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Phosphorus Losses from Agricultural Areas in River Basins: Effects and Uncertainties of Targeted Mitigation Measures

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ABSTRACT

In this paper we show the quantitative and relative importance of phosphorus (P) losses from agricultural areas within European river basins and demonstrate the importance of P pathways, linking agricultural source areas to surface water at different scales. Agricultural P losses are increasingly important for the P concentration in most European rivers, lakes, and estuaries, even though the quantity of P lost from agricultural areas in European catchments varies at least one order of magnitude ($<$0.2 kg P ha^{-1} to $>$2.1 kg P ha^{-1}). We focus on the importance of P for the implementation of the EU Water Framework Directive and discuss the benefits, uncertainties, and side effects of the different targeted mitigation measures that can be adopted to combat P losses from agricultural areas in river basins. Experimental evidence of the effects of some of the main targeted mitigation measures hitherto implemented is demonstrated, including: (i) soil tillage changes, (ii) treatment of soils near ditches and streams with iron to reduce P transport from source areas to surface waters, (iii) establishment of buffer zones for retaining P from surface runoff, (iv) restoration of river–floodplain systems to allow natural inundation of riparian areas and deposition of P, and (v) inundation of riparian areas with tile drainage water for P retention. Furthermore, we show how river basin managers can map and analyze the extent and importance of P risk areas, exemplified by four catchments differing in size in Norway, Denmark, and the Netherlands. Finally, we discuss the factors and mechanisms that may delay and/or counteract the responses of mitigation measures for combating P losses from agricultural areas when monitored at the catchment scale.

During the coming decades European river basin managers, limnologists, agronomists, and other stakeholders need to change focus from nitrogen (N) pollution to phosphorus (P) pollution. The EU Water Framework Directive (WFD) is the driving force behind this change in focus, since reduction of P loss to surface water bodies is one of the main factors for obtaining a good ecological condition as required in the WFD (European Parliament, 2000; Moss et al., 2003). Recently, more importance has been attached to the losses of P from diffuse sources as the influence of P from point sources has decreased considerably in most countries due to improved wastewater treatment (European Environment Agency, 1999; Pieterse et al., 2003; Kronvang et al., 2005a). Even though there has been a decreasing P surplus in European agriculture over the past 20 yr, most northwestern and southern European countries experience a net input of P to agricultural land (Leinweber et al., 2002). The total P content of agricultural soils is therefore steadily increasing, which makes the soil more vulnerable to loss via erosion and leaching (Heckrath et al., 1995; Sharpley and Rekolainen, 1997).

Thus, in many European river basins, P losses from agricultural areas are the main P source to rivers, lakes, reservoirs, and coastal waters. Algal growth due to excess P inputs is often the main cause for not fulfilling the requirements for a good ecological quality (Conley et al., 2002; Jeppesen et al., 2003). Phosphorus loss to streams from agricultural areas in smaller catchments has been shown to be significantly higher than the P loss from similar small non-agricultural catchments (Kronvang et al., 1996).

The newly adopted EU WFD aims at protecting different water bodies by performing pressure or impact analysis, introducing monitoring programs, setting ecological reference targets, and developing River Basin Management Plans before 2010 (European Parliament, 2000; Moss et al., 2003). As P is the key nutrient limiting plant growth in rivers, lakes, reservoirs, and at certain periods of the year in many estuaries, river basin managers need to reduce P losses from agricultural land by adopting plans for mitigation strategies. The adoption of management measures in river basins requires the ability of river basin managers to quantify the importance of different P pathways, map P risk areas with a certain spatial resolution, and estimate the effect of various management measures for changes in P losses.

In this paper we will focus on quantifying the importance of agricultural P losses in different European regions, including a quantification of the impacts of different major P pathways. We introduce a typology for different targeted mitigation strategies and investigate their potential effect on reducing P losses from agricultural areas, including information on requirements, uncertainties, obstacles, and side effects. Finally, we present experimental evidence on the effect of different main mitigation measures and discuss the uncertainty in quantifying reductions in agricultural P losses when relying on river basin monitoring programs.

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Abbreviations: DRP, dissolved reactive phosphorus; PP, particulate phosphorus; SS, suspended solids; TP, total phosphorus; USLE, Universal Soil Loss Equation; WFD, Water Framework Directive.

IMPLEMENTATION OF THE WATER FRAMEWORK DIRECTIVE

Implementation of the EU WFD requires river basin managers to produce a river basin management plan for each river basin before 22 Dec. 2009 (European Parliament, 2000). The river basin management plans must include mitigation measures for achieving a good ecological quality before 2016 in all surface water body types not classified as being either heavily modified or artificial.

River basin managers clearly need to follow a stringent scheme when analyzing the type and magnitude of significant anthropogenic pressures on water bodies leading to ecological impacts. Among these pressures are the point and nonpoint losses of P that may lead to eutrophication in rivers, lakes, reservoirs, and estuaries with algal growth, which can severely impact freshwater and marine ecosystems, as a result (Kronvang et al., 1993; Kronvang et al., 2005a). The river basin managers must analyze each catchment on the basis of existing data on land use, pollution sources, and monitoring data. Such an analysis can be performed stepwise, following a concept similar to that shown in Fig. 1, for example. A river basin analysis will start by studying monitoring data on the ecological impacts in surface water bodies being classified into five different ecological classes (high, good, moderate, poor, and bad). All water bodies that have not achieved a good ecological quality need to be mapped and further analyzed to clarify the reasons for the water body failing to achieve a good ecological quality (Fig. 1). In many cases this will be accomplished by establishing relationships between the chemical and biological state of the water body. If P is accountable for a water body not achieving a good ecological quality, the river basin manager will have to investigate the main P pressures by conducting a source inventory quantifying the importance of the main P sources in nature, whether point or nonpoint sources (e.g., Kronvang et al., 2005a). Finally, the river basin managers need to respond to the problem by planning a management strategy involving implementation of possible mitigation measures.

MITIGATION MEASURES FOR PHOSPHORUS

Mitigation measures to combat P losses from agricultural land can be divided into two groups: (i) general measures focusing on reducing the net P input to agricultural land in general, and (ii) targeted measures to be implemented in areas of the landscape with high risk of P losses (Withers et al., 2000). General measures aim at reducing the input of P to the agricultural area by improving the P utilization or the distribution of P and hence lowering soil P status (Poulsen, 2000; Withers et al., 2000). Several authors have shown a linkage between soil P status and P leaching from agricultural soils being arable or grassland (Heckrath et al., 1995; Haygarth et al., 1998; Turner and Haygarth, 2000; Maguire and Sims, 2002). Reduced P input to lower the soil P status has, however, little or no immediate effect on actual P losses from agricultural land to surface waters, although the long-term effect will be crucial, as a further buildup of areas with excess fertilization and excess soil P status will be prevented. Schoumans et al.

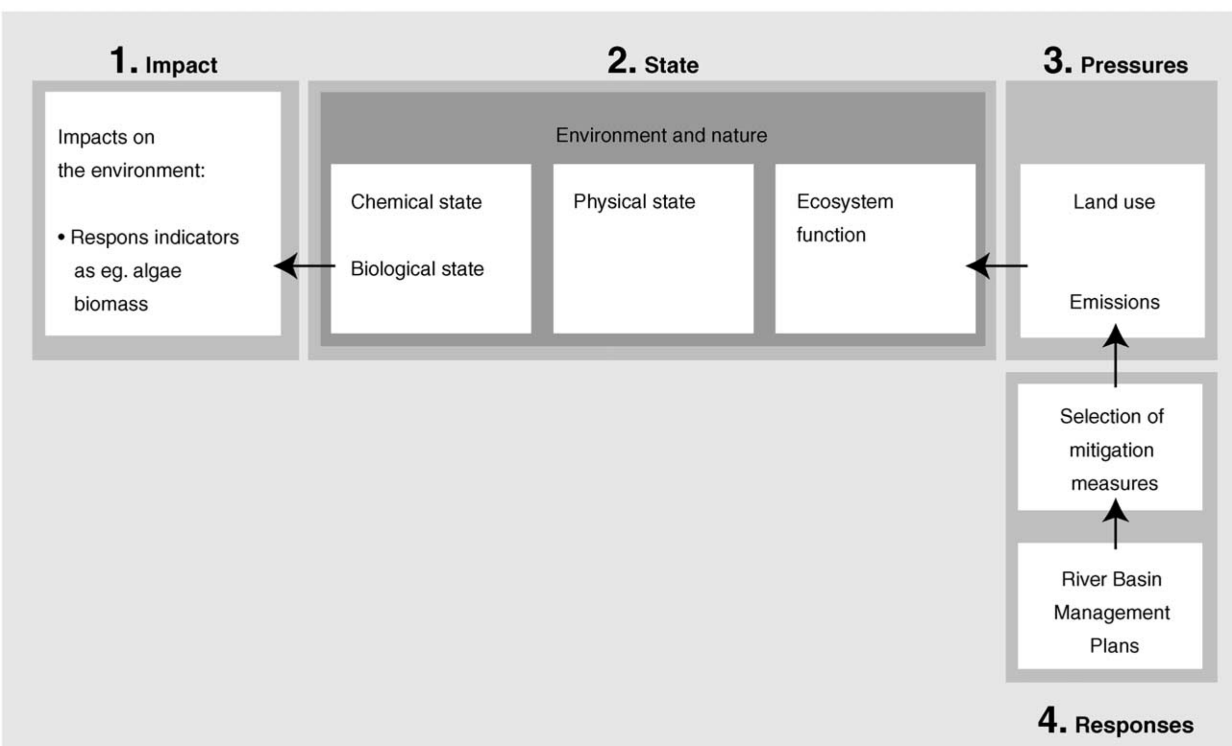

Fig. 1. A concept for river basin managers to use for their analyses under the EU Water Framework Directive, looking into ecological impacts, environmental state, pressures, and how to respond to implementing mitigation measures to achieve a good ecological quality.

