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Phosphorus Load from Agricultural Land to the Baltic Sea

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Introduction

Phosphorus losses from agricultural land may occur as point sources, diffuse pollution or in an intermediate form (Table 9.1). Transport of phosphorus from agricultural land may occur by channel flow through the soil profile. Since large agricultural areas of the Nordic and Baltic regions are artificially drained, this pathway is most important being both a diffuse source from the entire field and a point source at the outlet of the drain system to the water course. The factors with the greatest impact on phosphorus losses are the hydrology of the site and intrinsic characteristics of the soil: the texture and chemistry of the entire soil profile down to drainage depth. However

local transport by more shallow water flows may also be important and in this case top soil characteristics down to the plough pan are most important.

Beside hydrology and soil chemical and physical processes, a range of other processes are involved in phosphorus turnover and mobilisation. Manure, mineral fertilisers, soil, crops, crop residues and weeds are all potential phosphorus sources for water transport of phosphorus. The mobilisation also occurs in several ways and for instance Lithuanian studies have demonstrated phosphorus in manure to be more mobile than in mineral fertiliser (Triposkaja, 2004; Marcinkonis and Karmaza, 2007).

Table 9.1. Losses of phosphorus by different water pathways in the agricultural landscape.

Sources	Water flows		Phosphorus
	Dependency on precipitation	Flow pattern	Concentration
Point sources			
Wastewater from single houses	Low	Partly episodic	High
Diffuse sources			
Surface water	High	Episodic	High
Groundwater	Low	Continuously	Low
Intermediate sources			
Tile drain water	High	Episodic	High/Low

FACT BOX 1

Phosphorus forms and transformations in soil and water

In the soil there are many phosphorus forms, both inorganic and organic. The organic forms are dominated by hexainositol phosphates, which are strongly adsorbed to solid or suspended soil particles. By water, phosphorus is also transported off in different forms, from large aggregates to fine clay particles and colloids, or in completely dissolved form. The first form is usually defined analytically as particulate bound phosphorus (PartP) and the last as dissolved reactive phosphorus (DRP). The proportion of DRP in agricultural water can vary between 9-90% from place to place and time to time. Organically bound phosphorus in drain water only constitutes a minor proportion, generally <10%. In spite of the latter fact, a large part of the recycling of phosphorus to agricultural land may occur through manure and crop residues.

FACT BOX 2

Characteristics of phosphorus losses from catchments

A characteristic of phosphorus losses from catchment areas is that 90% of losses can occur from 10% of the area and during 1% of the time, which has a strong impact on any prevention strategies introduced to mitigate the phosphorus loss. It means that measures to reduce losses should be site-specific and operational during the times of the year when phosphorus flows are high.

Phosphorus Losses from Arable Catchments

In the Baltic Sea drainage area, phosphorus losses from arable land are monitored in small agricultural catchments (see fact box 2). The total transport from such monitored catchments offers a relatively acceptable prediction of the diffuse phosphorus losses from arable land, since contributions from scattered households and non-arable land are estimated to be of minor quantitative importance (Figure 9.1). Several countries have problematic areas with high phosphorus losses from agricultural catchments, as well as areas with low losses (Figure 9.2). In Sweden the agricultural areas on the East Coast and the Östgöta Plain are of special concern, since phosphorus retention in streams, rivers, and lakes has been estimated to be very small and the majority of phosphorus transported from agricultural land is lost to the Baltic Sea Proper (Brandt et al., 2006).

Phosphorus Forms in Water and Soil Types

High concentrations of dissolved reactive phosphorus (DRP) (see fact box 1) in streams can derive from private wastewater systems, an effect that is usually more obvious in summer, when water flow is low. High concentrations of dissolved phosphorus can also be the result of desorption of phosphorus from the soil, especially at snowmelt and in connection with heavy rain. A further source is phosphorus from the actual plant material, especially if the plant cells have been damaged by e.g. frost.

In the Baltic area, there is great variation estimated in the contribution of drainage loss of total phosphorus. This, together with the wide variation in the proportion of dissolved phosphorus lost by drainage, indicates that

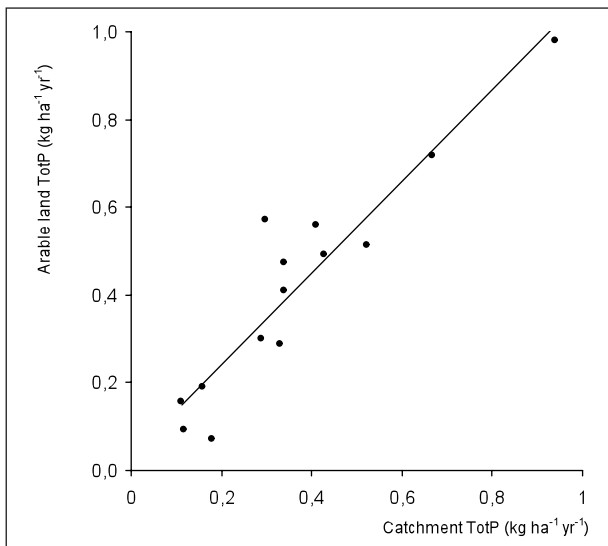


Figure 9.1. Contribution of diffuse losses of total phosphorus (TotP) from arable land compared with total transport from all sources in small agriculture-dominated catchments in Denmark, Estonia and Sweden. The figures represent annual averages for 1994-2006. The line represents a regression coefficient of 87%.

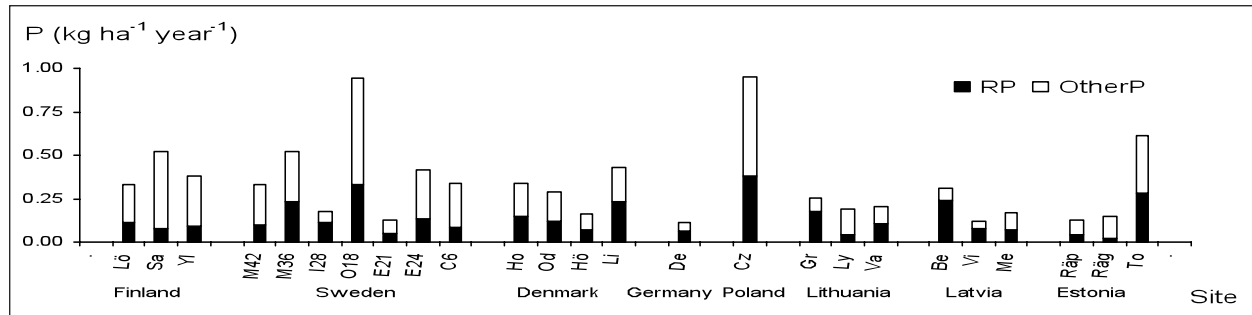


Figure 9.2. Average measured phosphorus losses: (usually dissolved) reactive phosphorus (RP) and other P (total phosphorus minus RP) ($\text{kg ha}^{-1} \text{yr}^{-1}$) from small agricultural catchments in countries bordering the Baltic Sea and Kattegat in 1994-2006 (or shorter periods). Germany and Poland are each represented by a single research catchment and six other countries by several monitored catchments (Own research by Barbro Ulén).

in some fields soil erosion causes a large influx, while in other fields leaching of dissolved reactive phosphorus is the main problem. Soil profiles with silt and clay generally have a high risk of erosion (Ulén and Jakobsson, 2005). Many Nordic and Baltic silt and clay soils are drained, which allows for good agricultural production. The drainage system can be an advantage if the aim is to achieve a low level of phosphorus leaching, since it contributes to more uniform and better infiltration. On the other hand, it means that drainage water can run directly to the watercourse. In situations with high concentrations of particulate phosphorus in the drainage water, the drainage system can therefore make an effective contribution towards carrying high concentrations of such phosphorus to recipient waters. Distinct silty soils are found along the Finnish and Swedish river valleys. Clay soils are mainly concentrated to the central part of Sweden and eastern Finland. The clay particles transported through the drains are partly in very fine colloidal form and this phospho-

rus can therefore be transported great distances (Ulén, 2004). In some areas with silt and clay soils, the subsoil has a very low infiltration capacity and the particles can be transported horizontally over the soil surface or above a dense plough pan (Lundekvam and Skøien, 1998). In contrast, soddy podsollic soils and podsoles are the main soil type in the Leningrad oblast (NW Russian), where the majority of soils have a sandy loam texture. Poland is predominantly a lowland. Central and northern parts have glacial deposits with both bolder clay and sand. About 52% of the Lithuanian relief is undulating hills where the soil is erodible. Here on very acid soils ($\text{pH} < 4.7$), the phosphorus content increased significantly when moderate rates of phosphorus mineral fertilisers were applied (17 P kg ha^{-1}). At higher pH (5.2-5.7 and 6.2-6.7), the

FACT BOX 3

Characteristic of phosphorus losses via drain water

In the Swedish part of the Baltic area, drainage losses via sub-surface drainage systems contribute 10-90% of total phosphorus losses by water. 22-86% of the total phosphorus lost from individual Swedish fields is in dissolved reactive form (DRP). The fields are situated in different parts of the country and are not affected by wastewater. (Johansson & Gustafson, 2008).

FACT BOX 4

Phosphorus sorption capacity in soils

Physically phosphorus may attach both on the outside and inside of the soil particles. It is usually impossible to separate the different processes and they may both be named sorption. Through desorption phosphorus is released back into the soil water. Important factors for the soil's ability to sorb phosphorus (sorption capacity) are the contents of aluminium and iron. Aluminium may exist as amorphous oxides without structure and also as hydroxides that may cover clay particles as a film. In contrast, iron oxides and iron hydroxides usually occur as clods.

