once the hydrologic impact is noticed, it is usually difficult to determine the relative importance of the different causal factors. In order to solve this problem, Povilaitis (2014, in press) attempted to apply multivariate statistical analysis methods (e.g. canonical correlation analysis).

The mean daily flow data from the six monitoring sites in the Mūša, Dotnuvėlė, Obelis, Lėvuo and Šušvė Rivers (see Figure 1), with the catchment area varying from 159 to 2280 km^2 between 1940 and 1990, were used. The Indicators of Hydrologic Alteration (IHA) method proposed by Richter et al. (1996), which includes the parameters of flow magnitude, frequency, duration, timing and rate of change (flashiness), was applied. In total, 20 flow variables (dependent variables) were analysed, together with their ranges. The independent variables that were selected comprise (1) the hydrothermic index (defined as a function of the annual amount of precipitation and the sum of the mean daily air temperatures); (2) the sum of positive January–March daily air temperatures; (3) the catchment size (converted into a natural logarithm); (4) the proportion of sandy soil and (5) the dynamics of the total drained land area in each river catchment. All of the independent variables were subsequently correlated with the 20 hydrologic variables according to the canonical correlation analysis (Ouarda et al. 2001; Rencher 2002).

The results obtained confirmed the dominant role of weather upon streamflow (i.e. the annual hydrothermic index appeared to be the primary factor determining the variability of most hydrologic variables). Concerning the hydrological effects of tile drainage, it was found that drainage alters the time and frequency of high flows the most, i.e. the extent of tile drainage in a river catchment led to a longer duration of high pulses (defined as a daily mean flow that rises above the 75th percentile of all daily values), as well as a later occurrence of annual peaks. In addition, it showed a link to the decreasing number of low pulses (daily mean flows that drop below the 25th percentile of all daily values). The extended duration of high pulses, along with the lag in the occurrence of annual peaks, can be attributed to the ‘sponge’ effect of drainage as described by Skaggs et al. (1994). Drainage decreases the water table, thus increasing the water storage capacity (Augeard et al. 2005) by creating a larger volume for water infiltration with subsequently lower evapotranspiration (Van den Eertwegh et al. 2006). By changing the flow pathways from the surface to deeper flows for drains, the travel time is increased. Consequently, this extends the duration of high pulses and increases the lag times to peaks.

The decreasing number of low pulses suggests that an efficient hydrological connectivity with the groundwater in the river catchment may exist through tile drainage. This may occur because the greater depth of tile drains provides a deeper outlet for shallow groundwater drainage. A larger groundwater inflow may also contribute by means of deepened stretches of canalised streams and newly dug ditches collecting water from subsurface drains.

Temporal changes in drainage run-off

Today, global warming is a major and controversial issue. It affects many aspects of life. Alterations to the natural environment caused by global climate change have also been noticed in Lithuania. An increase of 0.7°C–1.0°C in average annual air temperature from 1991 to 2006 was detected compared with the average annual air temperature from 1961 to 1990 (Bukantis et al. 2008). Air temperature is expected to increase by 1.0°C–1.7°C for the period 2011–2040; 2.0°C–3.4°C for 2041–2070 and 2.7°C–5.3°C for 2071–2100. Precipitation is expected to increase from 1.6% to 2.7% for the period 2011–2040; from 0.3% to 6.6% for 2041–2070 and from 3.6% to 7.9% for 2071–2100. Seasonal variations are expected to lead to increased precipitation during the winter (17%–53%) and spring (4.1%–30.6%) and decreased during the summer (5.5%) and autumn (2.7%). It is expected that the annual river run-off will decrease, but, importantly, run-off during the winter period is expected to increase. These predictions are based on the ECHAM5 and HadCM3 Global Climate models and the A1B, A2, B1 greenhouse gas emission scenarios (Kriaučiūnienė et al. 2008; Jakimavičius & Kriaučiūnienė 2013).

As 87% of agricultural land area in Lithuania is tile-drained, agricultural drainage has a large impact on the soil-water balance. An analysis of the seasonal values over the last four decades (1969–2009) identified an upward trend in precipitation amounts in cold seasons (November–March) and a downward trend in warm seasons (April–October). Furthermore, statistically significant ($p < 0.05$) increasing trends of tile-drainage run-off during the winter (December–February) and slightly increasing air temperature during the spring (March–May) were detected (see Figure 6; Miseckaitė 2010; Miseckaite & Gurklys 2011).

For Lithuanian conditions, the potential impact of climate change is associated with alterations in the precipitation pattern turning from snowfall to rainfall (Rimkus et al. 2007). As a result, tile-drainage run-off volume tends to increase in the winter months. These peculiarities were observed in an analysis of data from 1969 to 2009 from the measurements conducted at five field-scale research sites (each area $A = 0.44–0.45$ ha; tiles installed at a depth of 0.80–1.40 m with drain spacing of 12–18 m) in the Middle Lithuanian Lowland (54°52′46 N, 23°51′30 E) on calcar-hypogleyic luvisol with sandy loam in the top layer and loam in the deeper layers.