(2004) calculated that due to reductions in P manure and fertilizer application rates on agricultural land in the Netherlands the P loss from agricultural land to surface waters initially reduces, but increases again at the long term at constant P surpluses. This was ascribed to leaching of P built up in the soil profile (Schoumans et al., 2004).

To achieve larger and faster reductions in P losses from agricultural land to surface waters it is necessary to combine the general measures with targeted measures in areas with a high risk of P loss. Tools for localizing such high-risk areas have been developed and are currently being refined and adapted to different climatic, geological, and land-use situations in different regions and countries in United States and Europe (Andersen and Kronvang, 2005; Bechmann et al., 2005; Heathwaite et al., 2003; Sharpley et al., 2003). These high-risk areas for P loss are characterized by having both a high content of mobile P and a pathway for transport of P linking the high-risk areas to surface waters. The process of localizing high-risk areas in the landscape typically also identifies both the cause for the high content of mobile P and the pathway for transport (Gburek and Sharpley, 1998; Gburek et al., 2000). This knowledge may then be used for choosing a suitable measure to combat the P losses in each area (Djodjic et al., 2002). Targeted measures therefore aim at interrupting a transport pathway or at reducing the amount or the mobility of P in the high-risk area. Which measure to choose will be site-specific, according to the identified causes for the defined high-risk situation. Measures aimed at the source related to the transport (e.g., reduced tillage) or to the mobility (e.g., direct injection of manure on grass lands) are preferred as they generally have agronomic as well as environmental advantages by preserving soil and nutrients for crop production. However, many of the targeted mitigation measures currently applied are linked to the border of agricultural fields and riparian areas along the river continuum (Fig. 2). Examples of different types of targeted measures, their mode of action, side effects, and requirements are given in Table 1. In the following sections the effects of targeted measures adopted in European countries will be evaluated for use as options for river basin management.

MATERIALS AND METHODS

Quantifying Diffuse Phosphorus Losses

Quantification of the diffuse P losses is illustrated by using a source apportionment model (MONERIS) and by direct measurement of P losses from catchments dominated by agriculture. The model MONERIS (MOdelling Nutrient Emissions in RIver Systems) was developed as an export coefficient model for the investigation of nutrient inputs via various point and diffuse pathways in German river basins (Behrendt, 2004). The basis for the model is data on runoff and water quality for the studied river catchments and also a geographical information system (GIS), in which digital maps as well as extensive statistical information are integrated. While point inputs from municipal wastewater treatment plants and industry are directly discharged into the rivers, the diffuse loadings of nutrients to surface waters represent the sum of various hydrological pathways.

The source apportionment method is based on the assumption that the nutrient (total nitrogen or total phosphorus) transport at a selected river measurement site (L_{river}) represents the sum of the components of the nutrient discharges from point sources (D_P), the nutrient losses from anthropogenic diffuse sources (LO_D), and the natural background losses of nutrients (LO_B) (e.g., Kronvang et al., 2005a). Furthermore, it is necessary to take into account the retention of nutrients in the catchment after the nutrients have been discharged to surface waters (R). This may be expressed as follows:

$$L_{river} = D_P + LO_D + LO_B - R$$

The aim of the source apportionment is to evaluate the contributions of specific point and diffuse sources of nutrients to the total riverine nutrient load, that is, to quantify the nutrient losses from diffuse sources (LO_D) as follows:

$$LO_D = L_{river} - D_P - LO_B + R$$

Discharge, suspended solids, and P losses were measured in three Norwegian catchments. A Crump-weir (Mødre and Skuterud) and a V-notch weir (Kolstad) were used to measure discharge. Water levels were recorded automatically using a datalogger in combination with a pressure transducer, and discharges were calculated on the basis of the existing head–discharge relation. Composite water samples were collected on a volume proportional basis at each monitoring station. Water sampling was controlled by the datalogger so that each time a pre-set volume of water passes the measuring station, a small water sample of the stream water was taken and added to a glass container (20-L capacity). Composite water samples were collected every fortnight and analyzed for suspended solids and P forms. Filtered samples (<0.45 μm) were analyzed for the concentration of dissolved reactive phosphorus (DRP). Unfiltered samples were used to determine the total phosphorus (TP) concentration, by digestion with $K_2S_2O_8$. Concentration of P in all samples was analyzed spectrophotometrically by the ammonium molybdate method of Murphy and Riley (1962) with ascorbic acid as a reducing agent. Particulate phosphorus (PP) was calculated as TP minus DRP. The suspended solids (SS) concentration was determined by filtering an exact sample volume between 25 and 250 mL (containing at least 5 mg SS) through a pre-weighed Whatman (Maidstone, UK) GF/A filter.

Experiments on Impacts of Tillage Changes

Five Universal Soil Loss Equation (USLE) plot sites measuring surface runoff (all) and drain runoff (two) have been running since 1987 in southern Norway (Lundekvam, 1998). In this paper we focus on results from the period 1992–1999. The plots are 21 to 30 m long, with slopes around 13%, and soil types are: (i) leveled silty clay loam, (ii) clay, and (iii) loam with high aggregate stability. The topsoil contained from 800 to 1100 mg total P kg^{-1} dry soil. Annual fertilizing was about 100 kg N ha^{-1} and 19 kg P ha^{-1}, resulting in an annual P surplus of about 6 to 10 kg P ha^{-1} depending on yield. Cereal crops were grown under different tillage systems like autumn plowing (standard), autumn harrowing, no-tillage in autumn (only plowing or harrowing in spring), and removal or no removal of straw. Winter wheat and meadow were also included. Surface runoff was measured continuously with a tipping bucket and water sampling was conducted volume proportional.

Quantifying the Effect of Iron Additions to Soils on Reducing Phosphorus Loss to Surface Water

Phosphate sorption characteristics of several P fixing materials were determined in the laboratory. In a field experiment,