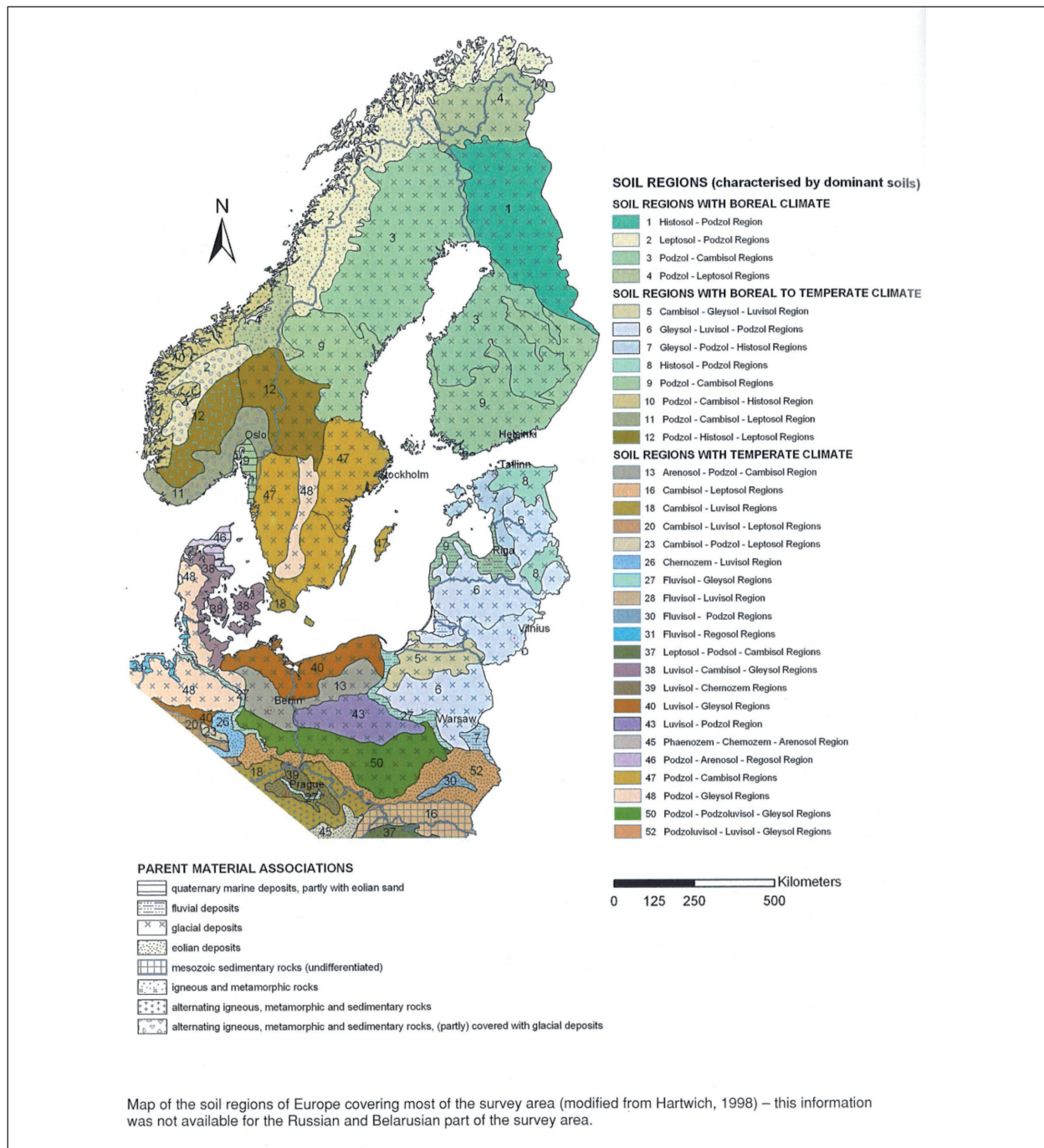


Figure 9.3. Map of soil regions and parental material in countries around the Baltic Sea, except for Russia and Belarus (Reinmann et al., 2003). Used with permission (BZ8-shub/jb) from Bundesanstalt für Geowissenschaften und Rohstoffe, © 2003 BGR, Hannover.

Reducing Nutrient Losses from Agriculture

Table 9.2. Agricultural phosphorus (P) balance in recent years (2000-2005) in countries bordering the Baltic Sea according to the soil surface gross method, mainly based on Csathó et al. (2007); average livestock density index in 2005 as livestock units per unit area utilised (LIU UUA⁻¹)(ESO, 2007); livestock units per unit area total arable land including pasture (LIU TAL⁻¹) (Henriksson, 2006 and internet sources) and actual animal density (AU) per capita (Isermann, 2007).

Country	Soil P balance kg P ha ⁻¹ year ⁻¹	LIU UUA ⁻¹ units ha ⁻¹	LIU TAL ⁻¹ units ha ⁻¹	LIUTAL per capita
Denmark	+13	1.75	0.92	0.85
Estonia	-4	0.38	0.3	0.24
Finland	+8	0.51	0.35	0.23
Germany	+4	1.08	<0.5*	0.23
Latvia	0	0.27	0.2	0.20
Lithuania	+3	0.46	0.2	0.34
Poland	+3	0.72	0.45	0.29
Russia NW	-10	-	0.2	-
Sweden	+2	0.57	0.40	0.21

* The federal state Mecklenburg-Vorpommern, which loads the Baltic Sea together with Schleswig-Holstein.

soil accumulated phosphorus only after higher loads of P fertilisation (51 P kg ha⁻¹) (Končius, 2007).

There are a variety of soils around the Baltic Sea. Figure 9.3 shows the soil regions and the parent material in the different countries neighbouring the Baltic Sea. The soils in northern Sweden are mainly Podsolis and Cambisols, while in central Sweden postglacial deposits of heavy clay dominate. In the Baltic States glacial tills and glaci-fluvial sediments are found, with a more or less clear gradient from the south to the north-west. Gleysols rich in humus are also quite common in central parts of Lithuania and Latvia (Reimann et al., 2003).

Use of Phosphorus Fertilisers and Livestock Density

From the beginning of the 1950s and up until the beginning of 1990s, large amounts of mineral phosphorus fertiliser were applied to farmland to increase yields. In addition, the soil received farmyard manure relatively often without any consideration being given to its value as a phosphorus fertiliser. After 1975, the amount of mineral fertiliser used in Sweden decreased rapidly. In Poland, the Baltic States and Russia, the use of mineral fertilisers decreased later, during the economically turbulent years in the early 1990s. In recent years the use of manure has decreased in several parts of the Baltic region with the decline in livestock farming. Total phosphorus fertilisation is now down to the same level as it was a hundred

years ago. Substantial surplus addition of phosphorus by fertilisers and manure is still taking place in Denmark and Finland (Table 9.2). In contrast Poland, the Baltic States and NW Russia have a low or even negative soil phosphorus balance. This is also the situation in Belarus, a country not bordering the Baltic Sea but covering a substantial part of the drainage area. According to EU statistics (ESO, 2007), livestock density is lower in all countries surrounding the Baltic Sea than in the EU as a whole. The only exception is Denmark. In the German federal states of Mecklenburg-Vorpommern and Schleswig-Holstein, which border the Baltic Sea, livestock density is also low, although Germany on average has a relatively high livestock density (Table 9.2).

Agronomic testing of the topsoil (see fact box 5) is used as a tool to decipher information on the phosphorus status of the soil which can be used when decreasing phosphorus sources and improving the phosphorus balance. Different extraction methods for soil phosphorus tests have been selected in the different countries (Table 9.3). This selection depends on soil pH and other criteria in order to interpret the results to the actual soil properties. Thus unifying the phosphorus test method all over the area may not prove very efficient. The acid extraction methods are generally adapted to the relatively acidic soils in many parts of the Nordic and Baltic region and may result in higher soil concentrations than the common

Table 9.3. Commonly used extraction methods for analysing plant-available phosphorus (P) in agricultural soil, average topsoil P concentration (Soil P) and average soil P class in Roman numerals (number of classes in brackets) in countries bordering the Baltic Sea. In the last column, average soil P values are related to fertiliser recommendations.

Country	Extraction and soil P method		Soil P (mg kg ⁻¹)	Soil P class	Soil P and fertilisation
Denmark	Sodium bicarbonate	P-Olsen	40	II (3)	Acceptable ^a
Estonia	Double lactate	P-DL *	50	III (5)	Acceptable ^b
Finland	Ammonium acetate	P-AAC	12 [§]	IV (7)	High ^c
Germany	Calcium lactate	P-CAL**	100 [#]	IV (5)	Acceptable ^d
Latvia	Double lactate	P-DL	60	III (5)	Acceptable ^b
Lithuania	Ammonium lactate	P-AL	125 [£]	III (4)	Acceptable ^e
Poland	Double lactate	P-DL	-	III (5)	Acceptable ^b
Russia NW	HCl-solution	P-HCl	20-40 ^{&}	-	Low ^f
Sweden	Ammonium lactate	P-AL	106	IV (5)	High ^g

*Since 2004, Mechlich 3 extraction has been implemented as the soil P method in the national survey

**The double lactate method is also used

§ Expressed as mg L⁻¹

The federal states Mecklenburg-Vorpommern and Schleswig-Holstein

£ Weight average in topsoil (Mažvila et al., 2005)

& Extraction with 0.2 N HCl. The results have been recalculated from P₂O₅

a At this level annual phosphorus is allowed to increase by up to 4 kg ha⁻¹

b Acceptable, but attention to negative soil balances also needed (Astover et al., 2006; Kopinski et al., 2006)

c At this level only low input is recommended in order to reach phosphorus balance

d Even above this level a surplus of 8.7 kg P ha⁻¹ yr⁻¹ is tolerated

e At this level the recommendation for phosphorus fertilisation rates is zero balance

f 25-60% of the soils have low P concentrations (< 10 mg kg⁻¹)

g Soil class III should be obtained

FACT BOX 5

Agronomic Phosphorus Soil Tests

Seven different extraction agents are used for an estimation of plant-available soil phosphorus concentrations in countries bordering the drainage basin of the Baltic Sea: Mechlich 3 extraction (Mechlich, 1984) in Estonia since 2004, sodium bicarbonate (Olsen et al., 1954) in Denmark, double lactate (Riehm, 1943) in Latvia and Poland, ammonium acetate in Finland (Vuorinen and Mäkitie, 1955), calcium lactate (Schüller, 1969) in Germany, HCl-solution (Kirsanov, 1935) in NW Russia, ammonium lactate according to Ivanov (1984) in Lithuania and according to Egnér et al. (1960) in Sweden. Some of the countries use two of these methods.

extraction methods used in southern and Western Europe (Neyrod and Lischer, 2003). This is due to some calcium-bound phosphorus being dissolved out of soils even if the soil has very low lime content. In particular, the HCl solution used for soil phosphorus tests in Russia is quite acid (pH 0.7).

Conversion factors between the analytical methods are site-specific and consequently no general comparisons between the different countries can be made. A measured soil phosphorus concentration may be attributed to several status and fertility classes depending on the practice of the country (Neyrod and Lischer, 2003). The mean value of P-AL in Sweden is 106 mg P per kg soil (Eriksson et al., 1997), which corresponds to the second highest (4) of five classes used to categorise available phosphorus in soil. Similarly average phosphorus status is regarded as high in many countries, although there is also concern about the long-term effects of imbalanced soil phosphorus applications (Table 9.3).

FACT BOX 6

Soil phosphorus balances

Soil phosphorus balance is commonly estimated as a measure of the soil surplus addition. The amounts of phosphorus added to the soil by fertilisers and manure, sometimes also by sewage sludge and atmospheric deposition are totalled and the removal by harvested products is subtracted. Direct relationships between soil phosphorus balances and phosphorus losses are seldom found, but in Finland models for different farming systems have been constructed.

Although a relationship may occasionally be found between the test and phosphorus loss by drainage water (Figure 9.4) this is not general. At low or medium discharge from experimental plots (Figure 9.4) the relationship was very weak (Bučienė et al., 2007). However, the agronomic tests may be more useful in combination with evaluations of the sorption capacity of the soil (see fact box 4). In contrast, the relationship between phosphorus accumulation zones and phosphorus sorption was found to be weak in Lithuanian soils loaded with dirty water or cleaning water from pigs. In addition there are a number of problems with using different types of soil tests. They do not take account of the way the fertiliser is applied, transport processes linking the field with surface water, or the sensitivity of the recipient waters.