Similar results were obtained from the study area (56°11′ N, 24 32′ E) in glacial lacustrine clay and clay loam soil in the North Lithuanian karst zone. The mean air temperature and precipitation from

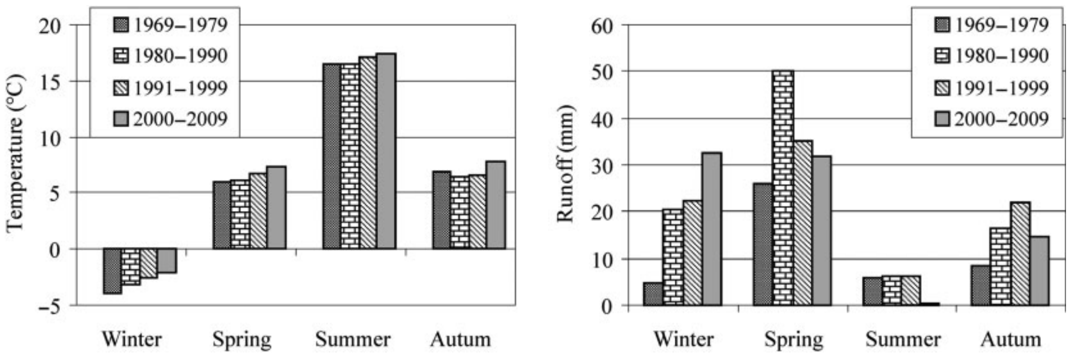

Figure 6. Seasonal distribution of mean air temperature (left) and tile-drainage run-off (right) from 1969 to 2009.

1988 to 1999 exceeded the corresponding data from 1976 to 1987 by 1.3°C and 34 mm, respectively (Rudzianskaite 2011). A significant increase in air temperature was observed in January and February (4.8°C). For this reason, a 3.3 times higher drainage run-off volume was observed in the winter (January–February) and a 1.6 times lower drainage run-off volume was observed in the spring (March–May) during the period 1988–1999, compared with the period 1976–1987. According to the Mann-Kendall test, statistically significant increasing trends in drainage run-off were detected in January and February. The increased run-off in the cold period and the overall changes in the drainage hydrological regime raise new questions regarding the solutions to environmental problems related to increased nutrient run-off.

Nutrient leaching via subsurface drainage

In has been widely reported that the use of organic and mineral fertilisers in intensive agricultural production leads to increased concentrations of nutrients in drainage run-off. The nutrients of greatest concern are nitrogen (N) and phosphorus (P) because drainage high in such substances can stimulate the eutrophication of the receiving water bodies (Hoorman et al. 2008). Numerous investigations conducted in Lithuania have shown that the typical concentrations of nitrate-N in drainage water can vary from 3 to 20 mg L^{-1} and the total P levels vary from 0.1 to 0.15 mg L^{-1} with annual losses ranging from 5 to 40 kg ha^{-1} for N and from 0.10 to 0.40 kg ha^{-1} for P.

N and P leaching from different cropping systems

The study carried out by Gužys and Petrokienė (2006) demonstrated that the leaching of nutrients through drainage systems is primarily influenced by the amount of precipitation and drainage run-off volume. It follows that meteorological conditions affect nutrient leaching more than do agricultural practices (Stålnacke & Bechmann 2002). However, other studies state that nutrient amounts transported via subsurface drainage systems are highly dependent on soil texture. According to Rimšelis and Šleinys (1996), N losses from sandy soils are often twice as high as losses from loam soils. Švedas et al. (2001) and Rudzianskaite and Miseviciene (2005) reported significant effects of the fertilisation rate on the NO_3–N concentration in drainage water: higher fertilisation leads to higher nitrate concentration. The field-scale (A = 0.34–0.38 ha) experiments conducted in the Middle Lithuanian Lowland (55° 18′N, 23°51′E) revealed that considerable amounts of N and P could be leached out via tile-drainage systems under different cropping systems (Table 1).

Table 1. Average annual leaching of nutrients (kg ha^{-1}) via drainage systems from various cropping systems[a] on gleic cambisols between 1995 and 2003 (Bučienė et al. 2007).

Year according to water abundance	CON		INTG		OB		GR		REF	
	NO_3–N	P_{tot}	NO_3–N	P_{tot}	NO_3–N	P_{tot}	NO_3–N	P_{tot}	NO_3–N	P_{tot}
Moderate	36.9	0.12	21.0	0.11	20.2	0.09	4.2	0.14	12.7	0.11
Dry	13.6	0.08	14.8	0.06	4.7	0.11	3.1	0.13	3.6	0.10
Wet	69.9	0.44	68.0	0.44	69.1	0.32	4.0	0.44	61.5	0.26

[a] CON – conventional (intensive) mineral fertilisation system, INTG – integrated application of mineral and organic fertilisers, OB – organic-biological crop management system with application of manure, GR – perennial grasses with moderate application of mineral fertilisers, REF – reference treatment (zero-input).

