Restriction of manure application on high phosphorus soils

Is current research supporting a restriction and what measures are in effect in different European countries?

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Abstract

The Swedish Water Authorities have proposed a measure to reduce phosphorus losses by restricting manure application on soils with high levels of plant available phosphorus.

The aim of this thesis was to investigate if leaching of phosphorus will decrease if the measure is implemented, if the effect is restricted to soils with high phosphorus content and if other European countries have implemented similar measures.

The measure was investigated by performing a meta-analysis on phosphorus leaching studies using lysimeters with undisturbed soil columns. Leaching was compared before and after application of manure. Data was split into subgroups in order to investigate which physical and chemical factors in soil and manure that affected phosphorus leaching. European legislation was investigated by contacting experts in the field from each country.

When all data was included the meta-analysis showed an overall increase in phosphorus leaching and that high phosphorus soils were least affected when manure was applied. Subgroups for the factors application rate, preferential flow and lysimeter length had a significant influence on the results. When these subgroups were combined, the overall effect was unchanged, however, the difference between soil phosphorus levels disappeared.

Among the investigated countries, Ireland is the only one restricting manure application on the basis of phosphorus concentration. Generally, manure application is restricted through the Nitrates Directive and by maximum application limits.

The measure will have an effect on phosphorus leaching, but it is not optimized to target soils that are most susceptible to leaching when manured. In order to further decrease phosphorus leaching, factors identified in this thesis should be included in legislative measures. The measure will also result in a decrease in soil phosphorus, but consideration must be taken with regard to increasing CO_2 emissions due to manure transports and the costs that follow for the farmers.

Keywords
Manure, agriculture, phosphorus, leaching, lysimeter, column, manure legislation, meta-analysis

I ate all your bees

Manny

Abbreviations

DPS – Degree of phosphorus saturation

DRP – Dissolved reactive phosphorus

M3-P – Mehlich-3-P

PSC – Phosphorus sorption capacity

PSI – Phosphorus sorption index

STP – Soil test phosphorus

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Introduction

Phosphorous is usually the primary limiting macronutrient in freshwaters. Leaching of phosphorous into freshwaters can cause eutrophication, which leads to an increased algal growth (Brönmark & Hansson 2005:223). Alongside an increase of algal biomass, cyprids also tend to increase, resulting in a higher grazing pressure on zooplankton. The reduction of zooplankton causes a feedback loop, allowing the number of algae to increase further (Brönmark & Hansson 2005:223). Some algae produce allelochemicals, harmful chemicals that give the algae a competitive advantage, that can render the water unfit for consumption. Another problem arises when bacteria begin to decompose the increased algal biomass. The decomposing bacteria consume the oxygen in the water, causing oxygen deficiency, which leads to fish-kills (Brönmark & Hansson 2005:223). These effects can have devastating consequences on the aquatic environment, which requires great effort to restore.

The Swedish government has formulated 16 environmental objectives, one of which is *zero eutrophication* (SEPA 2011). The objective states that nutrient concentrations in terrestrial and aquatic environments shall be below hazardous levels, based on the effects on biodiversity and the possibility of a versatile utilization of terrestrial and aquatic areas. Sweden has also committed to reducing the nutrient load that affects the Baltic Sea through HELCOM (Helcom 2007). Agriculture is considered to be the main source of phosphorus loading to the Baltic Sea (Helcom 2007).

Furthermore, phosphorous is along side nitrogen the most important nutrient in fertilizers. While the nitrogen cycle is relatively rapid, the phosphorus cycle is slow as it sediments and passes through the bedrock before it becomes available again (Smith & Smith, 2012:453-454). Phosphorous is therefore considered a non-renewable resource. House-holding of phosphorus is important for the future of a stabile and efficient food production.

In Sweden, phosphorus application to agricultural soil is regulated by the Swedish Board of Agriculture (Regulation (SFS 1998:915) through the Swedish environmental code (SFS 1998:808)). The Swedish Board of Agriculture has set up guidelines for phosphorus application on agricultural soils (Table 1, Albertsson et al. 2015). Recommendations for phosphorus application are based on the concentration of plant available phosphorus, measured as P-AL, crop type and the cost effectiveness of fertilization (Bertilsson et al. 2005).

Table 1
Recommendations from the Swedish board of agriculture regarding phosphorus application rates (kg P/ha) on soils with different STP and crop rotations (table recreated from Albertsson et al. (2015)).

Crop	Yield (tonnes/ ha)	P removed (kg/ha)	Recommended phosphorus application rate (kg/ha) for respective P-AL class					
			I	II	III	IVA	IVB	V
Spring Cereals	5	17	25	20	15	5	0	0
Winter Cereals	6	19	25	20	15	5	0	0
Spring Oilseed Crops	2	12	25	20	15	10	0	0
Winter Oilseeds	4	21	35	30	25	15	0	0
Ley	6	14	25	15	10	0	0	0
Feed Corn	10	26	35	30	25	20	15	15
Potatoes	30	15	70	50	40	30	15	15
Sugar Beet	45	18	35	30	25	20	15	0
Peas/Field Bean	4	13	25	20	15	5	0	0
Pasture	-	-	15	5	0	0	0	0