Livestock-intensive Areas

In several countries in the Baltic area, there are production areas with intensive livestock farming. In Sweden, these are located e.g. in the south-east (Blekinge) and south-west (Halland). Current phosphorus fertilisation in Sweden is generating a surplus (see fact box) of on average 2 kg P ha⁻¹. In Poland, agriculture and the associated management of nutrients are very heterogeneous. Higher livestock densities are found in Wielkopolskie province west of Warsaw (3 LIU/UUA) and in Pomorskie province close to the shores of the Baltic Sea, where the soil phosphorus surplus is +8 kg ha⁻¹ (Kopinski et al., 2006). This surplus is similar to those in common livestock-intensive areas in other countries (Table 9.4), whereas in cereal growing areas without livestock there is often a deficit. In an experiment in Lithuania, 50 ha of a natural grass-

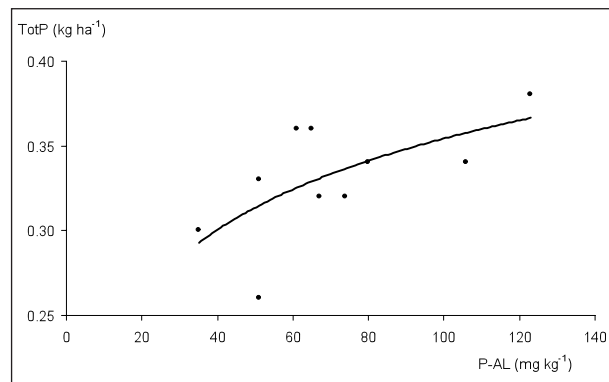


Figure 9.4. Relationship between leached amount of total phosphorus (TotP kg ha⁻¹) and concentration of soil available phosphorus extracted in ammonium-lactate (P-AL, mg kg soil⁻¹ according to Ivanov (1984)) from 10 experimental plots in Lithuania. This relationship was based on one year with high discharge (Bučienė et al., 2007). The logarithmic relationship has a coefficient of determination $R^2 = 39\%$.

land were irrigated by the slurry from pig units without taking into account the natural diversity (Marcinkonis and Karmaza, 2007). As a result of intensive anthropogenic influence and natural spatial variability of the area (0.36-18.9% organic C level), in these zones P-AL differed up to 26-fold (from 12-200 mg kg⁻¹) and the phosphorus sorption potential up to 53-fold (2-106 mg kg⁻¹). Generally in areas with extremely intensive livestock farming, soil build-up is still very high, at least 20 kg P ha⁻¹ yr⁻¹ in some of the countries.

Risk Assessments as an Abatement Strategy

Phosphorus flows from the soil are complex and difficult to predict. The relative importance of the mechanisms involved must be known, at least conceptually, before appropriate preventive measures can be selected. To focus prevention efforts, a so-called risk index for phosphorus has been drawn up in which each individual field is assessed (Djodjic and Bergström, 2005). The strategy can be to reduce the problem by either controlling the source of the losses or the actual transport. These two strategies can also be combined. For example, frequent attempts have been made to adjust fertilisation so that the phosphorus supplied corresponds to phosphorus removed with the harvested crop (control of source), while other attempts have focused on reducing the cause of erosion or on establishing buffer zones along waterways (primarily

control of transport). In areas of the USA, there are examples of strategies where the emphasis has been on one or other of these strategies (Baker and Richards, 2002). However, the concept of a risk index for phosphorus losses represents a combination of both strategies (Djordjic and Bergström, 2005). In the Baltic region, many countries have focused on controlling the source of the phosphorus losses but are also attempting to reduce the actual transport to some extent (Table 9.5).

Regulations

Regulations on stocking density and application of slurry usually take the form of laws specifying the permitted time of spreading (Table 9.5). In addition, slurry and fertilisers are not allowed to be applied to waterlogged or heavily snow-covered soils in most of the countries. In

Sweden the regulations are stricter in southern coastal areas and thus to a certain extent take account of the Baltic Sea Proper as the recipient. However, the regulations do not take the actual soil characteristics into account, although it is known that different soil textural classes have different soil hydrological properties and affect the dissolved/bound phosphorus relationship. In contrast the actual type of soil is considered in extension services. Spring ploughing of certain clay soils is not recommended, since they can be severely damaged by soil compaction. Finland has similar subsidies to Sweden (Table 9.5) but also provides subsidies for edge buffer zones with lime-sand and for controlled drainage. Lime filter drains and controlled drainage have also been subsidised in the past.

Table 9.4. Proportion of agricultural land in relation to total area of the country (%), amount of phosphorus (P) supplied (mean P to agricultural land in the form of manure, artificial fertiliser, sewage sludge and atmospheric deposition), mean soil P balance for all agricultural land in livestock-intensive (LI) areas in recent years, phosphorus losses, annual climate, annual number of days with snow cover and typical runoff in the countries Finland, Sweden, Poland and Lithuania. Source: Based on Antikainen et al., 2005 and other sources.

Country	Finland	Lithuania	Poland	Sweden
Agricultural area				
Total agricultural area (%)	8	43	58	8
Ploughed agricultural area (%)	4	29	40	6
Average P input				
Farmyard manure (kg P ha ⁻¹ yr ⁻¹)	6	3	6	7
Mineral fertiliser (kg P ha ⁻¹ yr ⁻¹)	13	3	8	5
Sewage sludge, seeds and tubers (kg P ha ⁻¹ yr ⁻¹)	-	0	0.6	0.2
Atmospheric deposition (kg P ha ⁻¹ yr ⁻¹)	0.2	0.3	-	0.3
Average total supply (kg P ha ⁻¹ yr ⁻¹)	20	6	15	13
Soil balance in relatively livestock-intensive areas				
Soil surplus LI areas (kg P ha ⁻¹ yr ⁻¹)	+10-15	+10-15	+8	+8
Phosphorus losses based on national publications				
Total phosphorus (kg P ha ⁻¹ yr ⁻¹)	0.8	0.3	0.2	0.4
Average total phosphorus concentration (mg L ⁻¹)	0.5	0.1	0.2	0.2
Proportion of dissolved phosphorus (%)	20-80	-	40 ^e	20-80 ^d
Climate/region				
	<i>Turku</i>	<i>Central Lithuania</i>	<i>Warsaw</i>	<i>Stockholm</i>
'Hardiness zone' (scale 1-11)	5	5	6	5-6
Days with snow cover (%)	28	19-29	17	20
Runoff from agricultural land (mm yr ⁻¹)	150	210	130	220

b Assuming 3% phosphorus in the sludge

c Maximum tolerated level

d Analysed after filtration

e Average

Reducing Nutrient Losses from Agriculture

Table 9.5. Methods to reduce phosphorus losses at farm level in Finland, Sweden, Poland and Lithuania.

Country	Finland	Sweden	Poland	Lithuania
Measures to reduce contributions at source				
Permissible livestock density (P kg ha ⁻¹)	25-50*	22	25-50*	25-50*
Required manure storage capacity (months)	12 ^a	6-10	4-6 ^f	6-8 ^b
Ban on spreading farmyard manure	15/10-15/4	1/1-15/2 ^c	1/12-28/2	1/12-1/4
Ban on spreading farmyard manure	>10% slopes	-	>10% slopes	-
Manure has to be incorporated:	always	within 4 hrs ^d	-	-
Ban on loading fertilisers and manure on waterlogged or snow-covered soils	X	-	-	X
Fertiliser planning based on:	Soil P tests	Soil P tests	-	Soil P tests
Subsidised measures to reduce phosphorus transport				
Decreased autumn ploughing	-	X ^e	-	-
Buffer zones/set-aside along watercourses	X	X	X ^g	X ^g
Establishment of wetland	X	X	-	-
Set-aside, EU fallow	(earlier)	X	-	-
Grassed water pathways	-	-	-	-
Catch crop	-	X ^e	-	-
Other subsidised measures	X ^b	-	-	-

* Based on the EU Nitrate Directive and a P/N ratio of 0.2-0.4 in stocking of cattle and pigs

a Less for grazing animals; b Precision farming, lime-sand filters, controlled drainage; c Refers to sensitive areas along the coast; d Only in nitrate-sensitive areas; e Catch crop only in southern Sweden and aimed at decreasing nitrogen leaching; f Only for big farms and in vulnerable zones, 6 months; g Legislation on buffer zones; h 8 months for pigs and poultry

Best Management Practice at Farm Level

Cultivation practices to optimise phosphorus utilisation in agriculture (Best Management Practice BMP) should aim to achieve efficient and safe use of any phosphorus applied in order to maintain satisfactory levels of yield, while keeping the phosphorus levels in the soil within acceptable limits. In other words, soil depletion or unacceptable accumulation should be avoided and the aim should instead be to achieve a balance between inflows and outflows in the system. Calculation of general farm phosphorus balances, appropriate storage of manure and additives for animal feed that increase uptake of phosphorus are practical measures at farm level.

Farm Phosphorus Balances

A good starting point for minimising phosphorus losses from agriculture is to have a farm system in balance, i.e. to have inflows and outflows of phosphorus balancing each other. A positive balance indicates that there is a risk of phosphorus accumulation in the system and environmental

impacts, while a negative balance indicates a risk of depletion and agronomic concerns. A significant and positive correlation between plant available P-AL content in topsoil and leaching of total P with drainage runoff has been demonstrated on Lithuanian Cambisols (Bučienė et al., 2007).

Manure Storage

There are a number of tried and tested measures to reduce phosphorus losses during storage and application of manure. The most important of these is to have sufficient storage capacity, which provides better opportunities for ensuring that the manure is spread when the risk of phosphorus losses to the environment is small. This also increases the value of manure as a source of nutrients. It requires a good manure container with a storage capacity corresponding to the amount of manure stored during periods when spreading is not permitted. The container dimensions should also be designed with regard to extreme weather conditions and other factors that can hamper manure spreading. In most countries bordering the Baltic Sea, the storage capacity for manure must be at least half a year

(Table 9.5). In practice, problems still arise in view of the fact that there are few opportunities during the year when conditions for spreading are good. This is particularly true in the case of slurry spreading on clay soils.

Feed Additives

It is a well-known fact that phosphorus utilisation in animal feed is poor, since 80-90% of the phosphorus in cereal grain is stored as phytate (inositol hexakisphosphate) (Jongbloed and Kemme, 1990). This substance is stable and poorly digestible for most species of animals, particularly monogastrics (pigs and poultry), which do not possess the advantage of having a rumen containing microbes that can release phytate-P. Because e.g. pigs have a very low utilisation rate of phytate, inorganic phosphorus is often added to pig feed. This further increases the risk of phosphorus losses, since the amount of phosphorus in the manure increases. There is a distinct correlation between pig intake and excretion of phosphorus. Studies have shown that the amount of phosphorus in pig manure increases to levels between 20 and 40 g P kg⁻¹ dry material with relatively high rates of phosphorus addition to the feed, while the levels are generally below 20 g P kg⁻¹ dry material with low or no additives.