It is known that nutrient losses can significantly increase, primarily because of the irrational and unbalanced fertilisation rates of both mineral and organic fertilisers. According to Morkunas et al. (2005) and Misevičienė (2006), areas covered with unfertilised or moderately fertilised perennial grass ensure high nutrient uptake and fewer losses of nutrients via drainage systems than do the areas where row and grain crops are cultivated. Therefore, the changes in land use and the ploughing of permanent grass cover consequently contribute to increased nitrate losses from the soil (Povilaitis 2000; Mališauskas et al. 2005).

A detailed study aimed at evaluating the agro-ecological aspects of different intensity cropping systems was carried out in Lithuania on endocalcari-endohypogleyic cambisols (55°41′N, 2°30′E), where organic and intensive cropping systems were compared on five small-scale (A = 0.50 ha each) autonomous tile-drained fields. The results from this study have shown that organic agriculture has no essential advantage compared with intensive agriculture, considering the amount of nutrients leached via drainage systems and crop productivity (Šileika & Gužys 2003). Other field-scale investigations concluded that the amount of N leached via drainage is mostly determined by the N fertilisation and N balance in the agro-ecosystem (Gužys 2012). However, agricultural intensification demonstrated only a limited increase in the amount of P leached from the different cropping systems (Gužys 2002, 2013). No significant impact of the applied crop rotations on phosphates leaching via drainage systems was determined. P losses were found to be much more dependent on the soil texture and soil P and humus content (Bučienė et al. 2007).

N and P leaching via subsurface drainage in slurry applied fields

In Lithuania, livestock husbandry has always played a significant role in agriculture. Large numbers of animals are reared in relatively small areas, with consequent large-scale manure production. The disposal of manure is locally aggravated by the limited available land area. Even if the local land is theoretically capable of accommodating the applied manure, related pollution problems may be hard to eliminate.

Regular application of slurry has a negative impact on soil structure, causing soil compaction and reduced aeration (Aksomaitienė et al. 1978). Therefore, drainage efficiency decreases and problems with surface water quality occur (Aškinis et al. 1999). For this reason, research has concentrated on the impact of liquid manure application on crop yield, soil agrochemical properties and drainage water quality. Table 2 summarises the results from various field-scale studies conducted in the Nevėžis and Mūša River catchments (Middle Lithuania) where the quality of drainage water in relation to the different forms of manure application was investigated.

Livestock waste products in Lithuania are mostly used for application in fields used for perennial grass and feeding crops. However, sometimes vegetables and cereals are also irrigated with slurry. Therefore, an ecologically optimal slurry rate of 40 t ha^{-1} that can be used for irrigation of vegetables has been determined (Čižauskienė & Misevičienė 2001). It was also found that slurry application in the spring results in reduced losses of N and P by 17% and 36%, respectively, in comparison with application in autumn (Misevičienė 2002). Čižauskienė et al. (1998) and Misevičienė (2006, 2013) reported that the highest amounts of nutrients are leached out via drainage systems in the fields which receive slurry and liquid manure during the cold periods of the year when the soil is without crops and there is more rainfall.

The effect of tillage on N and P leaching

The feasibility of reduced tillage application in Lithuania was suggested as long ago as the 1950s (Vasinauskas 1950). However, subsequent field experiments demonstrated that conventional tillage produced the improved soil physical properties (the lowest bulk density, low penetration resistance, the highest air permeability and others) compared with reduced tillage and no-tillage methodologies (Feiza et al. 2010). Nevertheless, the application of the no-tillage practice could be what is needed to preserve soil moisture in the early stages of crop development, as well as to save energy resources and reduce the NO_3 losses from the soil (Baigys et al. 2007, 2011).

Research on the effects of the different tillage systems on the drainage flow and N and P leaching through drainage systems was conducted in the Middle Lithuanian Lowland (55°19′N, 23°51′E), where three different tillage treatments were compared (Baigys et al. 2007): conventional tillage (commonly used by farmers), late ploughing (used to reduce nutrient leaching) and reduced tillage (used to incorporate stubble and eliminate soil compaction). The experiment was carried out from 2005 to 2010 on tile-drained fields (A = 9.0 ha) with prevailing loam soil in the top layer and sandy loam in the subsoil. The results obtained showed that with reduced tillage treatment nitrate leaching through drainage systems in moderate years of water abundance was 25% lower and in dry years, 33% lower, compared with conventional tillage. The differences between the treatments were highest (3.8 and 13.5

Table 2. Studies reporting N and P leaching via subsurface drainage systems from fields receiving slurry and liquid manure.