The Water Framework Directive is a EU directive aiming to improve the quality of waters in Europe. In Sweden, the directive is being implemented and monitored by the Swedish Water Authorities. The Swedish Water Authorities has charged the Swedish Board of Agriculture with formulating and managing the implementation of measures to reduce phosphorus transport from agricultural soils (Swedish Water Authorities 2014). One of the proposed measures in order to reduce phosphorous losses is to restrict the use of manure as fertilizers on soils with elevated phosphorous levels, i.e. soils with a phosphorus concentration of 12 mg P/100 g soil and higher measured with the P-AL method (Swedish Water Authorities 2014). Furthermore, consideration should be taken to the crop phosphorus requirement (Swedish Water Authorities 2014). The measure will hereinafter be mentioned as *adjusted phosphorous fertilization*. If the measure is implemented, the current Swedish recommendation to restrict phosphorous fertilizers to 22 kg P/ha and year (Albertsson et al. 2015) will be partially replaced. *Adjusted phosphorous fertilization* will be a way of achieving previous recommendations that soils should have a phosphorous concentration of 4-8 mg P/100 g soil (P-AL, corresponding to Class III) (Bergström et al. 2008).

17% of Swedish agricultural soils investigated in a national mapping were classified as P-AL class IVb-V, while 17 % fell under class IVa and 37 % under class III (Paulsson et al. 2015). Soils with high soil P content are generally restricted to the southern regions of Sweden (Paulsson et al. 2015). The implementation of adjusted phosphorus fertilization will therefore potentially affect a considerable portion of Swedish agriculture.

Other proposed measures include creating wetlands, buffer zones and structural liming (Swedish Water Authorities 2014). The use of adjusted phosphorous fertilization in the field is a relatively novel approach and is therefore of greater interest for this study than the other methods, which have been studied and in some cases used extensively. Since adjusted phosphorous fertilization might be implemented by law, the Federation of Swedish Farmers (LRF) is interested in the effectiveness of the measure and which mechanisms that are responsible for the reduction of phosphorous leaching from agricultural soils. LRF is also interested in if and how other countries in the European Union are going to implement the proposed measure, since farmers in these countries compete on the same market as Swedish farmers.

Aim and research questions

In this thesis, I aim to investigate how adjusted phosphorus fertilization can affect phosphorus leaching and place it in the context of the proposed Swedish measure and European manure legislation. The comparison between identified factors shown to influence phosphorus leaching and manure legislation will be used to propose a direction in which future legislation needs to develop in order to optimize the reduction of phosphorus losses.

Since phosphorus losses through runoff have been studied extensively and some mitigation methods are in use, I will focus on leaching of phosphorus through soil. Different studies show different types of responses in phosphorous leaching due to soil phosphorous concentrations. A holistic approach is necessary where the results of individual studies are combined and compared. Therefore, I will answer the questions posed in this thesis by performing a meta-analysis. A meta-analysis has previously not been performed on this subject. In order to investigate the focus area of this thesis, the following research questions have been formulated.

- Will fertilization with manure increase leaching of phosphorus with increasing soil phosphorus levels?
- What effect will adjusted phosphorous fertilization have on the leaching of phosphorous?
- Are there other factors than soil phosphorus levels influencing the leaching effect of manure application?

The implementation of adjusted phosphorus fertilization may in some cases reduce agricultural production and increase the cost for livestock farmers. Accordingly, the measure may cause loss in competitiveness for uncompensated farmers. However, the consequence for farmers in Sweden will depend on how other Members States have interpreted the Water Frame Directive and if and how they have chosen to implement the adjusted phosphorus fertilization measure. I will compare different member states' approach to the adjusted phosphorus fertilization measure to assess the risk of differentiation interpretations, focusing on how this may affect farmers. This will be done by answering the following questions:

- Which countries in the European Union have implemented a similar measure?
- How has the measure been implemented in these countries?

Disposition

This thesis constitutes of three major parts: a background section summarizing the research of phosphorus leaching; a meta-analysis investigating the effect of manure application on phosphorus leaching; and an investigation of European phosphorus legislation regarding manure. The background section will function as motivation for the analyses performed in the meta-analysis, which in turn will be used to discuss the proposed legislative measure.

Background

Phosphorus movement in soils is a complex field of research. Many different factors play important parts in deciding whether phosphorus will sorb or desorb and leach. This section aims to compile the most important factors governing phosphorus movement in soils and is meant as a foundation for the selection of relevant analyses in the meta-analysis.

Risk assessment of phosphorus leaching

The behaviour of phosphorus in soils has been studied extensively, for example in a summary report of 24 studies focusing on phosphorus losses and mitigating measures (Geranmayeh & Aronsson 2015). Prior to the late 1990s, surface runoff was considered the only quantitatively relevant cause of phosphorus loss from agricultural soils to surface waters (Sims et al. 1998). Djodjic & Kyllmar (2011) have summarized important factors controlling phosphorus runoff. They found that runoff increased both with increasing application rate of manure and with increasing plant available phosphorus (P-AL) measured with soil test phosphorus (STP) methods. They also found that incorporation of fertilizer could mitigate the losses and that the time between application of fertilizer and the first onset of rain as well as concentration of easily soluble phosphorus in the fertilizer are important factors controlling losses. A majority of studies performed on runoff responses to fertilization have applied worst-case scenarios, where rainfall events occur soon after application of fertilizer (Djodjic & Kyllmar 2011). This means that some conclusions regarding the size of phosphorus losses may have been exaggerated.