There are currently two ways to counteract the problem of low phosphorus utilisation in feed. One is simply to use feed that contains phosphorus in a more available form (smaller amounts of phytate-P), while the other is to add the enzyme phytase. Phytase is produced by microorganisms (e.g. *Aspergillus niger*), and the enzyme catalyses the hydrolysis of phytate in the digestive tract of animals to produce orthophosphate, which can be taken up by monogastrics. Addition of phytase means that the animals can utilise the phosphorus in the feed more efficiently and the phosphorus content can therefore be lowered. This in turn has been shown to decrease the amount of phosphorus in manure and thereby the risk of losses to the environment. The cost of adding phytase is usually lower than that of adding extra phosphorus to the feed. In other words, phytase (Figure 9.5) additives are a good measure to reduce phosphorus losses to surface waters and groundwater in a cost-effective way. Furthermore, phytase additives have a number of other positive effects, such as increased availability of nutrients such as Ca and Zn.

Best Management Practice at Field Level

Best management practice at field level should contribute to a system in balance at field level, restricting the transport of phosphorus to surface waters and groundwater from every field. Figure 9.6 shows a flow diagram describing preventive measures aimed at minimising phosphorus losses at field level. These measures have been divided into those that decrease the release of phosphorus from soil and fertilisers and those that affect the actual transport of phosphorus on the soil surface or in the soil.

Field Phosphorus Balance and Soil Testing

Accumulation of phosphorus in a field is usually revealed when a soil test is performed. Therefore the risk of phosphorus losses from agricultural land is currently often based on soil test values determining phosphorus available to crops to be similar to that available for leaching. A number of studies have shown that the risk of phosphorus losses is better predicted by determining the concentration of dissolved phosphorus in the soil (Leinweber et al., 1999), which may therefore be decisive for fertilisation recommendations aimed at avoiding overapplication of phosphorus. Table 9.6 shows a matrix indicating the relationship between phosphorus balances and soil test values. The risk of large excesses within a system is naturally greatest when large quantities of feed are bought in for an animal production unit. A more flexible approach to livestock density can be justifiable, but it is difficult to implement in practice.

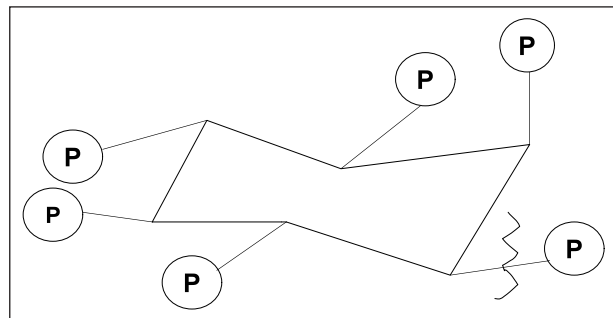


Figure 9.5. Phytase cleaves inorganic phosphorus from phytate to form orthophosphate, which can be taken up in the digestive tract of monogastrics.

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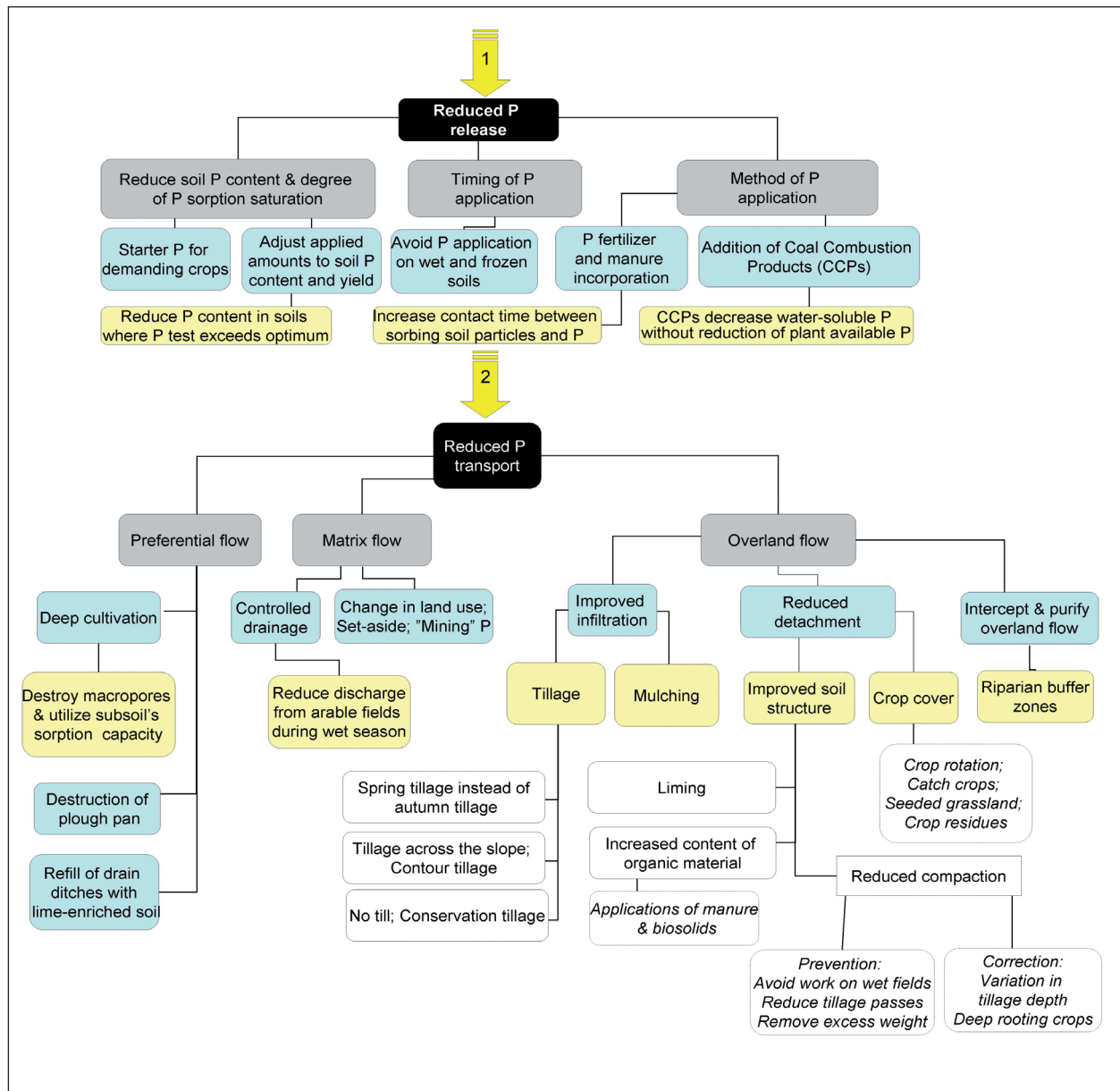


Figure 9.6. Flow diagram showing the relationships between measures for decreasing phosphorus losses from agriculture (Djordjic et al., 2005).

Fertiliser Placement

What can be done to improve the use efficiency of applied phosphorus and thereby decrease the risks of losses? A well-proven method is to apply fertiliser phosphorus in bands in the soil instead of broadcasting it on the soil surface. This applies equally to artificial fertiliser and manure. It decreases the risk e.g. of surface runoff losses and for manure also the risk of ammonia losses to the atmosphere. It has also been shown that a marked reduction in leaching losses of phosphorus can be achieved by incorporating fertiliser at the time of application (Djordjic et al., 2002). In soils with a low phosphorus content and a high phosphorus binding capacity, good crop growth is generally obtained if mineral fertiliser phosphorus is placed in bands beside the seed through combi-drilling (starter P). This also allows the fertiliser dose to be decreased. However, the disadvantage of band placement is that the root volume coming into contact with the phosphorus applied is often smaller. It has been demonstrated that maize (Richards et al., 1985), linseed and rapeseed can even be damaged by placement in seed rows of amounts of phosphorus fertiliser granules corresponding to the optimal dose. In such cases, it is important that the fertiliser granules are placed somewhat below the seed.

Manure Spreading

As mentioned before, phosphorus in manure is mobile and reduced manuring has been indicated to reduce phosphorus migration within the soil profile in central Lithuania (Tripolskaja, 2004). There are several measures that can be adopted to decrease phosphorus losses and to increase the efficiency of phosphorus use from manure, some of

which concern the time of application and incorporation requirements. The first measure is to analyse the nutrient content of the manure so that the correct amount of phosphorus is applied. Simply relying on standard values given in various books and other literature is not enough. For solid manure, which varies most, it is recommended that samples be taken from the manure spreader, while slurry samples can be taken from the storage tank. There are a range of chemical methods used to determine the total phosphorus content of manure (Peters et al., 2003). There are also examples of cases where the phosphorus content is stated in terms of water-soluble phosphorus in order to emphasise that it is the amount of phosphorus that can either run off the soil surface or be leached out that is important, i.e. to give an indication of the potential environmental load.

Another important factor for good phosphorus use efficiency is that the correct amount of manure is spread on fields, which requires a reliable manure spreader that is calibrated at regular intervals. If the spreader is not calibrated there is a risk of excessive amounts being applied, which in the long term can lead to unnecessary phosphorus losses to water courses. When calibrating a manure spreader it is important to check both the amount emitted and the area over which this amount is applied. There are a number of methods used for calibration, from those based on individual loads of manure to those based on the contents of the slurry tank on the farm. It is important to bear in mind that regardless of the calibration method used, the spreader must be re-calibrated after every effective change in the composition of the manure. In comparison with many other methods to decrease phosphorus losses from agricultural soil, it is very cost-effective to have a well-calibrated manure spreader.

Table 9.6. Matrix indicating the relationship between phosphorus balances and soil test values based on Beegle and Lanyon (2006) but modified for Baltic Sea conditions with need of high environmental concern.

	Phosphorus balance		
	Annual supply – Annual removal		
Soil test value	–	0	+
Low	Agronomic concern		Acceptable
Medium	Desirable	Optimal	Environmental concern
Excess	Desirable	Environmental concern	

Limiting the Release of Phosphorus

Even if the supply of phosphorus to agricultural land is in balance with its removal, high losses can still occur due to the fact that they are often concentrated to short episodes. To decrease the effect of these episodic losses, great attention should be given to the time of phosphorus application and the method of fertiliser application.

Infiltration of water into frozen soil is mainly governed by the soil structure and the water content of the soil at the time of freezing. When the soil freezes at a

high water content or at saturation, it becomes practically impermeable to water, which means that meltwater or rain falling during the winter often gives rise to severe surface runoff, which in turn increases the risk of high phosphorus losses. This risk is particularly great if manure is applied in late autumn or during the winter (Sharpley et al., 1994). However, air-filled macropores in frozen soil can also pose a risk of phosphorus losses, since water with its content of dissolved or particle-bound phosphorus can be rapidly transported downwards in the soil. Ulén (1995) demonstrated that considerable leaching losses can occur in such conditions. In contrast, liming was indicated to reduce phosphorus migration within the soil profile in central Lithuania (Tripolskaja, 2004).