Study site and period of study	Soil type and texture	Land use/Cropping system	Treatment	Fertilisation rate	Concentration in drainage water or leaching load		Citation
Josvainiai, Kėdainiai distr., A = 76 ha; 55°16′N; 23°49′E 1976–1977	*Endocalcari-endohypogleyic cambisols* Sandy loam	Perennial grasses	Slurry		N_{min} mg L^{-1}	P_{tot} mg L^{-1}	Aksomaitienė et al. (1978)
				240 kg N ha^{-1}	0.84	0.42	
				360 kg N ha^{-1}	1.30	0.95	
				480 kg N ha^{-1}	2.51	0.58	
				600 kg N ha^{-1}	3.89	0.99	
Juodkiškis, Kėdainiai distr., A = 5.5 ha; 55°16′N; 24°1′E 1990–1993	*Endocalcari-endohypogleyic cambisols* Sandy loam	Fodder crops:	Slurry		NO_3–N mg L^{-1}	PO_4–P mg L^{-1}	Stukonytė (1996)
		Barley + Vetch		$N_{160}P_{18}K_{114}$			
		Winter crop		$N_{80}P_9K_{57}$	10–14	0.04–0.11	
		Clover		$N_{160}P_{18}K_{114}$			
		Maize		$N_{200}P_{22}K_{142}$			
Juodkiškis, Kėdainiai distr., A = 6.46 ha; 55°17′N; 24°1′E 1990–1993	*Endocalcari-endohypogleyic cambisols* Sandy loam	Perennial grasses	Slurry Drain spacing:	Irrigation rate 200 × 3 m^3 ha^{-1}	N_{tot} mg L^{-1}	P_{tot} mg L^{-1}	Aškinis et al. (1999)
			20 m		13.9	0.34	
			15 m		9.8	0.12	
			10 m		9.9	0.13	
Juodkiškis, Kėdainiai distr., A = 1.62 ha; 55°17′N; 24°1′E 1995–1997	*Endocalcari-endohypogleyic cambisols* Sandy loam	Vegetables	Slurry + min. fertilisers		Kg Nha^{-1}	kg Pha^{-1}	Čizauskiene et al. (1998); Čižauskienė and Misevičienė (2001)
				40+$N_{60}P_{90}K_{120}$	18–45	0.10–0.39	
				80+$N_{60}P_{90}K_{120}$			
				120+$N_{60}P_{90}K_{120}$	21–33	0.14–0.27	
				$N_{60}P_{90}K_{120}$			
Juodkiškis, Kėdainiai distr., A = 4.86 ha;. 55°17′N; 24°1′E 1995–1998	*Endocalcari-endohypogleyic cambisols* Sandy loam		Mineral fertilisers Liquid manure		Kg Nha^{-1}	kg Pha^{-1}	Aškinis and Misevičienė (2003)
		Sugar beets		$N_{232}P_{75}K_{230}$	32.1	0.10	
		Barley + undersowing		$N_{44}P_{39}K_{63}$	6.2	0.04	
		Perennial grasses		$N_0P_0K_0$	11.0	0.05	
		Summer rape		$N_{66}P_{33}K_{108}$	26.3	0.10	
Juodkiškis, Kėdainiai distr., A = 1.62 ha; 55°17′N; 24°1′E 1999–2003	*Endocalcari-endohypogleyic cambisols* Sandy loam		Solid Manure		Kg Nha^{-1}	kg Pha^{-1}	Misevičienė (2004, 2005, 2006, 2007)
		Summer wheat + undersowing		$N_{62}P_{29}K_{103}$	8.6	0.01	
		Red clover		$N_{41}P_{16}K_{29}$	28.5	0.04	
		Red clover		$N_{74}P_{32}K_{80}$	4.8	0.03	
		Sugar beet		$N_{198}P_{74}K_{238}$	20.6	0.03	
		Summer rape		$N_{67}P_{56}K_{59}$	0	0	

Table 2 (*Continued*)

Study site and period of study	Soil type and texture	Land use/Cropping system	Treatment	Fertilisation rate	Concentration in drainage water or leaching load		Citation
					N_{tot} mg L^{-1}	P_{tot} mg L^{-1}	
Šukioniai, Pakruojis distr., *A* = 6.73 ha; 55°56′N;23°44′E 2008–2012	*Endocalcari cambisols* Sandy loam/loam	Maize for feeding	Solid manure	167 kg N ha^{-1} 28 kg P ha^{-1}	0.4–20	0.1–0.24	Misevičienė (2012, 2013)
'Pirmasis ūkis', Kėdainiai distr., *A* = 27.1 ha; 55°23′N; 23°49′E 2008–2012	*Endocalcari-epihypogleyi cambisols* Sandy loam	Maize for feeding	Solid manure	169 kg N ha^{-1} 29 kg P ha^{-1}	3.0–24	0.02–0.46	Misevičienė (2013)

kg ha^{-1} on average, respectively) in the wintertime. By investigating three cropping systems (arable, ryegrass and fallow), Gužys and Petrokienė (2008a, 2008b) also found that the highest inorganic N and P losses through the drainage systems were from fallow (42 and 0.09 kg ha^{-1}, respectively) and the lowest ones were from ryegrass (27 and 0.018 kg ha^{-1}, respectively).