Leaching, i.e. losses due to downward movement of phosphorus through the soil profile, started to receive increased attention in the 1990s (Ulén 1995; Heckrath et al. 1995) and many researchers have tried to explain the phenomenon. Some have aimed to explain what mechanisms are responsible and to create a risk assessment tool in order to pinpoint soils that have a high risk of leaching, while others have investigated the amount of phosphorus that leaches from different agricultural soils.

A classic example in the field of phosphorus research is the article by Heckrath et al (1995) in which the authors show that phosphorus leaching increases with increasing STP. They also propose a STP threshold value of 60 mg P/kg soil, measured as Olsen-P, after which phosphorus leaching increases manifold (Heckrath et al. 1995). The relationship between STP and phosphorus leaching has later been shown by other researchers (Wang et al. 2012; Jordan et al. 2000). Some studies have also reported the existence of a threshold value (McDowell & Sharpley 2001; McDowell & Sharpley 2004) while it is lacking in other studies (Ulén 1999; Ulén et al. 2013; Ulén et al. 2016). While McDowell & Sharpley use M3-P as an STP method, Ulén uses P-AL. Since different methods of estimating STP are in use in various countries, it is difficult to compare data and results from different countries (Djodjic 2001).

Applying an excessive amount of phosphorus on agricultural soils has been shown to increase the STP (Bergström et al. 2015; Butler & Coale 2005; Djodjic & Mattson 2013; Feyereisen et al. 2010; Olson et al. 2009). A build-up of phosphorus in the soil is generally considered to increase the risk of phosphorus leaching (Bergström et al. 2015; Eriksson et al. 2015; Kingery et al. 1994; Koopmans et al. 2007; Lehmann et al. 2005; Sims et al. 1998). It has also been shown that fertilizing with the amount phosphorus that is being removed by crop may not be sufficient in order to maintain the STP level (Bergström et al. 2015; Börling et al. 2004a) since part of the added phosphorus will be bound in the soil (Gustafsson et al. 2012). Fertilizing soils that have excessive STP may thus not lead to a further increase in STP, if the amount of phosphorus is roughly equal to the amount being removed by crop.

While fertilizing a field that has an excessive STP concentration might seem solely a wasteful endeavour, this is not always the case. Valkama et al (2009) investigated the effects of phosphorus fertilization on crop yield by performing a meta-analysis, compiling data from Finnish phosphorus fertilization trials ranging over 80 years. The results showed that phosphorus fertilization increased the yield regardless of STP status on clay soils, while other soils showed little or no response. Bergström et al. (2015) found that if no phosphorus was applied on soils, STP concentrations decreased by 0.062 mg P/100g soil and year. If phosphorus was applied at a rate equal to the removal by crops, STP concentrations decreased by 0.032 mg P/100g soil and year (Bergström et al. 2015). Reducing the STP levels from P-AL class V (16 mg P/100 g soil) to class III (8 mg P/100 g soil) would thus take 129 years with no phosphorus additions (16 years per mg P/100 g soil decrease) and 250 years with application rates balanced to crop removal (31 years per mg P/100 g soil decrease). Bertilsson et al. (2005) argue that soils with long term increase of STP will have a slower occlusion of phosphorus due to a higher saturation, which negates the lowering of STP in soils when applied phosphorus is balanced to plant uptake. According to

Bertilsson et al. (2005) application needs to be lower than plant uptake in order for STP to decrease.

Phosphorus leaching – mechanisms and correlations

Soil phosphorus consists of three distinct pools: labile, readily plant available, phosphorus, adsorbed phosphorus and fixed phosphorus (Djodjic 2001; Pierzynski et al. 1994). Of the total phosphorus in soil, labile phosphorus constitutes 0.02%, adsorbed phosphorus constitutes 2% and the rest is bound in the fixed pool (Djodjic 2001). The labile phosphorus pool is readily available for plants, while adsorbed phosphorus must desorb prior to plant uptake (Djodjic 2001). The labile phosphorus pool is measured with soil test phosphorus (STP) methods (Pierzynski et al. 1994) but depending on the extracant used, different fractions of the adsorbed pool may be included in when analysing available phosphorus. The fixed pool is regarded as irreversibly sorbed and will therefore not contribute to the labile phosphorus pool (Pierzynski et al. 1994). A long-term fertility experiment showed that 60% of added phosphorus was occluded within 6 days (Gustafsson et al. 2012).

When phosphorus is applied to soil, presence of iron (Fe) and aluminium (Al) oxides and hydroxides, calcium carbonates ($CaCO_3$), clay and organic matter results in adsorbation processes where phosphorus is removed from the labile pool (Pierzynski et al. 1994). Adsorbed phosphorus may be desorbed and thus replenish the labile pool. A large part of the adsorbed phosphorus is irreversibly fixed, or occluded, a process called adsorption hysteresis (Pierzynski et al. 1994).

There is a lack of consistency between amount of phosphorus in the soil, the amount of phosphorus applied to the soil and the leaching of phosphorus. Why some soils leach more than others can partially be explained by the mechanisms that control the sorption and desorption, and the formation of preferential pathways for water in the soil. There is a general consensus that measuring STP alone is not considered a reliable way of assessing phosphorus leaching risks. King et al. (2015) performed a review investigating previous research, identifying important factors controlling and revealing gaps in the understanding of phosphorus leaching. Preferential flow, soil phosphorus sorption capacity (PSC), redox conditions, drainage depth and spacing, tillage, cropping system, STP, organic versus inorganic phosphorus source, phosphorus placement, application rate, application timing, rainfall intensity and the hydrology of the soil were identified as factors influencing phosphorus leaching (King et al. 2015).