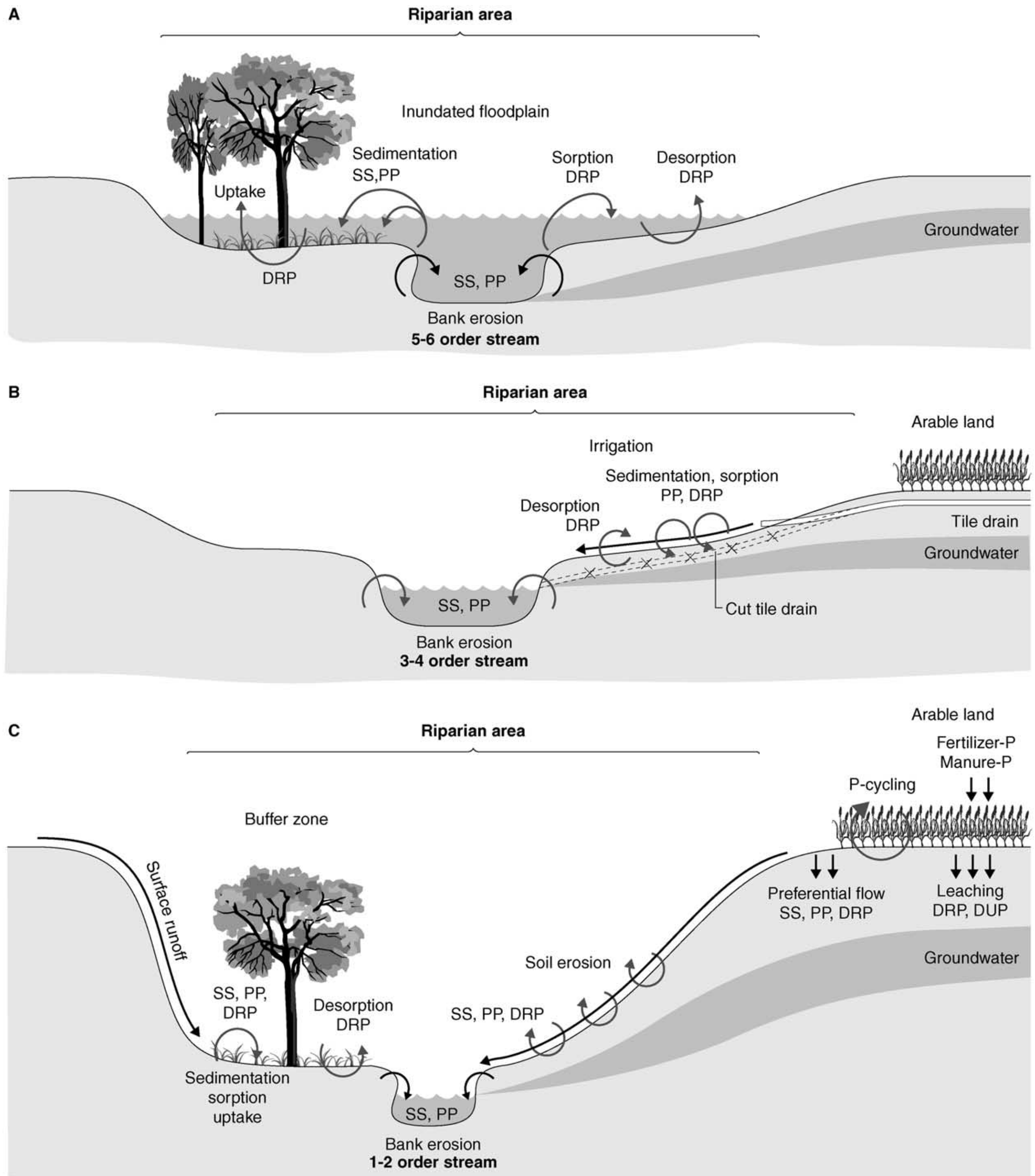

Fig. 2. Schematic diagram of important P pathways and targeted mitigation options taking place along the border of agricultural fields and riparian areas. (A) Downstream part of the river continuum where under natural conditions the river often inundates the floodplain. (B) Middle part of the river continuum where tile drainage pipes often penetrate the riparian areas with water and substances from upland agricultural fields, thus short-cutting the biogeochemical processes in riparian areas. Cutting tile drains and inundating riparian areas can help re-start these retention processes. (C) Most upstream in the river continuum agricultural fields bordering the streams are often steep, resulting in both soil erosion and surface runoff and tillage erosion transport soil and P toward low-lying areas or across the stream edge so that over time low-lying soils bordering streams are enriched in P content.

the overall impact of the most promising P fixing material, suspended amorphous iron-hydroxide solution, was tested (Schoumans and Köhlenberg, 1995). The iron suspension was made by a combination of an iron nitrate solution and a lime solution. Subsequently, the ANIMO model was used to calculate the impact of different quantities of iron additions to the soil and the impact of depth of iron addition on the reduction in P losses by leaching from the field to the nearby ditch (Kruijne et al., 1995). The overall effects of iron addition were described by Schoumans et al. (1995).

Experiments on Functioning of Buffer Zones

An experimental study consisting of two sites (Grorud and Mørdre) located in the southeastern part of Norway was performed to document runoff and retention processes in buffer

Table 1. Targeted measures to mitigate P losses from agricultural areas to surface waters and the effect, requirements, uncertainties, obstacles, and possible side effects of these measures.

Type	Target of measure	Measure	Effect	Requirements, uncertainties, obstacles, and side effects
On-farm regulations	erosional P losses	reduced soil tillage	reduce soil erosion and risk of soil and P mobilization	can both reduce and increase P losses depending on site-specific erosion risks; can increase the demand for pesticide application
		contour soil tillage		difficult on very steep fields
		avoid or remove tramps in crops sawn across contours		
	surface runoff	winter cereals directly sawn without soil tillage	reduce erosion and surface runoff with risk of P transport to surace waters	requires winter cereals to be directly sown in stubble of previous crop
		band of winter cereals on erosion risk fields		demand for other crops and use of catch crops, etc.
		establishment of permanent grassland		difficult to apply on pig farms and crop farms; risk for increased loss of dissolved P
	surface runoff and leaching through macropores to tile drains	avoid application of fertilizer and manure on steep areas before periods with heavy rain and snow melt	can reduce P transport with surface runoff and P transport via macropores	can increase the risk of ammonia volatization from application of animal manure
	erosion and surface runoff	introduction of perennial nonfood crops	can reduce P mobilization with soil erosion and P transport via surface runoff	specialized crops with a limited potential for farming
	increased P harvesting from soil	introduction of crops with a high P demand	reduces the net input of P to the soil	
	immobilization of soluble P	application of P sorbents to soil and manure (Fe or Al salts)	increases the P binding potential in soils	risk for crop yields due to introduction of too low soil P status; risk of leaching of Al under low soil pH conditions
	surface runoff and leaching through macropores to tile drains	optimized handling and use of animal manure (application shortly before or during growing season and fast incorporation in soil)	reduces the risk of direct losses of manure P	improves utilization of N and P in animal manure
Changes in land use	elimination of P application to soils; can reduce P loss with soil erosion and surface runoff	set-aside of arable land	eliminates further buildup of soil P content; reduces P mobilization and P loss via soil erosion and surface runoff	no removal of P from the soil; reduces the nitrogen loss; creates refuges for flora and fauna; certainly a measure against erosion but unknown impact for P leaching
	elimination of P application to soils; can reduce P loss with soil erosion and surface runoff	afforestation	reduces P loss	effect depending on the kind of forest raised; can, on the shorter time scale, increase erosion and leaching of P; reduces the input and output of P to soils; reduces N loss; creates corridors in the landscape for wild life and game refuges
	retain P through sedimentation and P uptake in plants	riparian buffer zones	reduces P transport to surface waters	reduces N losses; creates corridors in the landscape for wildlife and game refuges; more uncertain for dissolved P than for particulate P; increases sediment P pool in areas near to surface waters
	reduce soil erosion, surface runoff, and wind erosion	barriers in the landscape (living fences, etc.)	reduces P mobilization via water and wind erosion and transport to surface waters	creates corridors in the landscape for wild life and game refuges; certain effect regarding P loss with wind erosion but uncertain for other P losses
	retain P through sedimentation	re-establishment of former wetlands and lakes	increases the natural capacity for P retention	reduces N losses through reduced leaching, increased denitrification and sedimentation; benefits for flora and fauna; certain regarding sedimentation of P, but uncertain regarding releases of soil P from formerly agricultural land being re-wetted

Continued next page.

Table 1. Continued.

Type	Target of measure	Measure	Effect	Requirements, uncertainties, obstacles, and side effects
	retain P through sedimentation	extensivation and allowing temporary inundation of formerly drained agricultural land on floodplains	increases the natural capacity for P retention	reduces N losses through reduced leaching, increased denitrification and sedimentation; benefits for flora and fauna; certain regarding sedimentation of P, but uncertain regarding releases of soil P from formerly agricultural land being re-wetted
Environmental management	sedimentation of particulate P	cutting tile drainage pipes at valley edge allowing drainage water to irrigate meadows	reduces P transport to surface waters through sedimentation and P uptake in plants	reduces N losses through increase in denitrification; beneficial for flora and fauna; certain regarding sedimentation of P, but uncertain regarding transformation of P and release of dissolved P
	prevention of P transport through tile drains and ditches	cutting of tile drains and blocking of ditches	reduces P transport to surface waters through cutting of pathways	reduces N losses through increase in denitrification; can create local wet areas with a risk for releases of dissolved P; reduced draining of uphill bordering farmland
	establishing new sinks for P	sedimentation ponds for tile drainage water	reduces P transport to surface waters through sedimentation of particulate P	excavation and management of large quantities of deposited material
	reduces stream bank erosion	protection of stream banks against erosion	reduces particulate P mobilization and transport to surface waters	reduction in stream maintenance (excavation and weed cutting); protection against trampling of banks by animals
	remove P from buffer zones	harvest plant material in buffer zones	removes P with plant material thereby preventing freezing out of P and reducing soil P content	no experience with the possibility of applying the measure and its short- and longer-term effects

zones (Syversen, 2002, 2003). The experiment was based on 8 and 5 yr of surface runoff collection from 5- and 10-m-wide buffer zones, respectively, and plots without buffer zones. The slope of the study sites was 12 to 14% and soils consisted of silty loam (Grorud; 19% clay, 64% silt, 17% sand of minerogenic content, and 4% organic matter) and silty clay loam (Mørdre; 44% clay, 51% silt, 5% sand of minerogenic content, and 1.5% organic matter). The buffer zones had a high diversity of plant species and the predominant plants were common couch (*Elytrigia repens* L. Desv. Ex Nevski), thistle [*Circium arvense* (L.) Scop.], wild angelica (*Angelica sylvestris* L.), and green sandpiper (*Equisetáceae sylváticum* L.). Measurement of accumulated runoff was accomplished by a tipping bucket with a mechanical counter (Grorud) and a datalogger measuring discharge rate (Mørdre). For every second bucket (about 12 L) a sample was collected in a sampling tank. Volume proportional mixed samples were taken after every runoff event or more frequent, if necessary (e.g., during snowmelt).