Lime filter drainage

Various literature sources affirm that clayey soil treated with lime amendments could significantly prevent the migration of P (Rhoton & Bigham 2005; Murphy & Stevens 2010). Therefore, in order to investigate the effect of lime added to the trench backfill on subsurface drainage hydrology and its water quality, field-scale research was performed in the south-western part of Lithuania (55°18′N; 23°06′E) on orthi-haplic (LVh-or) and hapli-epihypogleyic luvisols (LVg-p-w-ha) with clay loam. The research site (*A* = 14.6 ha) was tile-drained in 1989. The tile pipes were installed at a depth of 1.1 m with drain spacing of 16–24 m and drain trench width of 0.5 m. Drain trench backfill was mixed with lime (0.6% CaO for soil mass). Shale ashes containing 16.8% of CaO were used as liming material. The optimal liming rate was adjusted to accommodate the content of clay in the soil (Šaulys & Bastienė 2006).

The obtained results demonstrated that there are significant differences between phosphate concentrations in conventional drainage (CD) outflow and treatments where lime is added to the trench backfill. In the water of CD, these concentrations appeared to be 2.8 times higher. The addition of 0.6% CaO for soil mass reduces the annual load of total P and phosphates by two and three times, respectively, compared with CD systems (Šaulys & Bastienė 2008). Also, it was found that the addition of lime in trench backfill leads to increased specific drainage discharge of 30%–50% because of the increased soil conductivity (Šaulys & Bastienė 2007). The data from the research site also revealed that the average lifetime of lime filter drainage (LFD) can exceed 20 years without any loss in treatment effect (Bastienė et al. 2011). Statistically significant differences ($p < 0.01$) confirmed that the lime admixture in heavy soils could considerably reduce P concentrations in drainage water. In the outflow of LFD, the average total P concentrations were 52.3% lower and the average PO_4–P concentrations were 68.7% lower than those in the outflow of CD. However, seasonal fluctuations in LFD effectiveness have been established: in the cold season (November–January), the total P concentrations were 2.3–2.7 times lower ($p < 0.01$) in the water of LFD than in the water of CD, whereas from February to May, the differences were less significant (1.5–2.0 times, $p < 0.05$). No significant differences have been established for June–October period. The results also indicated that PO_4–P concentrations in LFD treatments were significantly lower than those in CD in all months, with the exception of the June-October period, when the drainage usually does not function.

The results from the above-mentioned investigations revealed that, in heavy clay soils, P concentrations in LFD water do not respond either to the precipitation amount or to fluctuations of air temperature. This leads to the conclusion that the effectiveness of the lime addition does not depend on these meteorological factors and, in general, LFD positively affects the quality of drainage water and reduces the transport of P into the surface waters.

Water table management in controlled drainage

The required field drainability for agricultural production is not the same in all seasons of the year from a multi-year perspective. Although wetness is the major concern, weather conditions vary, so crops may also periodically suffer from drought stress. CD systems necessary to reduce waterlogging in the soil and to provide trafficability during wet periods can also limit soil water availability during the drier periods. Therefore, problems with drought on drained soils in many countries have resulted in a transition from CD methods to CWD (subirrigation) systems. In Lithuania, such drainage practices, with the exception of several research and demonstration sites, were not applied because of limitations related to the apportionment of suitable (flat) sites. Existing tile-drainage systems were not designed for drainage outflow control and retrofitting them is costly. According to various literature sources CWD is best suited to soils where ground surface slope does not exceed 2%. The most relevant slope is up to 0.3%. Morkūnas and Ramoška (2001) estimated that CWD practice in Lithuania is economically inexpedient on slopes greater than 1%.

An eight-year (2000–2007) field-scale study aimed at researching drainage control possibilities and their effectiveness from the perspective of soil hydrology and nutrient loss was carried out in the area intensively developed by agriculture in the Middle Lithuanian Lowland, with typical endocalcari-endohipogleyic cambisol soils and flat topography. A site (A = 5.4 ha; 55°19′N; 23°50′E) that had an existing subsurface water removal system operating as a CD was retrofitted for CWD (Morkūnas & Ramoška 2001). The control device installed at the drain outlet allowed the groundwater table to rise to 68 cm (maximum) above the tiles. The groundwater rise was adjusted to the site's topography (slope steepness 0.2%–0.9%) and the required groundwater depth for crop growth. Thus, the area impacted by the raised groundwater table covered 52% of the research site.

According to the study results, no statistically significant differences in nitrate concentrations were found in CD and CWD systems: the average annual concentration of NO_3–N in CWD water was only 5%–13% lower than in CD treatment (Ramoška et al. 2011). According to Evans et al. (1995), CWD can reduce nitrate-N concentrations in drainage outflow by up to 20%. The results from the Lithuanian study revealed that higher differences were detected during the growing season when the NO_3–N concentration decreased by 40% and 53% in CWD and CD treatments, respectively, compared with the winter–spring period (Ramoška et al. 2011). Other researchers (Lalonde et al. 1996) also indicated that during the growing season, when plants assimilate more nutrients, nitrate concentration in the outflow of freely operating drainage decreases by 44%. Simultaneously, in CWD, when the water level above the drains is 0.25 m and 0.50 m, nitrate concentration decreases by only 12% and 28%, respectively.