Soil properties affecting phosphorus leaching

Soil phosphorus levels have been proposed as a risk assessment measure of phosphorus leaching from soils. Börling et al. (2004a) showed that phosphorus extracted with $CaCl_2$ in different soils correlated with STP (measured as P-AL and Olsen-P) but that the response depended on the phosphorus sorption capacity of the soils. Börling et al. (2004b) suggested that a ratio between P-AL or Olsen-P and a phosphorus sorption index (PSI_2) could be used for risk assessment of phosphorus release from the subsoil. The PSI_2 is attained by leaving a soil sample to equilibrate with 50 mmol P kg^{-1}, after which the amount in the solution is subtracted with the amount added to attain the amount phosphorus sorbed by the soil (Börling et al. 2001). PSI_2 is thus a measurement of the phosphorus sorption capacity of the soil.

The mechanisms for phosphorous sorption in soils differ between acidic and calcareous soils. Soil pH determines which minerals are responsible for adsorption (Devau et al. 2009; Gustafsson et al. 2012). In acidic soils, Al, Fe and clay content are responsible for sorption of phosphorous, while $CaCO_3$ and clay content are responsible in calcareous soils (Sharpley 1983). In a study where phosphorus speciation in soil was investigated, PSC was found to be related to the amount of Fe, Al and Ca (Eriksson et al. 2015). Another study showed that neither soil P nor PSC could explain phosphorus leaching, which instead was attributed to the degree of which the soil was saturated with phosphorus (DPS) (Hooda et al. 2000). Eriksson et al. (2013) investigated soil P content in Baltic and Swedish soils and found that neither STP nor PSI correlated with dissolved reactive phosphorus (DRP) in effluents, but that DRP correlated with clay content in the topsoil. Liu et al. (2012b) used lysimeters from soils with different history of application rate and type of fertilizer and found that leaching of DRP was correlated with DPS. Nelson et al. (2005) suggested that a 45% DPS could be considered a threshold-value, after which the ability of the soil to retain phosphorus declines significantly. Pautler & Sims (2000) and De Smet et al. (1996) suggested a slightly lower threshold-value of 30% for DPS. Fe and Al as well as Ca have widely been correlated with PSC and DPS (Brock et al. 2007; Börling et al. 2004a; Liu et al. 2012c; McDowell & Sharpley 2003; Sharpley 1983; Zheng et al. 2015). Many researchers are thus in agreement that sorption capacity and saturation is of importance when investigating phosphorus losses.

Soil temperature is also important for phosphorus leaching. Williams et al. (2012) investigated the effect of temperature on phosphorus leaching when manure was applied to lysimeters and found that leaching increased with decreasing temperature. Application in fall and winter can thus increase phosphorus losses from agricultural soils (Williams et al. 2012).

Phosphorus source: organic versus inorganic

Phosphorus from manure or slurry has been shown to differ in its leachability compared to phosphorus in mineral fertilizers (Eghball et al. 1996; Tarkalson & Leytem 2009). There is, however, some controversy regarding which type of fertilizer is responsible for the higher risk of leaching. King et al. (2015) concluded in their review that organic phosphorus sources were more prone to leach, compared to inorganic sources. Eghball et al. (1996) also reported a greater mobility of phosphorus from manure than from mineral fertilizer while Tarkalson & Leytem (2009) showed that liquid manures had greater mobility than mineral manures, which in turn had greater mobility than solid manures. Butler & Coale (2005) showed that dairy manure resulted in greater leaching than poultry manure, and attributed the difference to a higher content of organic acids which competed with phosphorus binding sites. Bergström & Kirchmann (2006) reported unexpected results when they showed that phosphorus leaching decreased with increasing manure application rate in a sandy soil, a phenomenon they attributed to a manure induced change in soil chemistry. When applying manure or slurry as fertilizers, dry matter content has been shown being related to leachability of phosphorus (Vadas 2006). Manure with a dry matter content above 25% does not have free draining liquid, while manure with a dry matter content below 15% does (Vadas 2006). While studies are contradictive in some extent regarding what types of phosphorus fertilizers leach more, dry matter content and soil properties seem to influence leaching in most cases.

Transport pathways influence phosphorus leaching

The ability of the soil to retain phosphorus is affected by how water is transported through the soil profile. As a soil receives water, surface tension causes the water to adsorb to soil particles. As more and more water is added, the force of gravity on the water increases, field capacity is achieved when gravity equals surface tension (Fetter 2014). At that time, a pulse of water will start to move downward through the soil profile, the speed is determined by Darcy's law, which describes the transport of a fluid through a porous media, i.e. soil (Ulén 1997). According to Darcy's law, a soil with smaller particles, e.g. a clay soil, will have a greater field capacity than a soil with bigger particles, e.g. a sand soil (Fetter 2014). If the field capacity is not reached, the water will not start moving. As long as the water is still in the soil profile, it can equilibrate with the soil – thus a soil with a high PSC and low DPS has opportunity to retain phosphorus. In a soil with macropores the water will partly bypass the soil profile by preferential flow (Fetter 2014; Jensen et al. 2000; Geohring et al. 2001; Kleinman et al. 2015; Ulén et al. 1998). Geohring et al. (2001) used packed lysimeters, with and without recreated macropores, and found that macropores were the main cause of leaching from the soil. Preferential flow does not allow for equilibrium between soil and solution (Geohring et al. 2001), which means that leaching of phosphorus may occur regardless of soil P content, PSC or DPS. Preferential flows mainly occur in structured soils, rich in clay or silt. Koestel et al. (2012) performed a meta-analysis on solute transport through soil and found that preferential solute transport primarily occurred in soils with over 8 % clay content.