Reduction of Phosphorus Losses by Influencing Transport pathways

As mentioned above, measures to reduce phosphorus losses must take account of the dominant transport pathway in phosphorus flow, which can occur through surface runoff, macropores in the soil or more slow flow through the soil matrix (so-called piston flow). The type of flow that dominates is dependent on a number of factors such as soil sorption capacity and rain intensity. Leaching of phosphorus through the soil profile by piston flow is strongly affected by the sorption capacity of the soil, while surface runoff is completely unaffected by this parameter. When suitable preventive measures are being sought to decrease phosphorus losses in an area or from a field, it is therefore essential to identify the dominant transport pathway.

Reducing Phosphorus Losses by Surface Runoff

In some regions of the Baltic Sea area a large proportion of the phosphorus losses from agricultural soils may occur through surface runoff. In some areas, such losses are considered to be completely dominant, which means that remediation strategies to decrease phosphorus emissions have been linked to a greater extent to methods designed to prevent and reduce erosion. Surface runoff losses can occur both in the form of dissolved reactive phosphorus and phosphorus bound to soil particles. In general, phosphorus losses decrease with increasing soil infiltration capacity and thus decreasing runoff (Turtola

and Jaakola, 1995). Knowledge based on research into the dependency of erosion on rain intensity, soil characteristics, topography and soil tillage has been used to rectify problems relating to surface runoff losses of phosphorus. Tillage and mulching methods have since been developed to improve soil infiltration capacity and decrease the release of particles from soil, while various measures have been designed to control the transport of phosphorus (Figure 9.6).

The prevention of erosion demands systematic and often comprehensive efforts. However, it is important to take action in fields where erosion causes phosphorus losses, not just where erosion occurs, since erosion is not necessarily associated with losses of phosphorus (Sharpley et al., 1994). The fact is that large phosphorus losses can occur even during periods with low rainfall intensity and small erosion losses. However, knowledge within this area needs to be improved and to encompass not only particle-bound phosphorus but also phosphorus bound to colloidal material (Ulén, 2003).

Soil Tillage

A number of soil tillage strategies to decrease the velocity of water flow during surface runoff events, and thereby the transport of soil particles and any phosphorus bound to these, have been developed over the years. These include carrying out tillage operations perpendicular to the slope of the field and contour ploughing, which are methods applied in a number of countries where sloping fields are a commonly occurring feature. However, there is little experience of these in the Baltic area. Reduced soil tillage is also used to decrease surface runoff losses of phosphorus. Leaving harvest residues on the soil surface increases infiltration and decreases soil drying and thus more water is retained in the soil for the following crop. A problem is that not all erosion control measures decrease phosphorus losses. Plant residues left on the soil surface can act as a phosphorus source (Gaynor and Findlay, 1995) and increase the losses of dissolved reactive phosphorus. Dissolved phosphorus creates considerably greater problems in most water ecosystems than particle-bound phosphorus due to its high bioavailability.

Spring tillage, which is normally better than autumn tillage as regards reducing phosphorus losses, can destroy the soil structure and thereby decrease infiltration capacity



Figure 9.7. A cultivator for shallow soil tillage. Photo: B. Ulén.

and increase runoff, if carried out when the soil has a high degree of hydraulic saturation. If soil tillage operations are not carried out, the macropore flow in certain soils can increase, which in turn often contributes to greater phosphorus losses (Petersen et al., 1997). In the US, McDowell and McGregor (1984) also found that even though losses of total phosphorus were considerably reduced when no soil tillage was performed, the losses of dissolved phosphorus were eight-fold higher compared with after conventional tillage operations. Generally, the effects of cultivation on phosphorus mobilisation are highly dependent on soil type, and reduced cultivation must be linked to improved crop and nutrient management to achieve lasting environmental benefits (Withers et al., 2007).

Buffer Zones

Other measures that have been proven to significantly decrease surface runoff losses of phosphorus in the agricultural landscape include vegetation filters along watercourses, often referred to as buffer zones (Leinweber et al., 2002). The mechanisms that control phosphorus retention in vegetation filters are sediment deposition, infiltration capacity and uptake of phosphorus by the vegetation. The efficiency of vegetation filters along watercourses is strongly linked to filter width, while vegetation type and density of the vegetation cover have been shown to be of secondary importance. In a Nordic study, the total phosphorus content was reduced by between 27 and 97% depending on filter width, which was equivalent to 0.24–0.67 kg P ha⁻¹ yr⁻¹ (Uusi-Kämpä et al., 2000).

There is often a greater accumulation of particles in a vegetation filter than of phosphorus. Vegetation filters have also been used to decrease phosphorus losses from different types of wastewater generated in agriculture, e.g. wastewater from dairy units. Such wastewater, which contains large amounts of phosphorus, can be spread on a vegetated area that captures up to 90% of the phosphorus. Several international studies (e.g. Timmons et al., 1970; Miller et al., 1994) mention that with vegetation filters in cold regions there is a risk of the plant material in the filter freezing. This can lead to increased losses of phosphorus since freezing bursts the cell membranes and releases the phosphorus in the plant cells, which is then carried away by runoff water. Increased phosphorus losses as a result of freezing of plant material have also been demonstrated in Swedish studies.

Catch Crops

It can be assumed that the introduction of a catch crop, which is a proven method of decreasing nitrogen leaching from lighter soils in southern Sweden, also has a decreasing effect on phosphorus losses. This would occur through decreased surface runoff and erosion, phosphorus uptake by the catch crop and improved infiltration. Studies have shown that a catch crop that is allowed to grow for several months can bind 10–30 kg P ha⁻¹ in aboveground biomass. However, freezing-out of the phosphorus in plant cells, and thus the potential for increased losses, is also a risk with catch crops under Baltic climatic conditions. However, in a study in south-west Sweden this effect was demonstrated to be of minor importance as long as the surface runoff was low (Ulén, 1997).

Reducing Phosphorus Losses from Drained Soils

Large losses of phosphorus occasionally occur through water, and the dissolved or particle-bound phosphorus contained therein, is transported through large pores in the soil profile. During such transport, the phosphorus usually does not have time to react with the soil material, but bypasses sorption surfaces in the soil and continues to deeper layers in the profile. The effect on phosphorus losses is then similar to that described above for surface runoff. This type of loss is often referred to as internal erosion, since particles and their bound phosphorus are ripped from the pore walls when the water



Figure 9.8a. Buffer zone on a field outside of Västerås, Sweden in March 2009. Photo: B. Ulén.

rushes past. Soil tillage is one way to break the continuity of macropores in the topsoil and thus decrease phosphorus transport (Thomas and Phillips, 1979). A number of studies have also shown that phosphorus losses are lower in tilled soil compared with undisturbed (McDowell and Monaghan, 2002). However, there are also studies showing that soil tillage does not have this effect. In a Swedish study, this was explained by macropores in the topsoil being recreated by repeated freezing/thawing and the resultant fracturing of soil aggregates (Djordjic et al., 2002). Another explanation may be that soil tillage contributes to percolating water having a longer retention time in the phosphorus-rich topsoil layer, which means that leaching increases. However, in the subsoil the structure is relatively unaffected and the downward transport of phosphorus through macropores to the drain system can be rapid. One way to decrease leaching of phosphorus would be to promote rapid flow in the topsoil through e.g. breaking up the plough pan, while another would be to decrease the flow velocity in the subsoil through e.g. deep ploughing. Some studies have shown that phosphorus leaching decreases substantially after ploughing to greater depth in certain conditions (Calvert, 1975), although this has not been tested in the Baltic area.

The disturbed backfill soil over a tile drain represents a good pathway for generating rapid phosphorus transport in the soil similar to the flow through macropores, especially in the first few years after drain installation. A method



Figure 9.8b. The same site but without a buffer zone. The direct effect of surface water can be seen. Photo: B. Ulén.

of backfilling developed for clayey soils in Finland (the FOSTOP method, Nordkalk Oy Ab) involves incorporating burnt (i.e. unslaked) lime (CaO) with the backfill material in drains. The result is a stable and porous backfill that efficiently binds the phosphorus in percolating water. The lime requirement has been determined in trials to be 3-8% of soil wet weight. The method has been tested in a number of experiments and has been found to reduce the phosphorus concentrations in running water by more than 80% in most cases. In addition to phosphorus removal, the lime filter drain can also lead to improved drainage in impervious clay soils and can thus contribute towards decreasing erosion. The average lifetime for the lime filter drain has been shown to exceed 10 years without any loss in treatment effect. The method has only been tested at one experimental site in Sweden and the long-term effects have not been monitored.

Large leaching losses of phosphorus have been measured from sandy soils with a low sorption capacity for phosphorus, particularly in combination with large phosphorus doses in the form of manure or artificial fertiliser. The highest phosphorus losses occur from sandy soils with distinctly low sorption capacity and a high degree of phosphorus saturation (Djordjic and Bergström, 2005). There can be no doubt that such soils are very susceptible to high phosphorus leaching and will probably give rise to considerable leaching losses over a long period even if they are not fertilised. Mining phosphorus by taking away large amounts of phosphorus by fast-growing grass



Figure 9.9. Spreading of unslaked lime. Photo: B. Ulén.

or other crops seems to be the only way to reduce phosphorus losses from such soil profiles

Crop Rotation

Another option to reduce the risk of phosphorus leaching is to grow crops such as lucerne, which due to their deep root system have the capacity to take up large amounts of phosphorus from the soil without any being added, a process usually referred to as mining. At harvest, the phosphorus is then removed from the field. However, the difficulties in establishing a dense lucerne crop can decrease the effect (Ulén and Mattsson, 2003). Perennial ley crops are generally better suited to mining than cereal crops and the practice works best on soils with high phosphorus levels. Maize has been demonstrated to decrease the phosphorus level in the soil by 150 kg P ha⁻¹ during a period of 10 years, which markedly lowers the risk of phosphorus leaching.

Conceptual Evaluations of Countermeasures

For sandy soils there may be limited possibilities to bind dissolved reactive phosphorus (DRP) especially when the soil already contains much phosphorus. Suggested effective measures to reduce leaching are relatively few (Table 9.7). Reducing losses of DRP, which is usually the main problem from this type of soil, is most urgent. Mining of phosphorus, i.e. growing crops that can accumulate high amounts of phosphorus from the soil and at the same time generate large biomass, has been proposed as an attractive measure to reduce P. However, in several Baltic States ac-

cumulated uptake and transport of phosphorus by biomass is limited due to the moderate mean annual temperatures and this measure will probably have limited effects.