Sedimentation on Inundated Floodplains

Sedimentation of P was measured in transects perpendicular to the river channel using sediment traps on a frequently inundated riparian wetland in the lower part of the River Gjern and along a newly re-meandered 4.5-km reach of the River Brede in Denmark (Kronvang et al., 1998). Content of P in deposited sediment was analyzed according to Svendsen et al. (1995).

RESULTS AND DISCUSSIONS

Agricultural Phosphorus Losses in European River Basins

The main sources and pathways for P losses in different European river basins were modeled by application of the MONERIS model (Behrendt, 2004). Total P export from the river basin loss varied between 0.27 to 1.06 kg P ha^{-1}, whereas P emissions to surface waters were more consistent when taking into consideration the modeled P retention in surface water (0.81–1.41 kg P ha^{-1}) (Table 2). A source apportionment of P emissions in these larger river basins showed that a relatively large proportion of the average annual P emissions to surface water originated from agriculture (Table 2).

Similarly, Kronvang et al. (2003) and Vagstad et al. (2001) documented large differences in the agricultural P losses in small agricultural catchments in Europe. Kronvang et al. (2003) showed that agricultural P losses seemed to vary markedly from country to country, although the countries have the same proportion of agricultural land. Vagstad et al. (2001) found no relationship between P loss and the P surplus in the catchments studied. The apparent great differences in P loss from agriculture within European microcatchments and major river basins therefore seem to be linked to the existence and strength of the P pathways from source areas in the different regions rather than to the P surplus or soil P status (Heathwaite et al., 2000). The P loss from agricultural areas in river basins arises from the contribution of dissolved phosphorus (DP) and particulate phosphorus (PP) losses to surface water via different pathways (soil erosion and surface runoff, bank erosion, leaching, tile drainage water; Kronvang et al., 2002b).

Table 2. Model-estimated (MONERIS) contribution of agricultural total P losses to total P emissions to surface water within major European river basins (according to Behrendt, 2004).

River basin	Catchment area	Mean annual runoff	Population density	Total P export from river basin	Total P emission to surface waters	Total P loss from agriculture
	km^2	mm	inhabitants km^{-2}	kg P ha^{-1}		
Elbe	148 270	159	166	0.36	0.81	0.36 (44%)
Rhine	185 300	430	309	1.06	1.28	0.27 (21%)
Danube	802 888	269	102	0.27	0.84	0.36 (43%)
Odra	118 148	149	134	0.38	1.09	0.19 (17%)
Po	73 761	681	192	1.06	1.41	0.34 (19%)

The importance of soil erosion for the loss of P forms from agricultural catchments can be seen from the increasing loss of both PP and DP with increasing erosion soil risk in three Norwegian catchments (Table 3). However, the results also illustrate the enrichment of TP to SS for the Kolstad catchment with low erosion risk. The enrichment ratio results from the selective nature of the erosion process, which has also been discussed elsewhere in relation to reduced tillage, in addition to the increased relative contribution of DP originating partly from subsurface drainage pathways.

The average annual total P loss from Danish agriculture to surface waters has been quantified in two ways, by (i) conducting a source apportionment of riverine loads to coastal waters and (ii) upscaling the P loss from a combination of source areas and pathways based on empirical evidence from field experimental data and knowledge on the extent of source areas and pathways. Both methods provide comparable results for total P loss to surface waters (Table 4). However, the results from quantifying the importance of different P pathways are much more valuable for river basin managers, as they indicate where mitigation measures can be used most effectively to reduce P losses from agricultural areas. Based on the findings of Laubel et al. (2003) the breakdown of total P losses showed that stream bank erosion is a main P source to Danish surface waters (Table 4). This finding is of great importance as bank erosion as a P source is rarely included when P losses in river basins are modeled.

Effects of Targeted Mitigation Measures for Reducing Phosphorus Loss

Effects of Soil Tillage Changes on Phosphorus Losses

Runoff and loss of soil material and P from five USLE plots on different soil types in Norway using the standard autumn-plowing system is shown in Table 5. The artificially leveled Soil Type A with low organic matter content and low aggregate stability had clearly the highest soil loss, surface runoff, and total P loss. A relationship was obtained between the concentration of total P (Y in μg P L^{-1}) and suspended solids (X in mg L^{-1}): $Y = 223 + 1.033X$ ($n = 35$; $R^2 = 0.986$; $P < 0.0001$). The equation is based on average values for several years for each site and treatment. The relationship between TP and SS in runoff water has a large intercept indicating that the soil particles may be enriched in P at low soil erosion levels and/or that DP may contribute more to TP during periods of low soil erosion. Enrichment of P in runoff water at low erosion levels has often been reported (Smith et al., 1993; Catt et al., 1994) and generally relates to the selective nature of soil erosion. Phosphorus is associated primarily with the finer fractions of the soil (Syers and Walker, 1969), which are often transported preferentially. In some cases, however, P enrichment is less pronounced (e.g., soil erosion during snowmelt on frozen soil) (Bechmann et al., 2005). The annual data presented here did not reflect the snowmelt.

Because of the high constant term, it also follows that measures reducing soil losses will be less efficient in reducing P losses, especially if erosion levels are low. This is also reflected in the experiments comparing no tillage in autumn with plowing in autumn (Fig. 3). Soil and P losses were greatly reduced with no autumn plowing in the plots with Soil Type A and high erosion risk (Sites BJ, AS, and HE) (Fig. 3). The reduction in soil and P loss was less pronounced in plots with Soil Type B and medium erosion risk (Site OS), whereas only a minor reduction in soil losses and a net increase in P loss was measured in the well-drained Soil Type C with low erosion risk (Site SY) (Fig. 3). The latter could partly be explained by the increase in surface runoff observed from the medium to low erosion risk plots but also the transport of small P enriched particles with the higher surface runoff (Fig. 3). The following reductions for the three soil types were found: Soil Type A (Sites BJ, AS, and HE with high erosion risk): soil loss 89%, P loss 76%; Soil type B (Site OS with medium erosion risk): soil loss 80%, P loss 66%; Soil type C (Site SY with well-drained soil): soil loss 22%, P loss −71% (Fig. 3). The reduced P loss by no autumn plowing has been reported in many studies in Europe (e.g., Catt et al., 1998; Chambers et al., 2000) and the United States (e.g., Sharpley, 1995). Since most runoff and erosion in Norway occur during winter the effect of no-tillage in autumn is important for the annual losses. The studies on measures

Table 3. Average soil erosion risk and average annual losses of suspended solids (SS), total phosphorus (TP), particulate phosphorus (PP), and dissolved reactive phosphorus (DRP) from agricultural areas in three catchments in Norway. Mørdre and Kolstad were monitored during the period 1991–2002, whereas Skuterud was monitored during the period 1993–2002.

Catchment	Size	Soil erosion risk	Loss			
			SS	TP	PP	DRP
	ha	Mg ha^{-1} yr^{-1}	kg P ha^{-1} yr^{-1}			
Skuterud	450	0.9	1.5	2.4	2.1	0.4
Mørdre	680	0.6	1.1	1.5	1.3	0.2
Kolstad	310	0.07	0.2	0.5	0.4	0.2

Table 4. Estimated contribution of different phosphorus pathways to agricultural total P losses in Denmark and the total P loss from agricultural areas calculated by upscaling and by applying the source apportionment method during the years 1993–2001.

	Soil erosion and surface runoff	Wind erosion	Bank erosion	Leaching to tile drains on mineral soils	Leaching to tile drains on organic soils	Upper ground water	Total via upscaling	Total via source apportionment
	Mg yr^{-1}							
Estimated annual P loss	7–35	5–15	275–645	55–200	30–225	<60	432–1180	450–1050

to reduce erosion were mainly performed under conditions of high erosion risk (like Soil Type A). Other investigations have also found that no tillage can increase the P loss (Carter, 1998; Withers and Jarvis, 1998) as was shown for Soil Type C.