If macropores are present in the soil profile, nutrients can leach from soils that would otherwise be expected to have a good retention, such as a low soil P or DPS. Djodjic et al. (2002) hypothesised that tillage may discontinue macropores and that incorporation of fertilizers into the soil may allow for soil-phosphorus equilibration as well as placing phosphorus aside from the water moving down through the macropores. While tillage did not reduce phosphorus leaching, incorporation did, but only during the first year of fertilizing (Djodjic et al. 2002). Feyereisen et al. (2010) found that surface incorporated manure had significantly higher leaching losses of phosphorus than surface applied manure in initial rainfall events. Furthermore, when the ground water table raises it may cause reduced conditions in the subsoil where retained phosphates may be released (Ulén & Persson 1999; Martin et al. 1997).

Measuring phosphorus leaching

A general problem that arises when predicting the leaching of phosphorus from a soil is that it has not been properly linked to the actual leaching from agricultural soils. There are many factors that differ between, and even within, soils which makes it difficult to devise a general risk assessment. This problem becomes apparent when actual leaching of phosphorus is investigated in regards to the dominating factors affecting the risk of leaching. Phosphorus leaching losses are either measured in field or with lysimeter studies.

Field leaching studies

Phosphorus leaching has been studied in field studies with varying results. Liu et al. (2012c) investigated long term fertilizing with manure and found that leaching of phosphorus was smaller than expected, which was attributed to a high phosphorus sorption capacity (PSC) in the subsoil. Aronsson et al. (2014) investigated a soil with moderate STP, low DPS and a higher phosphorus content in the subsoil, compared to the field investigated by Liu et a. (2012c). Aronsson et al. (2014) found that pathways that facilitated fast transport of phosphorus during wet conditions constituted a major problem, which needs to be addressed. Soil phosphorus content, sorption capacity and preferential flow have been identified as important factors controlling phosphorus leaching in field experiments (Djodjic & Bergström 2005; Geohring et al. 2001).

Field studies face the problem that a majority of phosphorus leaching originates from a fraction of the arable land during yet a fraction of the year, often during intense rainfall. (Djodjic & Kyllmar 2011; King et al. 2015; Ulén 1995; Ulén 2005; Ulén & Persson 1999). Consequently, there is no homogenous flow to monitor. Another problem with leaching studies in field experiments is that when the ground water table is high, it risks diluting the leachate and thus offsetting the result (Ulén et al. 2016). Furthermore, Djodjic & Bergström (2005) argued that field scale leaching investigations are practically impossible to compare statistically, due to the large amount of confounding factors. They do, however, propose that comparison is possible by using locally weighted scatterplot smoothing (Djodjic & Bergström 2005).

Lysimeter leaching studies

An alternative to field studies when investigating leaching of phosphorus from soils with different properties is to utilize lysimeters. Lysimeters are soil columns used to investigate leaching through a soil profile (Ulén 2005). The lysimeter experiments can be divided into two groups: re-packed and undisturbed (Goss & Ehlers 2009). In re-packed lysimeters, soil is collected, sieved and packed in order to simulate field conditions while undisturbed lysimeters aim to retain the initial soil structure. The undisturbed lysimeters are preferable due to the fact that they are preserving the naturally occurring soil structure, such as macropores. Lysimeters are preferable when comparing results from different fields since they allow for controlled conditions in a laboratory.

A majority of the included lysimeter experiments sample the topsoil (20-30 cm) (Glæsner et al. 2011; Liu et al. 2012a; Liu et al. 2012b; Pavrage et al. 2015; Svanbäck et al. 2013; Ulén et al. 2013) and are thus investigating the migration of phosphorus into the subsoil, i.e. the soil beneath normal tillage depth. Results similar to the field study performed by Liu et al. (2012c) have been shown with lysimeters including the subsoil (Andersson et al. 2013; Djodjic et al. 2004). Andersson et al. (2015) later showed that the subsoil could act both as a phosphorus source and as a sink, depending on the degree of phosphorus saturation (DPS). Therefore, long lysimeters may prove crucial when investigating actual leaching of phosphorus from topsoil to surface or ground waters. Short lysimeters could serve as a compliment to long lysimeters and as a risk assessment of increase in phosphorus loading of the subsoil, but might prove inadequate when investigating actual phosphorus leaching (Andersson et al.

2013). However, short lysimeters do show the tendency of leaching under certain conditions, which may be extrapolated to the entire soil profile, if the conditions are constant. A short lysimeter taken from the topsoil may prove adequate in order to describe phosphorus movement in subsoils with similar properties. It may also be useful when investigating preferential flow, if the investigated soil can be considered to have continuous macropore systems.