Silty soils usually suffer from surface erosion and several measures to reduce erosion may be highly effective (Table 9.7). Structured clay soils are also often characterised by rapid fluxes of water. Agricultural production on such soils means that they are tilled, usually in autumn, which always includes a risk of much transport of phosphorus bound to particles (Part P) in the following winter. Reduced ploughing means shallow tilling with a cultivator or disc harrow. One should bear in mind that reduced ploughing is a complex measure and experiences from Canada, have brought it into question regarding phosphorus losses (Gaynor and Findlay, 1995). The tile drainage losses of P may increase, probably as a result of increased P on the soil surface and transport of P through macropores. Surface water inlets may be regarded as point sources for P emissions to rivers and lakes. On the other side, conducting surface water to the tile drain system by such inlets may offer a better alternative than ponding water or pure surface runoff above the clay soil. The hydrological impact of water from ponded depressions is reduced by such a measure. Grassed buffer strips around the surface water inlets should reduce P losses significantly in certain areas. However, in general surface water inlets should be regarded as an emergency measure and they should, under acid soil conditions, be dug under the soil surface with limed backfill in order to avoid negative effects such as a direct conduit to tile drains.

Improved Drain Systems

Sub-surface drainage systems may be fundamental for rapid water flow out of the root zone, especially on clayey soil with dense structure in the near-surface horizon. Efficient sub-surface drainage is thus essential for achieving the full yield potential in the Baltic climate with excess rainfall. Drain trenches are very conductive and form routes for water which would otherwise flow as surface, near surface or plough pan runoff towards the lowest end of the field. Less surface runoff means lower erosive risk, especially at the lower end of the fields. Further water infiltration increases the potential for sieving of surface-eroded soil particles in soil pores and of sorption of surface-derived dissolved reactive phosphorus in the drained water.

Reducing Nutrient Losses from Agriculture

Table 9.7. Measures and mechanisms to reduce the phosphorus losses of dissolved reactive phosphorus (DRP) and particulate phosphorus (PartP) from sandy soil, silt soil and clay soil. The effects are usually conceptual, and are indicated by 0, +, ++ or +++ so that more plus signs mean a better effect.

Measure	Mechanism	Sand		Silt		Clay	
		DRP	PartP	DRP	PartP	DRP	PartP
Balance and soil P testing							
Adding balanced manure/fertilisation	No increased surplus P in the soil	+++	+	+++	+	+++	+
Fertiliser placement							
Combi drill or instant incorporation (not only ploughing)	Improved contact with soil at application	+++	++	+++	++	+++	++
Grass/reduced erosion							
Densely vegetated winter soil: permanent grass, ley or catch crops	Filtration of particles	0	+	0	+++	0	+++
Spring ploughing	Less detachment and P desorption	++	+	++	+++	+	+
Improved water infiltration							
Reduced soil compaction	Less water channel flow	++	++	++	+++	++	+++
Trapping in artificial drainage							
Limed backfills in the tile drain system	Improving water infiltration and chemical precipitation of SRP	++	++	++	+++	+	++
Buffer zones							
Buffer zones including zones around surface water inlets	Intercepting surface-runoff P and improving water infiltration	-	+	-	+++	-	+++
Grassed strips within the field	Intercepting surface-runoff P and improving water infiltration	-	+	-	+++	-	+++

By improving infiltration and percolation, subsurface drainage systems will decrease the proportion of surface run-off. In addition, improvement of soil structure and better root growth after the operation are likely to be followed by a rise in yield level and effective use of phosphorus in soil and added fertilisers. A short-term reduction of 15-25% for soil erosion and dissolved reactive phosphorus has been measured (Turtola and Paajanen, 1985), but on the other hand, nitrogen leaching may slightly increase. With increased yield, phosphorus soil balance may improve markedly, with long-term positive effects on phosphorus loss potential.

Reducing the Amount of Polluted Water at Farm Level and Protection of Slurry Stores

Options for minimising the amount of phosphorus-containing water at farm level include: covering slurry stores (regulated in many countries); avoiding excessive use of water in washing down yards and buildings; roofing over yard areas; minimising unnecessarily dirty yard areas and

avoiding accidents with slurry stores. Spreading of slurry is restricted in time in most countries and slurry may not be applied to water-saturated soil. Reducing the amount of water means less risk of slurry stores becoming over-filled and slurry or urine having to be spread at times when more P losses may occur. In Denmark, more restrictions and rules were introduced for functional pumps in summer 2008. By 2009, farmers must arrange some form of barrier to prevent any spill water reaching the surface water. If the store is placed more than 100 m away from a lake or river, an earthen mound must be constructed with dimensions to keep the entire volume of the slurry store (Danish Ministry of Environment, 2008).

Controlled Drainage for Reducing the Amount of Water Leaving the Field

Preferential flow of phosphorus through cracks may be enhanced after a dry season or a drought period in clayey soil. By controlled drainage, soil wetting from “the bottom” occurs, and in addition, the amount of drainage



Figure 9.10. Missing ditch and poor drainage in the county of Östergötland, SE Sweden. Photo: B. Ulén.

water may be somewhat reduced. The site must have groundwater with up-pressure. In addition, the groundwater must not be too high in periods when the field is managed and the water level has to be controlled. There is very little experience of this kind of measure in the Baltic region.

Mitigation of Phosphorus Losses by Improved Land Infrastructure

Manage Downslope Field Boundaries, Re-site Gateways and Avoid Tramlines

Downslope boundaries (hedges, fences, banks, vegetative buffers) represent a change in the hydrological and biogeochemical properties. If properly managed they can buffer water quality of surface and subsurface flow. If field boundaries are located so as to force run-off flow across them in sheet flow, they may trap and filter sediment and phosphorus. Gateways, livestock and tractor pathways represent a network of preferential pathways that connects fields situated up-slope to down-slope. Moving the gate is a simple way to decrease any surface runoff of phosphorus that may occur.

Tramlines are semi-permanent wheel-ways for farming machines to travel down during spraying and fertilising operations without causing wheel damage to the rest of the field, a practice sometimes referred to as ‘con-

trolled traffic’. Thus tramlines are important vectors of runoff, causing increased mobilisation of sediment and phosphorus. Uncultivated wheel tracks have a very low infiltration rate and are effective paths for sediment and P transport via surface run-off, especially after multiple tractor passes. Avoiding their use in the winter reduces run-off volumes while mechanical disruption of tramlines can minimise their negative effect. Compacted tramlines can further result in channelling of surface water into rills and gullies on erosion-susceptible soil. The reason is the critical shear stress of water flow created by the channelling effect and subsequent encroachment on surrounding soil. In addition, tramlines can act as a flow pathway during periods of snow melt and avoiding tramlines over the winter is therefore a highly significant option to prevent soil erosion under Baltic climate conditions. The solution could be either to delay the establishment of tramlines until crop cover has been established (or alternatively until the spring), or to shallow cultivate them using a simple goose-foot tine.

Improved Placement of Grazing Land within the Farm and in Connection to Streams

Through grazing, phosphorus is distributed in patches which increase the losses by surface runoff and drainage. The pattern for grazing land around the farm centre has an impact on which grazing system that is used. Few animals per hectare and rotation between the grazed fields will reduce this point source for water. The feeding and drinking site could also be moved and not be at the same place from year to year.

Free access to water has an impact on water quality by direct defecating and urination into the water course. In addition, trampling can lead to erosion of riverbanks and resuspension of river sediment. Modifying or restricting the access of livestock to the stream may reduce such phosphorus losses that follow. Measures may include; fences along the stream, bridging the necessary crossing areas instead of wading across the stream and avoiding gateways close to the stream but keeping the grazing cattle higher up in the watershed.

Constructed Wetlands

Constructed wetlands are designed to remove nitrogen and may in addition store phosphorus. Nitrogen is re-



Figure 9.11. A reversible plough for conventional ploughing to the depth of 23 cm. Photo: B. Ulén.

duced by denitrification and phosphorus by sedimentation and adsorption. The wetland may include overflow zones for oxygenation of water and sedimentation of fine particles under small runoff situations and shallow vegetative filters for sedimentation of phosphorus enriched particles (Braskerud et al., 2005). Constructed wetlands can be made up of a combination of sedimentation basins and infiltration basins with horizontal flow through the soil matrix for sorption of P. Another type of wetland is installed in open ditches and has an initial sedimentation pond area for capturing sediment-associated phosphorus. A certain hydraulic retention time is important for any retention. The phosphorus retention is more certain for particulate phosphorus than for dissolved phosphorus. The experience from some constructed wetlands is even net leaching of dissolved reactive phosphorus. This is a serious risk when the wetlands are constructed on former agricultural land, since this is usually rich in phosphorus. The sedimentation ponds may have to be emptied now and then and if sorption material is included it may have to be changed at time intervals.

Re-establishment of Riparian Wetlands at the Flood Plain

Low-lying organic soils along lowland rivers have usually been drained and used as agricultural land. Re-establishment of such wetland may reduce the flood risk, increase denitrification and, in addition, sedimentation of particulate suspended sediments and phosphorus may take place in the flood plain. Biomass should be removed

since phosphorus from the former agricultural land and iron-bound phosphorus may desorb from the riparian soil for some years and the biomass should be removed. Buffers have been indicated to be more effective if planted with trees.

Streambank and Shoreline Protection

Structural or vegetative measures may be used to protect streambank and shoreland from erosion. These include vegetative planting, and structural measures as sock riprap, piling revetments, jacks and gabion. Such measures avoid the detachment of soil particles. However, this cannot be considered a long-term strategy since phosphorus accumulated in the soil bank can reach the saturation level, or the hydrological conditions can change.

Summary and Conclusions

Phosphorus concentrations in the arable soils and phosphorus losses to waters are high in certain areas around the Baltic Sea. Even though phosphorus losses, apart from soil chemistry, also are controlled by hydrological conditions and soil physics, such losses can be decreased through cultivation practices. Of the measures introduced to decrease phosphorus losses, restriction of manure doses based on the phosphorus concentration in the soil has been the most effective, at least in the short term. Some of the problems with manure have decreased in recent years due to extensive regulation of storage and spreading. However, the problem will never be completely solved as long as manure continues to be applied to soils in the high soil phosphorus classes. Manure treatment at farm level by both simple and more complicated methods should be prioritised so that the manure can be transported at a reasonable price, as should technology for spreading and mobile grazing (moving animals around). All phosphorus fertilisers should be applied in such a way that the phosphorus has as good soil contact as possible while at the same time being available to the crop.

Soil hydrology can be affected by surface water management through good drainage tillage and liming to produce good, uniform infiltration into the soil, while all forms of channel flow must be avoided. Appropriate pre-

ventive measures must be adapted to the local soil type and cropping system. Functioning strategies and sufficiently advanced tools for this local adaptation of preventive measures within agriculture are currently lacking but need to be developed.