Small P-enriched particles and dissolved P may stay a long time in water bodies and may have a high bioavailability (Ekholm, 1998; Maguire et al., 1998). Therefore, the effects of measures reducing erosion on eutrophication will be even smaller than the effects on reducing total P. Still it will be sensible to reduce erosion by changing autumn to spring soil tillage, especially on soils with moderate to high erosion risk. Plant residues, fertilizer, and manure left on top of the soil may be an extra P source, as justified in the Norwegian P Index (Bechmann et al., 2005). Therefore, a relatively high total P loss to soil loss ratio may occur in systems like direct drilling, changing autumn to spring soil tillage, or shallow tillage (harrowing). For the same reasons permanent grassland will be more vulnerable to such P losses, because there is no incorporation of plant residues, nor fertilizer or manure in the soil. This is reflected in the ratios of TP to SS (Y/X): meadow (6–12); harrowing in spring (1.8–5.8); plowing in spring (2–4); harrowing in autumn (1.4–3.4), and plowing in autumn (1.03–2.26).

Impact of Iron Additions to Soils to Reduce Phosphorus Losses by Leaching

Different types of measures to reduce the impact of P accumulation in soils on P losses to surface water under leaching conditions have been studied in the past, including changes in manure application rates, soil treatment with (for example) iron-containing material, and hydrological measures changing the pathways of soil water transport (Schoumans et al., 1995). As previously discussed the short-term impact of general measures restricting manure application is limited under conditions with P accumulation in the subsoil. As the length of the pathway from the upper part of the soil to the ditches increases with increasing distance from the ditch under natural leaching conditions (without tile drainage), only a restricted part of the field (besides the ditches) needs to be treated with (for example) iron-containing material to retain P (Fig. 4). In a field study on sandy soil in the center of the Netherlands, 0.002 g Fe per gram soil (0.2%) added to the soil material to a certain depth seems to be sufficient to reduce the P loss by up to 80% (Fig. 4). Figure 4 shows to what extent the P losses to surface waters will be reduced at different treatments (Fe addition and depth of Fe treatment). Moore et al. (2000) showed beneficial impacts of treating poultry litter with aluminium sulfate [$Al_2(SO_4)_3{\cdot}14H_2O$] for reductions in P runoff from agricultural land in the United States. Although Fe or Al treatment of soil and manure effectively reduces P losses to surface waters at the short term, such treatments are not commonly used in Europe. For the Netherlands, the most important arguments are the costs and the fear of negative impact on environment, animal welfare, or crop production.

Table 5. Average annual runoff, soil loss, total phosphorus (TP) loss, concentration of suspended solids (SS) and TP, and the ratio of TP to SS concentration measured in surface runoff and tile drainage water from five Universal Soil Loss Equation (USLE) plots during 1992–1998.

Soil type	Runoff	Soil loss	TP loss	SS concentration	TP concentration	TP to SS ratio
	mm	kg ha^{-1}	g P ha^{-1}	mg L^{-1}	μg P L^{-1}	
			Surface runoff			
A	226	3310	3850	1465	1704	1.16
B	120	940	1130	778	940	1.21
C	82	120	273	146	332	2.26
			Subsurface drainage water			
A	210	1040	1300	495	620	1.25
C	292	37.4	144	12.7	49	3.9

Effect of Establishing Vegetated Buffer Zones for Phosphorus Trapping

An experiment on the effect of establishing 5- and 10-m-wide buffer zones was performed at two sites in

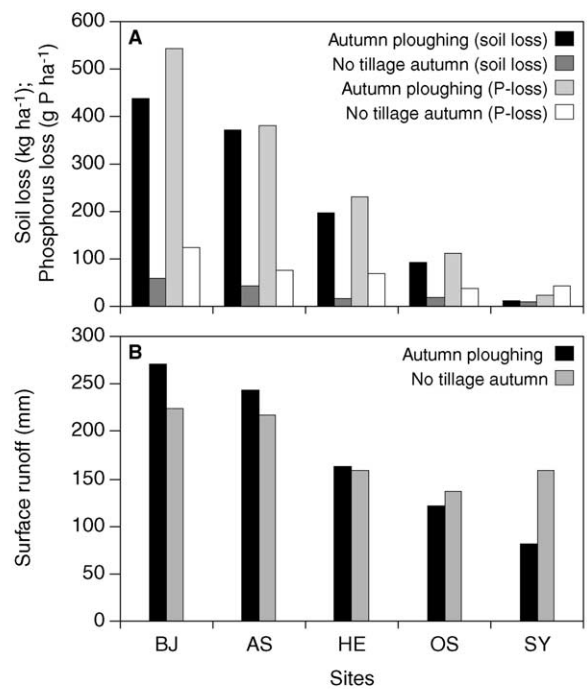

Fig. 3. Soil and total phosphorus losses (A) and surface runoff (B) at five sites with Universal Soil Loss Equation (USLE) plots of different soil erodibility. The USLE plots were either plowed in autumn or not (only spring tillage) during the period 1992–1999.

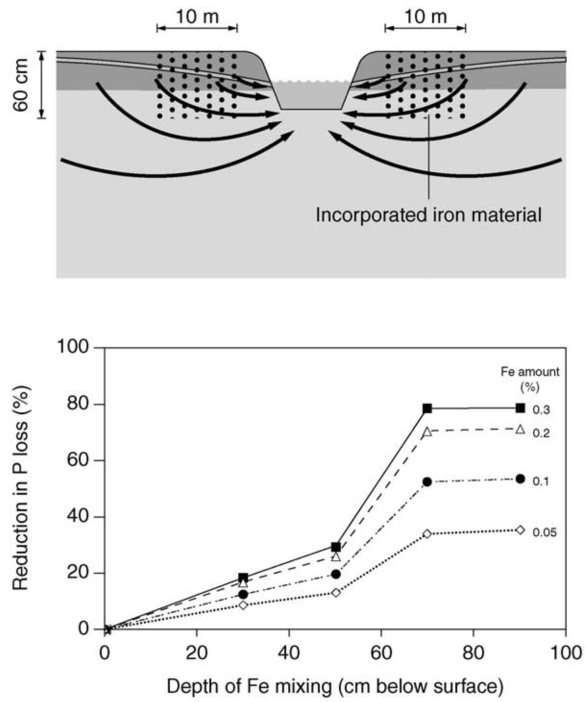

Fig. 4. Schematic diagram (A) of the iron treatment of soils in different depths along stream channels or ditches, and (B) the modeled reduction in phosphorus loss to surface waters following mixing of iron material in different concentrations into various depths of the soil column near ditches.

southeastern Norway. The removal efficiency for SS and P was very high at the Grorud site for both 5- and 10-m-wide buffer zones, whereas the removal efficiency was lower for the 5-m buffer zone at the Mørdre site (Fig. 5). A possible reason for the lower removal efficiency for the 5-m buffer zone at the Mørdre site compared to the 5-m buffer zone at the Grorud site is the higher silt and sand content at the Grorud site (71%) as compared to the Mørdre site (56%). The 5-m buffer zone at the Grorud site is therefore more efficient at retaining the coarser soil material entering the buffer zone with runoff water than at retaining the finer soil material entering the 5-m buffer zone at the Mørdre.

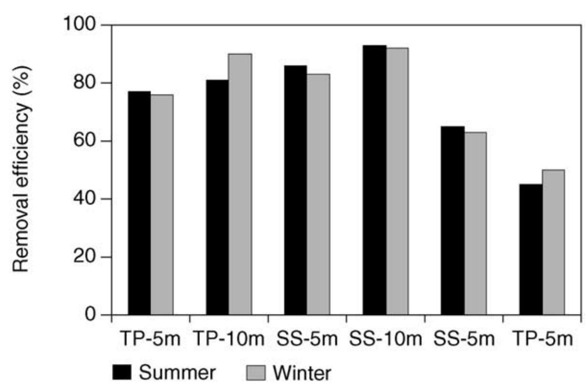

Fig. 5. Removal efficiency (%) for suspended solids (SS) and total phosphorus (TP) in surface runoff during summer and winter. Experiments were conducted with 5- and 10-m-wide buffer zones at the Grorud site during 1992–1999 and 5-m-wide zones at the Mørdre site during 1999–2003.