Soil test phosphorus – extraction methods

In this study, three methods for extracting plant available phosphorus from soils are included. Other extraction methods exist, but are not prevalent in research studies, why they are excluded from this study. Firstly, in Sweden, plant available soil phosphorus (soil test phosphorus - STP) is measured as P-AL. The P-AL method uses ammonium lactate in an acid solution (Egnér et al. 1960), which enables estimation of STP in acid soils (Eriksson et al. 2013). A second method, the Olsen-P method, uses sodium bicarbonate at a higher pH, which enables estimation of STP in calcareous soils (Olsen et al. 1954). Finally, another extraction method that is widely used is Mehlich-3 (M3-P), which can be used to analyse multiple element in one extract (Mehlich 1984). M3-P uses acetic acid, ammonium nitrate, ammonium fluoride, nitric acid and ethylenediaminetetraacetic acid (EDTA) as extracants (Mehlich 1984).

Since these extraction methods use different extracants, they measure different fractions of the soil phosphorus pool. Different extraction methods may thus yield different results depending on how the phosphorus is bound in the soil. Comparisons between measurements with different methods are therefore not possible. Measurements can instead be compared indirectly, by investigating what STP is considered low, moderate and high when extracting with each method. This approach contains considerable margins of error, since different countries may have different opinions on what STP levels are low, moderate and high.

In this study, three classification systems used, respectively, in Sweden, Denmark and the state of Pennsylvania, USA, were chosen in order to classify if STP status to be considered low, moderate or high. In Sweden, soils are grouped in 6 classes, based on P-AL (Table 2, Gustafsson 2010). Class III is considered to have an optimal STP for plant growth, while IVb and V is considered to have excessive STP. On IVb and V soils, phosphorus application is usually not recommended (Albertsson et al. 2015). In Denmark, STP is estimated by using the Olsen-P method. Classes similar to the Swedish ones are appointed by using *fosfortal* (Pt, phosphorus number), which is the Olsen-P value (mg/kg) divided by 10 (Table 3, Kronvang et al. 2001). In Pennsylvania, soils are grouped in 4 classes based on STP extracted with the M3-P method (Table 4, Beegle et al. 2007).

Table 2
The Swedish classification of soils in regard to the phosphorus content, measured with the P-AL method

Class	P-AL (mg P/100g soil)	Soil P status
I	0-2	Very low
II	2-4	Low
III	4-8	Moderate
IVa	8-12	Slightly elevated
IVb	12-16	High
V	>16	Very High

Table 3
The Danish classification of soils in regard to the phosphorus content, measured with the Olsen-P method

Pt	Soil P status
<1	Very low
1-2	Low
2-4	Moderate
4-6	High
>6	Very High

Table 4
Classification of soils in regard to the phosphorus content measured with the Mehlich-3-P metod, used in Pennsylvania, USA

M3-P value	Soil P status
0-59	Low
60-79	Moderate
80-99	High
>100	Very high

Methods

Phosphorus leaching study – meta-analysis

A meta-analytic review has been performed in order to investigate if adjusted phosphorous fertilization affect phosphorous leaching, if leaching can be related to soil STP and if there are other important factors to consider. Since recent studies have suggested that organic and inorganic phosphorus fertilizers differ in leachability, this study will only focus on organic fertilizers. Selected studies have been analysed and data have been extracted in order to perform a meta-analysis. This study aimed to investigate if and how a higher phosphorus concentration in the soil affects vertical leaching when applying manure fertilizer. Studies with intact lysimeters were chosen as a study method. The lysimeter allows for controlled conditions that cannot be achieved in the field, and by using intact soil columns, the properties of the soil that influence phosphorus leaching are retained. The lysimeter will also eliminate lateral losses due to freezing (cracking) of the soil and surface losses due to erosion from the analysis – thus restricting the analysis to vertical leaching.

Data selection and extraction

The search engine Web of Science was used for the data search, where the databases *Web of Science Core Collection, BIOSIS Previews, CABI : CAB Abstracts, KCI-Korean Journal Database, MEDLINE, SciELO Citation Index* and *Zoological Record* were included. The search phrase used is stated below:

(Manure* OR slurry) AND (lysimeter* OR column*) AND (Phosph* OR P)

The phrase yielded 640 results, of which 27 were conducting lysimeter experiments where manure was applied. Since the search used to obtain studies for this thesis, Lund University have added more databases. If the search is conducted with the search phrase in Web of Science with all databases included, the search will yield 873 results. The articles relevant for the meta-analysis were selected based on a few inclusion criteria. The following inclusion criteria were applied on the literature search for the meta-analysis and yielded 8 studies, containing 53 sub-studies, which were included in the meta-analysis:

- Studies are performed with intact lysimeters/columns
- Studies are from Europe, USA or Canada
- Studies have investigated agricultural soils
- Studies have presented type and amount of manure as well as the P concentration
- Studies have measured P leaching as tot-P as a concentration or in a manner that allows converting to concentration
- Studies include standard deviation or corresponding value and number of replicates
- Studies have determined soil P concentration
- Studies have investigated soil type (at least the amount of clay)

Furthermore, relevant references from selected articles and articles provided by experts in the field, mainly researchers from the Swedish agricultural university, SLU, in Uppsala, have been included in the analysis. If the data needed in order to perform a meta-analysis (mean, standard deviation and number of replicates) were not reported in the study, the corresponding author was contacted and asked to share the raw data for the study. Svanbäck et al. (2013), Liu et al. (2012a) and McDowell & Sharpley (2004) provided raw data for this thesis. The data from McDowell & Sharpley (2004) was not included since I was unable to identify the necessary input data. Mean values, standard deviations and numbers of replicates of the included studies are presented in appendix 1, table 11.