Chapter 8

- Aronsson, H., Torstensson, G. and Bergström, L. 2007. Leaching and crop uptake of N, P and K from a clay soil with organic and conventional cropping systems. In: *Soil Use and Management* vol. 23 71-81
- Baltic Nest Institute (<http://nest.su.se/>)
- Claesson, S. and Steineck, S. 1996. *Plant nutrient management and the environment*. SLU.
- De Clercq, P., Gertsis, A.C., Jarvis, S.C. and Neeteson, J.J. 2001. *Nutrient management legislation in European countries*. Wageningen: Wageningen Pers.
- EEA, 2005. *EEA web site*, <http://www.eea.europa.eu>
- EU, 1991. *Nitrate directive*. http://ec.europa.eu/environment/water/water-nitrates/index_en.html
- EU, 2000. *Water framework directive* http://ec.europa.eu/environment/water/water-framework/index_en.html
- Fleischer, S., Gustafson, A., Joelsson, A., Pansar, J. and Stibe, L. 1994. Nitrogen removal in created ponds. In: *Ambio*, 23, 1994 pp. 349-357.
- Gustafson, A. 1983. *Leaching of nitrate from arable land into groundwater in Sweden*. Environmental Geology, Vol. 5, No 2, pp. 65-71
- Gustafson, A. 1987. *Simulation of Nitrate Leaching from Arable Land in Southern Sweden*. Acta Agriculturae Scandinavica, 38, pp. 13-23.
- Gustafson, A., Kyllmar, K. and Ulén, B. 1999. Leakage of nitrogen and phosphorous. In: Lundin, L.-C. (ed.) *Water use and management*. Uppsala: The Baltic University Programme. pp. 111-123.
- Gustafson, A., Fleischer, S. and Joelsson, A. 2000. A catchment oriented and cost-effective policy for water protection. In: *Ecological Engineering*, 14, pp. 419-427.
- HELCOM, 2007. *Baltic sea action plan* (adopted on 15 November 2007 in Krakow, Poland). http://www.helcom.fi/BSAP/ActionPlan/en_GB/ActionPlan/
- Humborg, C., Mörh, C.-M., Sundbom, M. and Wulff, F. 2007. Riverine transport of biogenic elements to the Baltic Sea – past and possible future perspectives. In: *Hydrol. Earth Syst. Sci. Discuss.*, 4, pp. 1095-1131.
- Johansson, G. and Gustafson, A. 2008. *Observation fields on arable land. Discharge and nutrient losses for the agro-hydrological year 2006/07 and a long term review*. Technical report no. 121. Uppsala: Swedish University of Agricultural Sciences. (In Swedish) http://www.mv.slu.se/Vv/jrk/obs/obs_result.htm
- Johnsson, H., Larsson, M., Mårtensson, K. and Hoffmann, M. 2002. SOILNDB: a decision support tool for assessing nitrogen leaching losses from arable land. In: *Environmental Modelling & Software*, 17, pp. 505-517.
- Johansson, S., Wulff, F. and Bonsdorff, E. 2007. The MARE Research program 1999-2006: Reflections on Program Management. In: *Ambio*, 36, No. 2-3, pp. 119-122.
- Iital, A., Stålnacke, P., Deelstra, J., Loigu, E. and Pihlak, M. 2005. Effects of large-scale changes in emissions on nutrient concentrations in Estonian rivers in the Lake Peipsi drainage basin. In: *J. Hydrol.*, 304, pp. 261-273.
- Kirchmann, H. et al. 2007. Comparison of Long-Term Organic and Conventional Crop-Livestock Systems on a Previously Nutrient-Depleted Soil in Sweden. In: *Agronomy Journal* 99:960-972. doi:10.2134/agronj2006.0061.
- Kronvang, B., Jeppesen, E., Conley, D.J., Sondergaard, M., Larsen, S.E., Ovesen, N.B. and Carstensen, J. 2005. Nutrient pressures and ecological responses to nutrient loading reductions in Danish streams, lakes and coastal waters. In: *J. Hydrol.*, 304, 274-288.
- Kyllmar, K., Carlsson C., Gustafson A., Ulen B. and Johnsson H. 2006. Nutrient discharge from small agricultural catchments in Sweden – Characterisation and trends. In: *Agriculture Ecosystems & Environment* vol 115, pp. 15-26
- Kynkäänniemi, P. and Kyllmar, K. 2008. *Nutrient losses in small agricultural catchments 2006/07*. Ekohydrologi nr 101. Uppsala: Swedish University of Agricultural Sciences. (In Swedish) http://www.mv.slu.se/Vv/publ/Ekohoedrologi_101.pdf
- Larsson, M.H. and Jarvis, N.J., 1999. Evaluation of a dual-porosity model to predict field-scale solute transport in a macroporous soil. In: *Journal of Hydrology* 215, pp. 153-171.
- MARE NEST model, <http://nest.su.se/nest/>
- Torstensson, G., Aronsson, H. and Bergström, L. 2006. Nutrient use efficiency and leaching of N, P and K of organic and conventional cropping systems in Sweden. In: *Agronomy Journal*, Vol 98, p 603-615.
- Vagstad, N., Stålnacke, P., Andersen, H.E., Deelstra, J., Gustafson, A., Itäl, A., Jansons, V., Kyllmar, K., Loigu, E., Rekolainen, S., Tumas, R. and Vuorenmaa, J. 2001. *Nutrient losses from agriculture in the Nordic and Baltic countries. Results of measurements in small agricultural catchments and national agro environmental statistics*. TemaNord 2001:591. 74 pp
- Willer, H. and Yussefi, M. (eds.) 2007. *The world of organic agriculture – Statistics and emerging trends 2007*. International Federation of Organic Agriculture Movements (IFOAM), DE-Bonn and Research Institute of Organic Agriculture, FiBL, CH-Frick.

Chapter 9

- Antikainen, R., Lemola, R., Nousianen, J.I., Sokka, L., Esala, M., Huhtanen, P. and Rekolainen, S. 2005. Stocks and flows of nitrogen and phosphorous in the Finnish food production and consumption system. In: *Agriculture, Ecosystems & Environment*, Vol 107, Iss. 2-3 Pp 287-305.
- Astover, A., Roostalu, H., Lauringson, E., Lemetti, I., Selge, A., Talgre, L., Vasilier, N., Mõtte, M., Tõrra, T. and Penu, P. 2006. Changes in agricultural land use and in plant nutrient balances of arable soils in Estonia. In: *Archives of Agronomy and Soil Sciences* 52(2): pp. 223-231.
- Baker, D.B. and Richards, R.P. 2002. Phosphorus budgets and riverine phosphorus export in northwestern Ohio watersheds. In: *Journal of Environmental Quality*. 31:1, pp. 96-108.
- Beegle, D. and Lanyon, L. 2006. *Phosphorus balance*. SERA 17. Minimizing phosphorus losses from agriculture. (http://www.sera17.ext.vt.edu/SERA_17_Publications.htm)
- Brandt, M., Ejhed, H. and Rapp, L., 2006. *Nutrient loads to the Swedish marine environment in 2006*. Swedish Environmental Protection Agency.

- Braskerud, B., Tonderski, K., Wedding, K., Bakke, A.G., Blankenberg, B., Ulén, B. and Koskiahio, J. 2005. Can constructed wetlands reduce the diffuse phosphorus loads to atrophic water in cold temperature regions? In: *Journal of Environmental Quality* 34, pp. 2145-2155.
- Bučienė, A., Antanaitis, Š., Mašauskienė A. and Šimanskaitė, D. 2007. Nutrients N, P losses with drainage runoff and field balance as a result of crop management. In: *Communications in Soil Science and Plant Analysis* Vol. 38, Issue 15 & 16, September 2007, pp. 2177 – 2195.
- Calvert, D.V. 1975. Nitrate, phosphate, and potassium movement in drainage lines under three management systems. In: *Journal of Environmental Quality* 4, pp. 183-186.
- Csathó P., Sisák, I., Radimsky, L., Lushaj, S., Spiegel, H., Nikolova, M.T., Nikolov, Y.N., Čermák, P., Klir, J., Astover, A., Karklins, A., Lazauskas, S., Kopyński, J., Hera, C., Dumitru, E., Čuvardić, M., Bogdanović, D., Torma, S., Leskošek, M. and Khristenko, A. 2007 Agriculture as a source of phosphorus causing eutrophication in central and eastern Europe. In: *Soil Use and Management* 23, Suppl., 1, pp. 36-56.
- Djordjic, F., Börling, K. and Bergström, L. 2004. Phosphorus leaching in relation to soil type and soil phosphorus content. In: *Journal Environmental Quality* 33, pp. 678-684.
- Djordjic, F., Bergström, L. and Ulén, B. 2002. Phosphorus losses in relation to tillage practices on a structured clay soil. In: *Soil Use and Management* 18, pp. 79-83.
- Djordjic, F. and Bergström, L. 2005. Conditional phosphorus index as an educational tool for risk assessment and phosphorus management. In: *Ambio* 34, pp. 296-300.
- Egnér, H., Riehm, H. and Domingo, W. R. 1960. Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung de Nährstoffzustandes der Böden. II. *Kung.l Lantbrukshögskolans Annaler* 26, 199-215.
- Eriksson, J. Andersson, A. and Andersson, R. 1997. *Current Status of Swedish arable soil*. Swedish Protection Agency report 4778.
- Gaynor, J.D. and Findlay, W.I. 1995. Soil and phosphorus loss from conservation and conventional tillage in corn production. In: *Journal Environmental Quality* 24, pp. 734-741.
- Henriksson, A. 2006. *Actions against phosphorus losses from agriculture in the countries around the Baltic Sea*. Report Food 21 www-mat21.slu.se
- Isermann, K. 2007. *Phosphorus balances in Europe and implications for diffuse pollution policy*. Extended abstract International Phosphorus Workshop 5, Silkeborg Denmark 3-7 Sept 2007.
- Ivanov, P. 1984. *New acetate-lactate method for determination of plant-available phosphorus and potassium in soil*. (in Bulgarian).
- Johansson, G. and Gustafson, A. 2005. *Observation field on arable land*. Technical report 107, Div. Water quality Management, SLU. 38 pp.
- Johansson, G. and Gustafson, A. 2008. *Observationsfältet på åkermark*. Teknisk rapport 121, Avd. Vattenvårdslära SLU. 38 pp
- Jongbloed, A.W. and Kemme, P.A. 1990. Apparent digestible phosphorus in the feeding of pigs in relation to availability, requirement and environment: 1. Digestible phosphorus in feedstuffs from plant and animal origin. In: *Netherlands Journal Agriculture Science* 38, pp. 567-575.
- Karklins, A. 1998. Plant available phosphorus in Latvian soils and trends in fertiliser use. In: *Bibliotheca Fragmenta Agronomica Tom. 3*, pp. 310-316.
- Končius, D. 2007. The effect of periodical liming and fertilization on the forms of phosphates and on the chantes in its fractional composition in the soil. In: *Zemdirbyste-Agriculture*. Vol. 94, No. 1, pp. 74-88.
- Kopinski, J., Tujaka, A. and Igras, J. 2006. Nitrogen and phosphorus budgets in Poland as a tool for sustainable nutrient management. In: *Acta agriculturae Slovenica*, 87, pp. 173-181.
- Leinweber, P., Meissner, R., Eckhardt, K.V. and Seeger, J. 1999. Management effects on forms of phosphorus in soil and leaching losses. In: *European Journal of Soil Sciences* 50, pp. 413-424.
- Leinweber, P., Turner, B.L. and Meissner, R. 2002. Potential source of water pollution: phosphorus. In: Haygarth, P.M. and Jarvis, S.C. (eds.) *Agriculture, Hydrology and Water Quality*. CABI International, Oxon, UK and New York, USA, pp 29-55.
- Lipiński, W. 2005. The content of available phosphorus in soils of Poland. In: *Nawozy i Nawożenie* (Fertilisers and Fertilization), Nr. 2(23). Polish Fertiliser Society – CIEC, Puławy 2005. pp. 49-54.
- Lundekvam, H., and Skøien S., 1998. Soil erosion in Norway. An overview of measures from soil loss plots. In: *Soil Use and Management* 14, pp. 84-89.
- McDowell, L.L. and McGregor, K.C. 1984. Plant nutrient losses in runoff from conservation tillage corn. In: *Soil & Tillage Research* 4, pp. 79-91.
- McDowell, R.W. and Monaghan, R.M. 2002. The potential for phosphorus loss in relation to nitrogen fertilizer application and cultivation. In: *New Zealand Journal Agriculture Research* 45, pp. 245-253.
- Marčinkonis, S. and Karmaza, B. 2007. Visualisation of phosphorus accumulation data in potential pollution sources. In: *Zemdirbyste-Agriculture*. Vol. 94, No. 1, pp. 64-73..
- Mažvila, J. and Adomaitis, T. 2005. Judriuju fosforo ir kalio liekiu kaita Lietuvos žemės ūkio naudmenu dirvožemiuose. In: *Zemdirbystė Mokslo darbai*, 3,9, pp. 3-36.
- Mechlich, A. 1984. Mechlich 3 soil test extractant: a modification of Mechlich 2 extractant. In: *Communications in Soil Science and Plant Analysis* 15, pp. 1409-1416.
- Miller, M.H., Beauchamp, E.G. and Lauzon, J.D. 1994. Leaching of nitrogen and phosphorus from the biomass of three cover crop species. In: *Journal Environmental Quality* 23, pp. 267-272.
- Neyrod, J-A. and Lischer, P. 2003. Do different methods used to estimate soil phosphorus availability across Europe give comparable results? In: *Journal Plant Nutrition Soil Science* 166, pp. 422-431.
- Olsen, S.R., Cole, C.V., Watanabe, F.S. and Dean, L.A. 1954. *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*. USDA Circular No. 939. 19 pp. Washington, DC., U.S.
- Petersen, C.T., Hansen, S. and Jensen, H.E. 1997. Tillage-induced horizontal periodicity of preferential flow in the root zone. In: *Soil Science. Society. American Journal* 61, pp. 586-594.
- Peters, J., Combs, S., Hoskins, B., Jarman, J., Kovar, J., Watson, M., Wolf, A. and Wolf, N. 2003. *Recommended Methods of Manure Analysis*. University of Wisconsin Extension Publ., Madison, WI. (<http://www1.uwex.edu/ces/pubs/pdf/A3769.pdf>; <http://www1.uwex.edu/ces/pubs/pdf/A3769.pdf>)
- Reimann, C., Siewers U., Tarvainen, T., Bitjukova, L., Eriksson, J., Gilucis, A., Gregorauskiene, V., Lukashev, V.K., Matinian, N.N. and Pasieczna, A. 2003. *Agricultural soils in northern Europe. A geochemical atlas*. Hannover: E. Schweizerbartsche Verlagsbuchhandlung,