Also, Schauder and Auerswald (1992) found a sorting of particle sizes along a vegetated buffer zone where sand was trapped in the upper part (first 13 m), while trapping of silt particles increased up to 20 m, after which the trapping of clay started to increase. All fractions, also clay (possibly as aggregates), were deposited in the beginning of the buffer zone. No significant differences in removal efficiency between summer and winter (winter being defined as 1 November to spring snowmelt) were measured for any study site, buffer zone width, or substance (Fig. 5). The removal efficiency was expected to be higher during the summer period than the winter period due to the higher vegetation density and biomass, the possible uptake of nutrients in the vegetation, and lower surface runoff intensity. However, a higher runoff intensity during winter caused detachment of coarser particles in the upland agricultural area, especially at the Grorud site, which resulted in a high sedimentation and hence high efficiency of the buffer zone in winter (Syversen, 2002). The Mørdre site had much higher clay content (44%) than the Grorud site (19% clay). Thus, during winter there was a higher portion of fine clay compared to summer and here the fine clay had possibly been transported and trapped as aggregates in the buffer zone at the Mørdre study site (Syversen, 2005). Also, Cooper and Gilliam (1987) and Cooper et al. (1987) found clay deposition downstream on a flood plain in a riparian area, while silt and sand were deposited near the field–forest edge. Overall, total removal efficiency for P is high in Norwegian buffer zone experiments. Also, buffer zone experiments performed in Europe and the United States show high removal efficiency of P through buffer zones (e.g., Dillaha et al., 1989; Vought et al., 1994; Dillaha and Inamdar, 1997; Kuusemets, 1999; Uusi-Kämppä et al., 2000; Uusi-Kämppä, 2002).

In many countries water erosion and surface runoff on field slopes are important sources and hydrological pathways for sediment and P delivery to surface waters (Johnes and Hodgkinson, 1998; Verstraeten and Poesen, 2000). Therefore, many authors have looked at the possibility of trapping sediment and P in uncultivated buffer zones established along streams and lakes (e.g., Dillaha et al., 1989). The efficiency of such buffer zones for trapping of sediment and sediment-associated P is well documented from experimental research on small field plots (e.g., Uusi-Kämppä et al., 2000). Less research has been conducted on water erosion and buffer zones under natural field conditions and some authors have questioned the long-term benefits of buffer zones and the functioning of buffer zones under natural conditions (Haycock et al., 1997).

This was corroborated by the finding in a Danish survey conducted within approximately 140 agricultural fields (slope units) of the trapping effect of buffer zones of different widths for soil material and P. The survey was conducted during early spring of 1998–2001 by counting the number of erosion rills within two size classes, number of sand deposits on the field, number of sites in buffer zones with sediment deposition, and number of sites with delivery of sediment to the stream (Kronvang

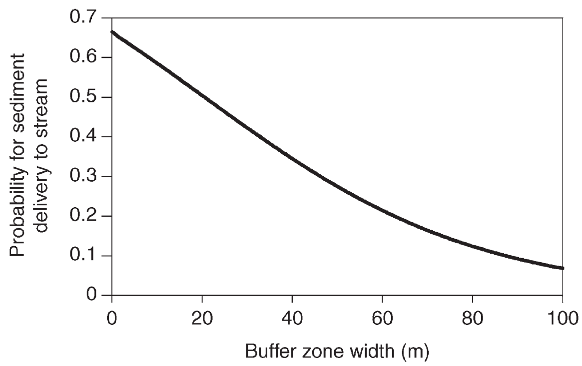

Fig. 6. The probability of sediment material to escape through a buffer zone of different widths under natural conditions when larger rills (>100 cm^2 cross-sectional dimension) are formed on the adjoining fields.

et al., 2005b). Figure 6 shows that, under natural conditions, the probability for sediment to escape through buffer zones receiving runoff water and soil material from larger rills seems to be very dependent on the buffer zone width.

Deposition of Phosphorus on Overbank Flooded Riparian Wetlands

The flux of particulate phosphorus (PP) in and out of river systems can be very discontinuous, with periods of suspension and transport alternating with periods of sedimentation on the river bed, in nonflowing, dead zones of the river channel, and on inundated floodplains (Svendsen et al., 1995). In many river systems, however, overbank flooding is prevented because watercourses have been regulated for the purpose of drainage of agricultural areas, ship traffic, dams, and reservoirs, etc. (European Environment Agency, 1999). In river and floodplain systems with natural temporary inundation, overbank storage has been shown to be an important sink for sediment and associated nutrients (Walling and He, 1994; Kronvang et al., 1999, 2002a; Walling and Owens, 2003). As an example, average deposition rates of sediment and PP during each of three flood events studied in the River Gjern, Denmark, are shown in Table 6. The sediment retention efficiency ranged from 5.6 to 23.9%, whereas the PP retention efficiency ranged from 2.7 to 5.4% during the three studied overbank floods. The lower efficiency of the floodplain to retain PP is probably caused by the enrichment of P in fine particles that escape the deposition process more easily. This is corroborated by the finding that the P content of deposited material increases from 0.41% at a distance of up to 20 m from the river channel to 0.72% more than 60 m from the river channel. Thus, fine particles enriched in P are deposited further away from the river channel.

Table 6. Average deposition rates of sediment and particulate phosphorus (PP) and the efficiency of the floodplain to retain sediment and PP calculated as deposition divided by the transport in the river during three overbank flood events in the naturally flooded lower part of the River Gjern during the winter of 1992–1993.

Length of inundation period	Sediment	Efficiency	PP	Efficiency
d	g dry wt. m^{-2}	%	g P m^{-2}	%
8	254	5.6	1.18	2.7
9	1205	11.3	3.75	5.0
19	3002	23.9	6.50	5.6

In 1998, the Action Plan on the Aquatic Environment II was passed by the Danish Parliament. To achieve the overall goal of reducing N pollution of the aquatic environment by 50%, 16 000 ha of wetlands should be re-established within a 5-yr period (Hoffmann et al., 2003). Of the 5000 ha re-established wetlands in 2003 more than 90% were established as riparian wetlands being temporary inundated in connection with re-meandering of formerly straightened and channelized river channels during major drainage schemes to reclaim agricultural land. Flood frequency, flooded area, and deposition of sediment, organic matter, and P were monitored after re-meandering of the River Brede in Denmark in 1994. A net deposition of 1710 g dry wt. sediment m^{-2} and 2.34 g P m^{-2} was measured on the restored floodplain during the first winter (1994–1995) following an increase in total flood duration of 300 h. The efficiency of the floodplain to retain sediment and PP calculated as deposition divided by the transport in the river during the winter was 47 and 7%, respectively. Thus, both natural and restored lowland river–floodplain systems have been shown to act as sinks for sediment and PP during shorter-term flooding periods. As transport of sediment and P in rivers mainly takes place during flood events, the results underline the importance of restoring even small inundated lowland floodplains for restricting the export to downstream water bodies.

Inundation of Riparian Areas with Tile Drainage Water

Subsurface P losses can be of great importance as a direct transfer route for DP and PP from fields to surface waters as shown for the two types of tile-drained Norwegian fields in Table 5. Similarly, Grant et al. (1996) found high DP and PP losses from four studied Danish tile-drained fields (DP: 0.028–0.445 kg P ha^{-1} yr^{-1}; PP: 0.043–0.182 kg P ha^{-1} yr^{-1}), whereas Foster et al. (2003) showed very high PP losses from four English tile drains, ranging from 0.04 to 1.91 kg P ha^{-1} yr^{-1}. An immediate way to reduce the loss of DP and especially PP from agricultural fields to surface waters could be by allowing formerly tile-drained lowland fields to become irrigated with tile drainage water from upland fields, thus creating constructed wetlands. Several such wetlands have already been constructed in Denmark to reduce N runoff (Hoffmann et al., 2003). The experience in the international literature with P retention in constructed wetlands indicates that both net releases and net retention can occur (Peterjohn and Correl, 1984) and the few Danish studies on the topic are also inconclusive (Table 7). Clearly, factors like hydraulic loading, P saturation status of the lowland soil, and binding capacity of Fe- and Al-oxides for P are important controls on retention and release of P from the irrigated and flooded soil (Peterjohn and Correl, 1984; Richardson, 1985).

Table 7. Phosphorus retention in Danish riparian areas irrigated with tile drainage water.

Inundated systems	Loading	Retention		Reference
	kg P ha^{-1} yr^{-1}		%	
Glumsø, full scale	7.5	−29.2	−389	Gervin et al. (1990)
Stevns Å, meadow†	460	26	96	Hoffmann et al. (1993)
Syv bæk, meadow	6.29	0.07	1	Ambus and Hoffmann (1990)
Stor Å, restored meadow	3.04	2.19	72	County of Funen (unpublished data)

† Concentration of dissolved reactive phosphorus (DRP) in drainage water (μg P L^{-1}).