The reductions in nitrate-N loads determined in CWD systems are generally conditioned by the reduction in drain outflow (Ramoška & Morkūnas 2006). Wesström et al. (2003) reports that up to 70%–90% of drainage outflow could be retained by controlling the water level. Evans et al. (1995) stated that the total drainage outflow could be reduced by 30%, primarily because of the reduction in outflow volume. There is less water leaving the field through the drainpipe and therefore a smaller N load leaves the drain, even if there is no change in nitrate concentration. According to the above-mentioned study performed in Lithuania (Ramoška et al. 2011), when the authors controlled the groundwater level at the drain outlet, the duration of annual drainage flow was reduced by 40%–62%. At the same time, the flow volume itself was reduced by 25% and the nitrate load by 20%–28%, in comparison with the flow in CD systems. These indices are variable depending on the weather conditions: in dry years, the differences between treatments are higher and in wetter years lower.

In Lithuania, where subsurface drainage systems are adapted for water removal only, the maintenance of optimal groundwater tables for agricultural crops is complicated. However, through the installation of CWD systems, more effective use of rainfall, soil moisture storage and reductions in nutrient losses can be achieved. Other possibilities of reducing NO_3

in agricultural drainage, like the installation of wood-based denitrification bioreactors, show promise (Povilaitis et al. 2011). However, they have only been investigated in laboratory studies and need to be examined in practice.

Management of open drain ditches: Preconditions for re-naturalisation

Although landscape can be damaged by land drainage, it is also capable of recovery (i.e. rehabilitating itself). Numerous patterns show this capability, which involves, in various ways, geodynamic, hydrological, biological and geochemical processes leading to soil conservation, bed process stabilisation, biota diversity and water quality improvements. It can also reduce the costs of ditch maintenance while increasing biodiversity.

The investigations of the processes in and around the drainage ditches were mostly conducted in the Nevėžis River basin in the Middle Lithuanian Lowland, within a territory of about 2600 km^2, where 545 random stretches of ditches were surveyed (Lamsodis & Poškus 2006; Lamsodis, Morkūnas et al. 2006). The age of the ditches, their catchment areas and the longitudinal gradients of beds in the selected stretches ranged from 14 years to 52 years, 0.1–40.8 km^2 and 0.5% to 7.5%. The dominant soils were of different textures: from sand to clay loam, with some occurrences of peat soil.

The study results revealed that long-operating ditches with grassland herbs botanically close to those introduced on the newly constructed ditch slopes make up about 20% to 25% of all the ditches (Lamsodis & Poškus 2006). In the remaining ditches, the communities of other herbs and phorbs that are better able to grow on poor slope soils succeeded grassland herbs.

Vegetation occupied the beds of about 80% of ditches as well (Lamsodis & Poškus 2006). Many of these ditches have smaller catchments. The herbs stopped growing in the beds when the ditch catchments reached areas $A \pm \mathrm{SE} = 8.8 \pm 1.5$ km^2. If the catchment area is rather small, $A \pm \mathrm{SE} = 1.2 \pm 0.1$ km^2, and even willow shrubs (*Salix* spp. L.) are able to grow in the bed of the ditch (Lamsodis & Poškus 2006). The occurrence of woody vegetation appeared to be much more frequent on ditch slopes than in beds, close to 63% to 79% (Lamsodis 2002; Lamsodis & Poškus 2006). In total, there were 36 species belonging to 22 genera and 13 families found growing in the area (Lamsodis 2002). The diversity of woody species and the chance of finding them on the slopes of ditches increase gradually with the approach of ditches to forests (Lamsodis 2002). Actually, this increase, as well as the succession of herbaceous vegetation on ditch slopes, evidences the ditches' efforts to retrieve their functions as refuges and ecological corridors for plant and animal life in agro-landscapes (Lamsodis 2002; Lamsodis, Morkūnas et al. 2006).

The annual increase of sediment in the small ditches of low longitudinal gradient (<1‰) in sandy loam and loam soils was found to be about 3–4 cm (Šukys & Poškus 1998). They also found that the sediment accumulation increased when the ditch bed was grass-covered, but it was 1.4 to 2.7 times less if the ditch slopes exhibited woody vegetation. The researchers related this phenomenon to a choking effect of woody vegetation on bed grasses.

The more comprehensive investigations demonstrated that the ditch bed-silting rate averages 1.9 ± 0.1 cm year^{-1} (Lamsodis, Poškus et al. 2006). The rate abates up to 1.17 ± 0.18 cm year^{-1} when there is no grass cover on the ditch bed, but increases up to 2.02 ± 0.13 cm year^{-1} if the grassy cover is present (Lamsodis & Poškus 2006). If the slopes exhibit woody vegetation, the increase of density by one stem per sq. metre results in a decrease in the silting rate by about 0.6 cm (Figure 7).