- Richards, J.E., Bates, T.E. and Sheppard, S.C. 1985. The effect of broadcast P applications and small amounts of fertilizer placed with seed on continuously cropped corn (*Zea mays* L.). In: *Fertilizer Research* 6, pp. 269-277.
- Riehm, H. 1943. Bestimmung der laktatlöslichen Phosphorsäure in karbonathaltigen Böden. *Phosphorsäure* 1, pp. 167-178.
- Schüller, H. 1969. Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphates in Böden. In: *Zeitschrift für Pflanzenernährung und Bodenkunde* 123, 48-63.
- Sharpley, A.N., Chapra, S.C., Wedepohl, R., Sims, J.T., Daniel, T.C. and Reddy, K.R. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. In: *Journal Environmental Quality* 23, pp. 437-451.
- Thomas, G.W. and Phillips, R.E. 1979. Consequences of water movement in macropores. In: *Journal of Environmental Quality* 8, 149-152.
- Timmons, D.R., Holt, R.F. and Latterall, J.J. 1970. Leaching of crop residues as a source of nutrients in surface runoff water. In: *Water Resources Research* 6, pp. 1367-1375.
- Tripolskaja, L. 2004. Ilgalaikio trąšų naudojimo įtaka dirvožemio savybėms lizimetriuiose įrenginiuose. In: *Žemdirbystė. Mokslo darbai*, 1, 85, pp. 17-27.
- Turtola, E. and Jaakola, A. 1995. Loss of phosphorus by surface runoff and leaching from a heavy clay soil under barley and grass ley in Finland. In: *Acta Agriculturae Scandinavica*, Section B 45, pp. 159-165.
- Turtola, E. and Paajanen, A. 1995. Influence of improved subsurface drainage on phosphorus losses and nitrogen leaching from a heavy clay soil. In: *Agricultural Water Management* 28, pp. 295-310.
- Ulén, B. 1995. Episodic precipitation and discharge events and their influence on losses of phosphorus from tile-drained arable fields. In: *Swedish Journal Agriculture Research* 25, pp. 25-31.
- Ulén, B. 1997. Nutrient losses by surface runoff from soils with winter cover crops and spring-ploughed soils in the south of Sweden. In: *Soil & Tillage Research* 44, pp. 165-177.
- Ulén, B. and Mattsson, L. 2003. Losses of different forms of phosphorus and of nitrate from a clay soil under grass and cereal production. In: *Nutrient Cycling in Agroecosystems* 65, pp. 129-140.
- Ulén, B. 2003. Concentrations and transport of different forms of phosphorus during snowmelt runoff from an illite clay soil. In: *Hydrological Processes* 17, pp. 747-758.
- Ulén, B. 2004. Size and settling velocities of phosphorus-containing particles in water from agricultural drains. In: *Water Air and Soil Pollution* 157, pp. 331-343.
- Ulén, B. and Jakobsson, C. 2005. Critical evaluations of measures to mitigate phosphorus losses from agricultural land to surface waters in Sweden. In: *Science of Total Environment* 344, pp. 37-50.
- Uusi-Kämpä, J., Braskerud, B., Jansson, H., Syversen, N. and Uusitalo, R. 2000. Buffer zones and constructed wetlands as filters for agricultural phosphorus. In: *Journal of Environmental Quality* 29, pp. 151-158.
- Uusitalo, R., Turtola, E., Grönroos, J., Kivistö, J., Mäntylathi, V., Turtola, A., Lemola, R. and Salo, T. 2007. Finnish trends in phosphorus balances and soil test phosphorus. In: *Agricultural and Food Science Finland*, 16, pp. 301-316.
- Vuorinen, J. and Mäkitie, O. 1955. *The method of soil testing in use in Finland*. Agrigeological Publication 63, pp. 1-44.
- Withers, P.J.A., Hodgkinson, R.A., Bates, A. and Withers, C.L. 2007. Soil cultivation effects on sediment and phosphorus mobilization in surface runoff from three contrasting soil types in England. In: *Soil & Tillage Research* 93, pp. 438-451.

Chapter 10

- Baker, D.B. and Richards, R.P. 2002. Phosphorus budgets and riverine phosphorus export in northwestern Ohio watersheds. In: *J. Environ. Qual.* 31:1, pp 96-108.
- Carpenter, S.R., Caraco, N.F., Howarth, R.W., Sharpley, A.N. and Smith, V.H. 1998. Nonpoint pollution of surface waters with P and nitrogen. In: *Ecol. Applic.* 8: pp. 559-568.
- Clark, G.M., Mueller, D.K. and Mast, M.A. 2000. Nutrient concentrations and yields in undeveloped basins of the United States. In: *Journal of the American Water Resources Association*. 36:4, pp 849-860.
- Dove, A. and Warren, G. 2008. Phosphorus concentrations and loadings. In: *State of the Great Lakes*, Environment Canada and U.S. and Environmental Protection Agency, pp 70-73. Available on-line: <http://www.epa.gov/solec/>
- Duvick, D.N. 2005. The contribution of breeding to yield advances in maize (*Zea mays* L.). In: *Advances in Agronomy*, 86 pp 83-145.
- Elmi, A.A., Madramootoo, C.A., Egeh, M., Liu, A. and Hamel, C. 2002. Environmental and agronomic implications of water table and nitrogen fertilization management. In: *J. Environ. Qual.* 31: pp 1858-1867.
- Fixen, P.E. and West, F.B. 2002. Nitrogen fertilisers. Meeting contemporary challenges. In: *AMBIO: A Journal of the Human Environment*. 31: 2, pp. 169-176.
- Frankenberger J., Kladivko E., Sands G., Jaynes D., Fausey N., Helmers M., Cooke R., Strock J., Nelson K. and Brown L. 2006. *Drainage Water Management: Questions and Answers about Drainage Water Management for the Midwest*. Bulletin WQ-44, Purdue University, W. Lafayette, Ind.; 8 pp.
- Fuller, K., Shear, H. and Wittig, J. (eds.) 1995. *Great lakes environmental atlas and resource book* (3rd Edition). Government of Canada and US Environmental Protection Agency. Available on line <http://www.epa.gov/glnpo/atlas/index.html>
- International Plant Nutrition Institute. 2008. *Crop nutrient balances in Ontario 1950-2007*. [http://www.ipni.net/ppiweb/canadae.nsf/\\$webindex/article=4EC4F7DF8525740A006843D6F653DBC5](http://www.ipni.net/ppiweb/canadae.nsf/$webindex/article=4EC4F7DF8525740A006843D6F653DBC5)
- McCabe, G.J., Palecki, M.A. and Betancourt, J.L. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. In: *Proceedings of the National Academy of Sciences USA* 101:12, pp. 4,136-4,141.
- Mclsaac, G.F. and Hu, X. 2004. Net N input and riverine N export from Illinois agricultural watersheds with and without extensive tile drainage. In: *Biogeochemistry* 70:2, pp 251-271.
- Mclsaac, G.F., David, M.B. and Mitchell, C.A. 2010. *Miscanthus* and switchgrass production in central Illinois: impacts on hydrology and inorganic nitrogen leaching. In: *Journal of Environmental Quality* 39:1790-99.
- Myers, D.N., Thomas, M.A., Frey, J.W., Rheaume, S.J. and Button, D.T. 2000. Water quality in the Lake Erie-Lake Saint Clair drainages Michigan, Ohio, Indiana, New York, and Pennsylvania, 1996-98.