The analysis has been performed with the software MIX pro, version 2.0. Mean values, standard deviations and number of replicates for the control and the treatment were extracted from each article and inserted into MIX. Other variables that were identified in the theory section and were available in the studies were also included, such as lysimeter length, manure type, application rate, degree of phosphorus saturation, clay content and soil texture. In the software, the effects within the studies were calculated and compared in order to give a total effect evaluation.

The inclusion criteria chosen for selection of studies are formulated in order to get an as homogenous and numerous sample of studies as possible. Studies from Europe, USA and Canada were chosen as they provide a large sample of studies while still sharing a similar climate. The same effect size (total phosphorus in mg/L) and the same study method (intact lysimeters) are two crucial criteria in order to attain homogenous data and thus being able to use an unstandardized mean difference (Borenstein et al. 2009) between manured and unmanured leaching events. All included studies have collected their lysimeters by pressing or hammering down a PVC-pipe in the soil without disturbing the soil structure. The PVC-pipe was subsequently excavated by removing the surrounding soil.

In order to obtain enough data to perform a meta-analysis, 4 included studies, out of 8, using dependent data were included. In these studies, one control is used for multiple treatments (Glæsner et al. 2011; Kleinman et al. 2009; Liu et al. 2012a; Pavrage et al. 2015).

Data management

In order to determine an appropriate effect size and whether the data should be analysed with fixed effects or random effects, the raw data (appendix 1, table 11) was analysed by using unstandardized mean difference (md) as effect size and a fixed effects model. The analysis of effect size revealed that 4 sub-studies out of 53 were given an extreme weight, accounting for 86% of the studies total effect size. A heterogeneity analysis with I^2 statistics showed that 93% of the variation was caused by differences between and within studies. The I^2 statistics show the percentage of the variation that is not caused by chance, and is, as opposed to Q statistics, not sensitive to a small study sample (Higgins et al. 2003). An I^2 value below 30% is considered to be mild, and a value over 50% is considered to be substantial (Higgins & Thompson 2002). One reason for the heterogeneous data may be that leaching events are performed during different time periods and with different amount of precipitation in different studies, which may affect the unstandardized comparison. Yet another reason for the high heterogeneity is the fact that soil and manure properties varies between and within studies.

To correct for the weighting problem, hedge's g (hg) was chosen as effect size resulting in an even distribution of weighting between the sub studies. When using Hedge's g, the mean difference is divided by the standard deviation, making it possible to compare studies with differences in measurement methods (Borenstein et al. 2009). Hedge's g is also suitable for analysis of small data sets (Mengersen et al. 2013). A Hedge's g value of <0.41 is regarded to be insignificant, a value of 0.41 as low, 1.15 is considered to be moderate and 2,7 or higher is regarded as a strong effect (Ferguson 2009). Due to the large heterogeneity, the true effect cannot be assumed to be equal in all studies (Borenstein et al. 2010), why a random effects model was chosen. The fixed effects model assumes the sampling of one "population", i.e. sampling will give rise to a normal distribution and a grand mean (the effect size), and an overall variance, derived from the variances within each sub-study (Borenstein et al. 2010). The random effects model assumes that the data is sampled from different populations, and thus includes both within sub-study and between sub-study variances (Borenstein et al. 2010).

In one study (Glæsner et al. 2011), the results were converted from kg P/ha to mg/L. The leaching study was performed under near-saturated conditions, why it was assumed that all water applied would also leach. First, the area of the lysimeter was calculated in order to convert kg P/ha to kg P/lysimeter, after which the volume of leachate was calculated by multiplying the amount of simulated rainfall with the area of the lysimeter. The concentration was calculated by dividing the amount of P per lysimeter with the volume leached.

Furthermore, a selectivity analysis was performed in MIX in order to ascertain if any publication bias could be detected.

Subgroup analysis

When investigating the relationship between STP and phosphorus leaching, other factors such as application rates, preferential flow, lysimeter depth, dry matter content of the manure, DPS, soil texture and type of manure may affect the results. Analyses were performed in order to investigate if difference in these factors caused significant difference in phosphorus leaching and therefore could skew the analysis of leaching depending on soil STP. In order to verify if two subgroups were different, equation 1 was used

$$X_1 - X_2 \pm 1{,}96\sqrt{SE_{X1}^2 + SE_{X2}^2} \qquad (1)$$

where X_1 and X_2 are the mean estimates (hg), and SE is the standard error derived from the confidence intervals by dividing it with 1,96. If the left side of the equation (X_1-X_2) was bigger than the right side, and if the equation did not contain 0, the two subgroups were considered significantly different. Data homogeneity was investigated in order to evaluate the grouping on the data inconsistency.

The influence of application rate on phosphorus leaching was investigated by dividing the data into two groups: high and normal application rate. Normal application rate was, in this thesis, considered as 11-30 kg/ha, application rates above were considered as high.

The influence of preferential flow was investigated by dividing the data into two groups based on clay content. Soils with a clay content above 8% were considered to have the potential for moderate or strong preferential flow (Koestel et al. 2012), while soils with a clay content below 8% were not considered to have any significant potential for preferential flow. The two subgroups were further compared by calculating a ratio between particulate and total phosphorus. A higher ratio indicated preferential flow. Statistical difference between subgroups with and without preferential flow was investigated using a student’s t-test.

Since current research has found that the subsoil plays a pivotal role in phosphorus leaching, the data was also grouped into sub-studies using short (0.2-0.3 m) and long (0.5 m) lysimeters. This analysis was meant to investigate how short topsoil lysimeters could be analysed compared to long lysimeters that included the subsoil.