The percentage of field erosion products and wintertime deflation products entering the ditch sediment make up 35% and 5% respectively (Lamsodis, Poškus et al. 2006). Račinskas (1983) estimated that almost all of the soil erosion products (66%–96%) tended to accumulate in riparian buffers, and these products contained more key nutrients (NPK), about 90%–95%, than did the surface run-off. The roots of woody vegetation and decaying fallen leaves and branches strengthened slopes, making them more resistant to slumps and erosion and improved the filtration properties of soil

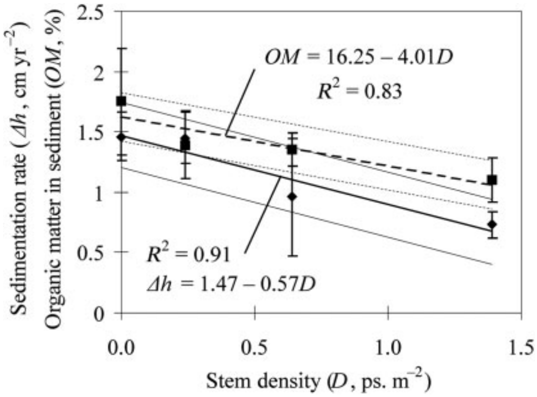

Figure 7. Dependence of sedimentation rate (Δh, diamonds) and sediment organic matter percentage (OM, squares) in ditches on the density of slope woody vegetation (D). 'Antennae' mark SE and thin solid and dotted lines mark the confidence bounds of regressions at p = 0.05 (Lamsodis, Morkūnas et al. 2006).

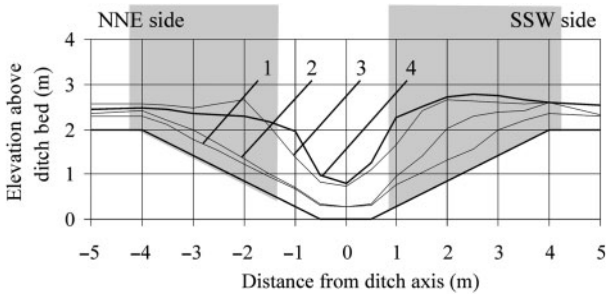

Figure 8. Snowdrift profiles formed in the Pakruostė-4 ditch in 1996. 1–4 – profiles measured on 22 January, 14 February and 6 and 20 March; grey fields mark rough spaces overgrown by trees; stem density averages 1.2 ps. m^{-2}; height of trees averages 5.4 m over upper edges of slopes (Vaikasas & Lamsodis 2007).

assisting in the interception of the dissolved pollutants (Danilov et al. 1980; Vought et al. 1994).

Usually, the ditches are clogged by snow. Woody vegetation on a ditch slope, as shown by Vaikasas and Lamsodis (2007), assisted with the interception of about 2.5 m^3 m^{-1} of snow in the riparian zone along the ditch. This contributed to the overgrown ditch preserving about 2.9 m^3 m^{-1} of ditch channel free of snow, although the winter was fairly snowy. The snow pack depth averaged 50 cm in the field and the probability equalled 3% (Figure 8). However, the next ditch of similar dimensions was snowed in completely.

Overgrown slopes not only preserve ditches from suspended sediment and chemical pollution but also assist in decreasing the concentrations of nutrients when water flows in sequence via non-overgrown and overgrown ditch stretches. The differences found in one study were not significant and did not exceed 4%–18% (Lamsodis, Morkūnas et al. 2006; Lamsodis et al. 2009). Nevertheless, they do indicate that ditch water quality does not get worse in the ambience of woody vegetation.

Unfortunately, woody vegetation growing on slopes determines the lower hydraulic capacity of the ditch. In current drainage systems, however, the depth of most ditches depends on the depth of subsurface collectors, which results in much deeper ditches with cross-section dimensions several times larger than those that would occur if they were determined by hydraulic calculations. It makes up the very reserve to compensate for the decrease in hydraulic capacity caused by woody vegetation. If a lack of hydraulic capacity still occurs, some measure can be taken: (1) all trees can be cut away from the bottom part of either slope; (2) dense woody vegetation cover can be thinned out on one of the entire slopes; (3) all woody vegetation can be cut down on one entire slope; and (4) all woody vegetation can simply be removed from both slopes (Rimkus et al. 2003).