Mapping Critical Source Areas at Different Catchment Scales

The area with different categories of P input to agricultural land from P in fertilizer and animal manure was mapped in four predominantly agricultural catchments covering different size scales in Norway, Denmark, and the Netherlands (Table 8 and Fig. 7). Questionnaire data from farmers were used in the two Norwegian catchments, whereas census data were used in the Danish catchment (8-ha level) and the Dutch catchment. Agricultural areas receiving high P inputs (>30 kg P ha^{-1}) constitute 17% in the Skuterud catchment, 20% in the Mørdre catchment, 33% in the Odense catchment, and 50% in the Vechte catchment (Table 8). Average annual P removal by harvest is lower in the Norwegian catchments than in the Danish and Dutch catchment. The differences in P inputs to agricultural soils in the four catchments are also reflected in the soil P status being generally much higher in the Dutch catchment than in the Danish and Norwegian catchments (Table 8). It is therefore more important to enforce general mitigation measures for reducing the P input to agricultural land in the Dutch catchment than in the Danish and Norwegian catchments, to reduce the P surplus and hence reduce P losses from soils to surface waters.

Soil erosion risks were mapped using soil erosion models in the four catchments (Table 9). Such mapping can help river basin managers to analyze the need for targeted mitigation measures and, when displayed in geographical information systems (GIS), to direct the measures to the individual field (Fig. 7). High risk areas defined as areas with an erosion risk of more than 1 Mg soil ha^{-1} accounted for 59% in the Skuterud catchment, 34% in the Mørdre catchment, 12% in the Odense catchment, and 0% in the Vechte catchment (Table 9). Targeted mitigation measures to prevent soil erosion and surface runoff of P are therefore more important for reducing P losses to surface waters in the two Norwegian catchments than in the Danish and Dutch catchments, the latter being completely without erosion risk areas (see Table 9). The targeted mitigation measures could be soil tillage changes (supported by the Norwegian government) or buffer zones, which are supported by the governments in both Norway and Denmark. The area with no autumn tillage has increased to 74 and 77% in the two Norwegian catchments since 1990 as a consequence of economic support and information to farmers. As can be seen from Table 9, large parts of the agricultural area in the Norwegian and Danish catchments are tile-drained (>70%), whereas the proportion is low in the Dutch catchment (<5%). Tile-drained areas have been shown to be able to lose large quantities of DP and PP due to preferential flow through macropores (Grant et al., 1996; Laubel et al., 1999). River basin managers should therefore pay attention to the combination of soils vulnerable to preferential flow, having high soil P status and being tile-drained. In addition, areas of vegetable production, which generally receive large amounts of P, are often located in areas with light or organic soils with a low sorption capacity of P and hence may constitute significant source areas within a river basin. Implementation of general or targeted mitigation mea-

Table 8. Description of the four catchments as to size, agricultural areas, livestock, soil P status, losses of phosphorus forms, and the phosphorus input with chemical fertilizer and animal manure to agricultural fields.

	Skuterud catchment† (Norway)	Mørdre catchment† (Norway)	River Odense‡ (Denmark)	Vechte§ (the Netherlands)
Catchment size, km^2	4.5	6.8	485.9	3703
Agricultural area, %	60	65	71	76
Livestock, units ha^{-1} total area	0.1	0.1	0.9	0.8–1.0
Soil P status, mg P-AL 100 g^{-1}	8.2 (4–18)	8.5 (2–22)	13.4	10–50
Average annual runoff, mm	526 (222–1042)	279 (182–476)	290 (122–454)	318
Average annual total P loss, kg P ha^{-1}	2.5 (1.2–5.8)	0.9 (0.5–1.7)	0.52 (0.21–0.75)	1.46
Average annual dissolved reactive P loss, kg P ha^{-1}	0.4 (0.2–0.8)	0.1 (0.06–0.3)	0.25 (0.1–0.35)	0.32
P input				
			Area	
kg P ha^{-1}	ha (% of agricultural land)			
0–10	2 (0.7)	20 (4.3)	9269 (28)	89 625 (25)
10–20	64 (23)	208 (44)	5989 (18)	75 244 (21)
20–30	163 (59)	147 (31)	7346 (22)	15 963 (4)
30–40	32 (12)	45 (10)	6951 (21)	0 (0)
40–60	9 (3.3)	16 (3.4)	3744 (11)	44 769 (12)
60–80	6 (2.2)	13 (2.8)	333 (1.0)	14 863 (4)
>80	0	20 (4.3)	123 (0.4)	122 444 (34)

† Year = 2000 (average and range from 1994–2003).
‡ Year = 2000–2001 (average and range from 1990–2000).
§ Year = 2000.

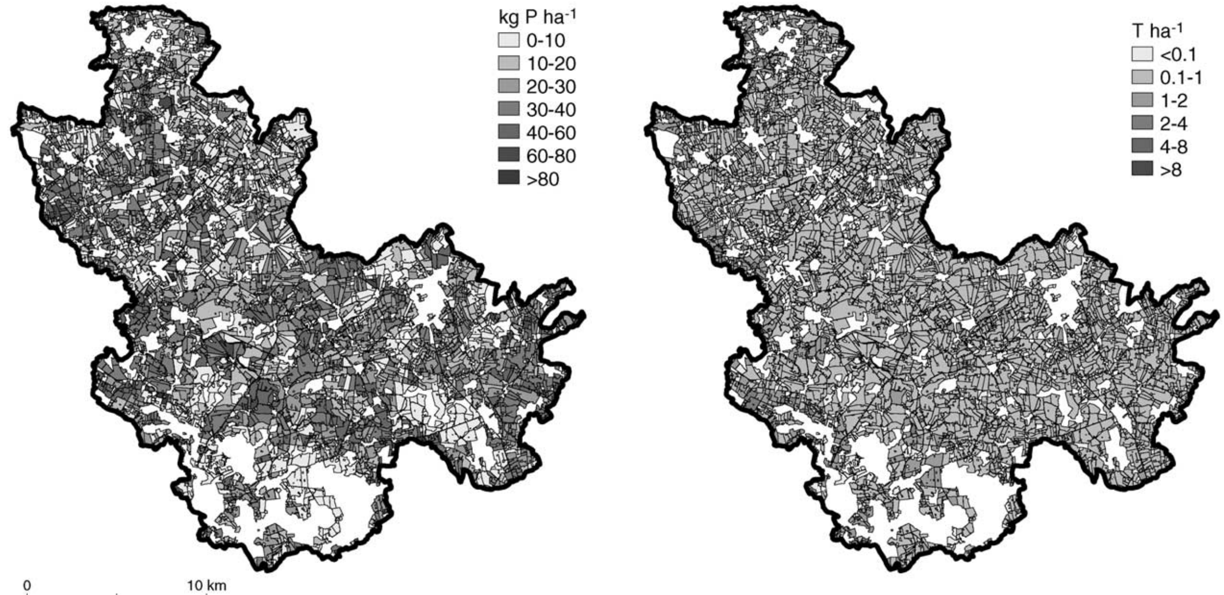

Fig. 7. Maps of phosphorus application with fertilizer and animal manure and soil erosion risk classes in the Danish River Odense catchment for agricultural blocks of an average size of 9 ha.

sures on these agricultural areas is very important for reducing P losses to surface waters. However, it is often very difficult to map these areas, due to lack of information on the soils vulnerable to preferential flow and lack of tile drain maps for larger areas.

Uncertainties in Catchment Responses to Phosphorus Mitigation Measures

Delays and modifications in catchment response to the implementation of general mitigation measures for combating N losses from agricultural land to surface waters have been reported by many authors (Stålnacke et al., 2003). Comparable knowledge on measures for combating P losses and the possible mechanisms responsible for creating delays and modifications is very important for river basin managers, stakeholders, and the public, as they rely on monitoring programs in surface water bodies to measure the benefits. Moreover, the WFD sets strict deadlines for achieving the objective of good ecological conditions in surface water bodies by the end of 2015 (European Parliament, 2000).

Table 10 shows the most important mechanisms influencing the catchment response to mitigation measures adopted to combat phosphorus losses from agricultural land. Climate conditions as inter-annual variations in climate or long-term changes in climate (temperature and precipitation) can strongly influence P mobilization in agricultural areas and the resulting P concentration and P transport in surface waters (Fig. 8A). The impact of mitigation measures implemented in catchments for the reduction of agricultural P losses may therefore be counteracted by increases in P mobilization and P loss from all P source areas. The well-documented enrichment of P in particles transported via surface runoff or with preferential flow through soil macropores to tile drains is another important mechanism that may influence the catchment response to mitigation measures adopted to reduce P loss via erosion (Krogstad, 1986). Fine sediments high in P content may still be transported to surface waters independent of the measures implemented to reduce erosion risks on agricultural land (Fig. 8B). An increase in the ratio between total P concentration divided

Table 9. Total area and percentage of agricultural area with different soil erosion risks and the percentage of agricultural area being artificially tile-drained in the four catchments.