In the spring of 1993, an experiment was conducted to overgrow the slopes of the Graisupis-1 ditch. Although there was no additional preparation of the slope's surface, and no staking, no watering, and no fertilisation were applied, about 70% of the 16 native species of trees planted produced roots and developed successfully. After eight years, they started to suppress and maintain the suppression of the herbaceous vegetation on the ditch bed over successive years (Figure 9a). The annual increase in sediment depth was reduced from 4.20 cm year^{-1} in 1994–1996 to 0.05–0.18 cm year^{-1} in 1997–2008. In 2013, after a 20-year growing period, the trees overgrew the ditch channel by about 10.5 m (max. 13.5 m) and currently resemble a field shelterbelt (Figure 9b), the wood volume of which is approximately 5.9 m^3 per 10 m of the ditch's length. Thus, the shelterbelt that has

Figure 9. Two views of the same stretch of Graisupis-1 ditch demonstrating: (a) suppressing effect of trees 12 years after planting on growth of bed vegetation, taken in 2005 (photo: V. Poškus); and (b) field shelterbelt formed over ditch channel over 16 years, taken in 2009 (photo: R. Lamsodis).

formed on the slopes of the Graisupis-1 ditch is able to suppress bed vegetation all over, markedly decrease sedimentation and make the slopes require no mowing.

The bidirectional character of the above-discussed effects leads not only to the environmental recovery of ditches as ecological corridors and refuges for native plant and animal life in an agro-landscape, as well as the preservation of soils from physical and chemical denudation and waters from pollution, but also the maintenance of their function to collect and discharge water from drainage systems (there is no need for slope mowing and no or a reduced need for sediment dragging; the cross-section of the ditch becomes more stable).

Summary

Artificial land drainage, which occupies 87% of the agricultural land area in Lithuania, has significantly altered the local environment. Although the economic benefit gained from drained agricultural land has substantially increased, this activity has led to a direct loss of habitat and biodiversity. Along with the concurrent land-use changes, such as the conversion of wetlands to agricultural land, the presence of drainage has, to some extent, affected the pattern of flow in streams and accelerated nutrient losses from the soil with subsequent enrichment of N and P in surface waters. Because of drainage, the natural vegetation area has rapidly decreased and large open spaces have appeared in the landscape. The patchiness and former mosaic land-use structure have been significantly lessened.

The introduction of drainage has altered the time and frequency of high stream flows in particular (i.e. the extent of tile drainage in a river catchment led to a longer duration of high pulses and the later occurrence of annual peaks, as well as showing a link to a decreasing number of low pulses). The extended duration of high pulses, along with the lag in the occurrence of annual peaks, can be attributed to the 'sponge' effect of drainage. The decreasing number of low pulses suggests that an efficient hydrological connectivity with the groundwater in the river catchment may exist through tile drainage.

Since the 1970s, upward trends in precipitation amounts during the cold season (November–March) and downward trends during the warm season (April–October) have been observed in Lithuania. The average seasonal spring, summer and autumn air temperatures have also tended to increase. For the winter season, this has caused alterations in the precipitation pattern turning from snowfall to rainfall. Altogether, it has resulted in increasing trends of drainage run-off in winter. Consequently, the increased run-off in the winter period raises new questions regarding how to find solutions to the problem related to increased nutrient run-off.

Numerous investigations have demonstrated that nutrient losses through drainage systems may considerably increase, primarily because of the irrational and unbalanced fertilisation rates. However, areas with perennial grass cover can ensure a higher nutrient uptake and fewer losses of nutrients via drainage systems than can areas with row and grain crops.

The changes in land use and ploughing of permanent grass cover, however, substantially contribute to increased nitrate losses from the soil. It has also been determined that organic agriculture has no essential advantage compared with intensive agriculture, considering the amount of nutrients leached via drainage systems. Furthermore, in the areas receiving increased slurry and liquid manure from big farms, slurry application in spring resulted in reduced losses of N and P by 17% and 36%, respectively, in comparison with the same application rates in autumn. The highest amounts of nutrients are leached out via drainage in the fields with slurry and liquid manure applications during cold periods of the year, when the soil is without crops, and there is more rainfall. In reduced tillage treatments, nitrate leaching through drainage systems is 25%–33% lower compared with conventional tillage. The largest differences between the treatments are observed during wintertime.

Experiments with clayey soil treatment with lime amendments revealed that it may significantly prevent P losses. Differences of up to three times were found between phosphate concentrations in CD outflow and the treatments where the lime of 0.6% CaO for soil mass was added to the trench backfill.

Although CWD as a water management practice is still not applied in Lithuania, in agricultural areas with a potentially high diffuse pollution load, it can be beneficial. A few research studies reveal that in CWD outflows NO_3–N concentrations are, on average, 5%–13% lower than in CD. The reduction in NO_3–N loads is achieved primarily because of the reduction in outflow volume. Therefore, under CWD conditions, the NO_3–N load is reduced by 20%–28% in comparison with the conditions under CD. These peculiarities are weather-dependent: in dry years, the differences between the treatments are higher, and in wetter years, lower.

Natural processes which occur in and around open ditches as well as the possibility of supporting these processes intentionally lead (1) to their environmental recovery as ecological corridors and refuges for native plant and animal life; (2) are able to assist in soil preservation from physical and chemical denudation and protect water from pollution; and (3) sustain the practical value of reducing the costs of maintaining the capacity of ditches to collect and discharge water.

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