Mapped soil erosion risk	Total area (percentage)			
	Skuterud catchment† (Norway)	Mørdre catchment† (Norway)	River Odense‡ (Denmark)	Vechte‡ (the Netherlands)
Mg ha^{-1}	ha (%)			
<0.1	0	0	2 030 (6.0)	281 428 (100)
0.1–1	144 (52)	292 (66)	27 498 (82)	0
1–2	105 (38)	39 (8.8)	3 778 (11)	0
2–4	30 (11)	93 (21)	438 (1.3)	0
4–8	0	5 (1.1)	11 (0.03)	0
>8	0	14 (3.2)	0	0
	Tile-drained area (approximate), %			
	80–90	70–80	71	<5

† Model applied: NIJOS (http://www.nijos.no/English/index_e.htm).
‡ Model applied: Revised Universal Soil Loss Equation (RUSLE).

Table 10. Factors and mechanisms that may influence catchment responses following adoption of mitigation measures to combat P losses from agricultural areas.

Factor or mechanism	Impact
Climate change impacts	Increases in temperature, precipitation, and runoff will counteract and thereby mask catchment responses in P export due to increases in P mobilization and P transport from source areas.
Reducing P input to agricultural areas implementing general measures	Delay in P leaching responses due to the present P status and P saturation in topsoils and subsoils.
Changing in farming practice such as soil tillage changes	The P loss from fields low in erosion risks may increase due to releases of dissolved P as a consequence of no autumn tillage.
Riparian buffer zones	If not harvested freezing of P from dead plant material may be a source of dissolved P. Storage of P in buffer zones may become a P source on the longer term through stream bank erosion.
Restoration of natural sinuosity in river channels	Increased stream bed and bank erosion for shorter or longer time periods and hence input of particulate P.
Restoration of wetlands, inundated riparian floodplains, irrigated riparian areas, etc.	Release of P from sediments enriched in P from former agricultural inputs may counteract the benefits from deposition of particulate P for shorter or longer time periods.
Retention in rivers, lakes, and reservoirs	Increased temperature and precipitation as a consequence of climate change will reduce the natural P buffering capacity of lakes and reservoirs. Reductions in P loading to lakes and reservoirs may increase the P release from sediments being formerly enriched in P.

by the suspended solids concentration was documented for spring harrowing, whereas no changes were found in autumn plowing during the 13 yr of plot experiments. Another important mechanism delaying soil and catchment responses is that the effect of general mitigation measures to reduce the P input to soils and hence the P leaching may be a prevailing high degree of P saturation of topsoil and subsoils (Schoumans et al., 2004). A time lag of several years or decades for reductions in P leaching following implementation of such general measures should be foreseen, the time lag being very dependent on the soil P saturation status. Uncertainties in catchment responses are also linked to the behavior

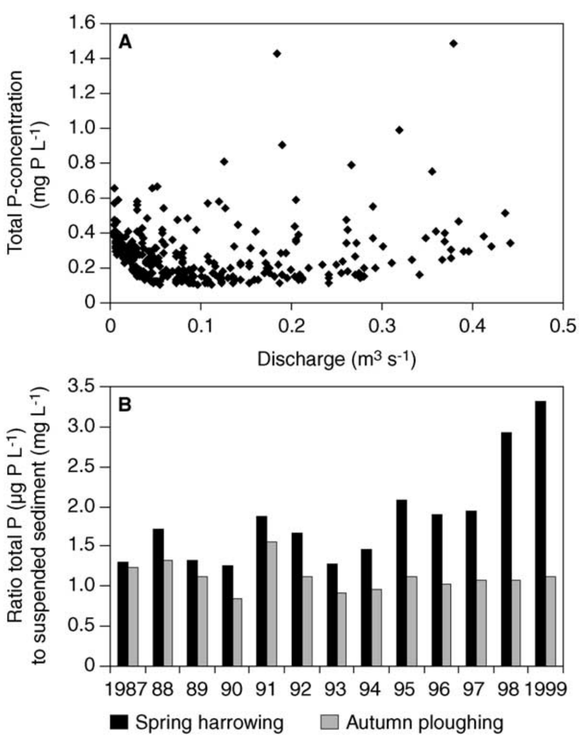

Fig. 8. Relationship between (A) one year of measured daily mean concentrations of total phosphorus and daily mean discharge in the Gelbæk stream, Denmark, and (B) the enrichment ratio between total phosphorus concentration (µg P L^{-1}) and the concentration of suspended solids (mg L^{-1}) applying autumn plowing and spring harrowing in two experimental Universal Soil Loss Equation (USLE) plots at Askim, Norway.

of restored wetlands, riparian areas, and buffer zones; P release from former agricultural land enriched in P may counteract the benefits in the form of increases in P sedimentation for a certain period of time. Finally, both climate changes and reduced P losses may actually reduce the natural retention of P in rivers and lakes and thereby mask or counteract positive responses at the catchment level. Higher water temperature and higher runoff in rivers will reduce the retention of P in lakes and reservoirs (Hejzlar et al., 2003). Reductions in the P input to lakes and reservoirs that formerly received high P loadings can transform the water bodies to net P sources for a certain time period due to P releases from the sediments (Søndergaard et al., 1996). Moreover, changes in river channel dimensions and increased bank erosion due to higher runoff in rivers as a consequence of climate change impacts will also counteract and thereby mask the benefits achieved from mitigation measures implemented on agricultural land to reduce P losses to surface waters (Table 10).

CONCLUSIONS

In this paper we have reviewed our current knowledge on the state of agricultural P losses in river basins, the potential contribution from different pathways as exemplified by Danish conditions, and how P losses can be reduced by implementing various targeted mitigation measures. We have shown that P losses from agricultural areas in many European river basins are among the main sources of total P (20–43%), although varying greatly in significance depending on the magnitude of point-source P discharges and the dominance of P pathways. We have reviewed results from experimental work and surveys to illustrate the present knowledge on the effects of different targeted mitigation measures applied hitherto. We have given evidence into how, where, with what effect, and with what risks such measures can be introduced by river basin managers to utilize the natural phosphorus buffering potential in the border between agricultural land and riparian areas. Our main findings are:

- P loss via bank erosion was found to be the dominant P pathway in Danish catchments with a relatively low contribution of P from soil erosion. Conversely, soil and total P loss from soil erosion from one of the Norwegian soil types studied were very large, amounting to an average of 3310 kg soil ha^{-1} yr^{-1} and 3850 g P ha^{-1} yr^{-1} (Table 5).

- Soil and total P losses via subsurface tile drains from the two types of Norwegian fields studied were high, amounting to 37.4 to 1040 kg ha^{-1} and 144 to 1300 g P ha^{-1}, respectively.
- Soil tillage changes (no tillage in autumn) have been shown to be able to greatly reduce soil and P losses from high to medium risk arable fields (soil: 80–89%; P: 66–76%), whereas changes in soil tillage on low erosion risk agricultural fields reduced the soil loss (22%), but increased P losses (Fig. 3).
- Treatment of soils high in P status on naturally drained fields near ditches with iron material can help to reduce leaching of P by up to 80%.
- Experiments with 5- and 10-m-wide vegetated buffer zones in Norway showed high removal efficiencies for both soil material and total P (>70%), although the removal efficiency was somewhat lower for a 5-m buffer zone where the adjoining field had a high clay content (44%).
- Field surveys of the trapping efficiency of natural buffer zones along 140 Danish agricultural fields were used to develop a model for predicting the probability of soil material to escape through the buffer zone to surface waters. The model shows that buffer zones should be very wide (90 m) to ensure 90% probability to capture all soil material delivered from erosion rills on the adjoining agricultural fields.
- Both natural and restored Danish downstream river–floodplains were shown to be able to retain large quantities of sediment (254–3002 g dry wt. m^{-2}) and PP (1.18–6.50 g P m^{-2}) during short overbank inundation periods (8–19 d).
- Danish experimental evidence on the effect of inundating lowland riparian soils with subsurface tile drainage water, thus creating constructed wetlands, has shown that both net releases and net retention can occur.
- We showed the usefulness of using GIS for mapping critical P source areas and P pathways as exemplified with catchments in Norway, Denmark, and the Netherlands. Our mapping clearly reveals that different mitigation measures are needed in the different catchments.

Although many of the targeted mitigation measures have proved effective in field experiments there are still uncertainties linked to each mitigation measure when put into practical use under natural conditions, and in regions differing in physiography and farming practice. Moreover, it is very important to be aware that different mechanisms counteracting the benefits of mitigation measures adopted at the field level can delay or mask the final effects at the catchment scale for shorter or longer time periods. We are, however, confident that P losses from agricultural areas can and must be combated, but are also aware that we are facing a major challenge for the coming years.

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