The data was grouped according to leaching potential based on dry matter content of the manure, where a dry matter content of less than 15% was considered to result in a high leaching risk, and a dry matte content of over 25% was considered to result in a low leaching risk (Vadas 2006). The data was also grouped by manure type.

An important factor that, according to the research, should affect phosphorus leaching is the DPS of the soil. Pautler & Sims (2000) and De Smet et al. (1996) suggested a threshold value of 30% for DPS. Alternatively, Nelson et al. (2005) suggested a slightly higher DPS threshold value of 45%, after which leaching increased substantially. It was not possible to perform a sub-group analysis on the higher threshold value since only one sub-study in the included studies has been reported to exceed a DPS of 45%.

The data was also divided into groups based on soil texture and manure type in order to control if these subgroups showed any difference in phosphorus leaching.

In order to ascertain if subgrouping affects the percentage of variance caused by within and between sub-study differences, a heterogeneity test was performed for each subgroup. It should be noted that subgroups can be statistically different even in a homogenous material (Groenwold et al. 2010), and that the increase in homogeneity may be the result of a lower number of sub-studies in the subgroups (Higgins et al. 2003).

Furthermore, leaching of phosphorus from previously unmanured soils (background leaching) was investigated assigning each study to three groups: supporting, not supporting and no trend, regarding if background phosphorus leaching increase with increasing STP levels. The studies were given a weight based on the number of replicates used divided by the total number of replicates.

European phosphorus legislation

The implementation in other countries has been investigated by contacting experts in the field in each country. Persons contacted in the investigation of the phosphorus legislation in Europe are reported appendix 2, table 12. Each person was asked if their respective country has implemented a measure where manure application is restricted based on STP, if they have a similar measure and how this measure has been implemented.

Results

Effects of manure application on phosphorus leaching

The studies (Article) and sub-studies (Nr) included in the meta-analysis and identified factors relevant to phosphorus leaching are shown in table 5.

Table 5

Input data for the meta-analysis. The column “nr” provides a number, which can be used to backtrack individual sub-studies in the forest plots. P-status refers to if the investigated soil has a deficit (low), optimal (moderate) or excessive (high) plant available phosphorus content, as determined by STP. The method with which plant available phosphorus has been investigated is shown in the column “STP method”. The column “Lys” shows the length of the lysimeters in the experiments. Soil texture is either given in the article or is estimated using a soil texture pyramide (Pierzynski et al. 1994:22). “Clay” gives the percentage of clay in the investigated soils. “Type of manure” and “DM” (dry matter content) gives information about the manure that has been applied on the soils. “Kg P/ha” refers to the application rate of manure.

Article	Nr	P-status	STP method	Lys (m)	Soil texture	Clay (%)	Type of manure	DM (%)	kg P / ha	DPS (%)
Glæsner	1	Low	Olsen P	0,2	Loamy Sand	10	Dairy manure	6,6	128	43
et al. 2011	2	Low	Olsen P	0,2	Loamy Sand	10	Dairy manure	6,6	128	43
	3	Low	Olsen P	0,2	Sandy Loam	14	Dairy manure	6,6	128	36
	4	Low	Olsen P	0,2	Sandy Loam	14	Dairy manure	6,6	128	36
	5	Low	Olsen P	0,2	Loam	23	Dairy manure	6,6	128	25
	6	Low	Olsen P	0,2	Loam	23	Dairy manure	6,6	128	25
Kleinman	7	Low	M3-P	0,3	Silty Clay Loam	28	Poultry manure	53	85	NA
et al. 2005	8	Low	M3-P	0,5	Silty Clay Loam	28	Poultry manure	53	85	NA
	9	High	M3-P	0,3	Clay Loam	31	Poultry manure	53	85	NA
	10	High	M3-P	0,5	Clay Loam	31	Poultry manure	53	85	NA
Kleinman	11	High	M3-P	0,5	Sandy Loam	18	Dairy manure	12,6	30	NA
et al. 2009	12	High	M3-P	0,5	Sandy Loam	18	Dairy manure	12,6	30	NA
	13	High	M3-P	0,5	Sandy Loam	18	Dairy manure	12,6	100	NA
	14	High	M3-P	0,5	Sandy Loam	18	Dairy manure	12,6	100	NA
	15	Low	M3-P	0,5	Clay Loam	33	Dairy manure	12,6	30	NA
	16	Low	M3-P	0,5	Clay Loam	33	Dairy manure	12,6	30	NA

Article	Nr	P-status	STP method	Lys (m)	Soil texture	Clay (%)	Type of manure	DM (%)	kg P / ha	DPS (%)
Liu et al. 2012a	17	Moderate	P-AL	0,2	Clay Loam	29	Pig Slurry	7,3	30	16.9
	18	Moderate	P-AL	0,2	Clay Loam	29	Pig Slurry	7,3	30	16.9
	19	High	P-AL	0,2	Loamy Sand	7	Pig Slurry	7,3	30	20.7
	20	High	P-AL	0,2	Loamy Sand	7	Pig Slurry	7,3	30	20.7
Liu et al. 2012b	21	High	P-AL	0,2	Loamy Sand	5,9	Pig Slurry	7,3	22	32
	22	High	P-AL	0,2	Loamy Sand	5,9	Pig Slurry	7,3	22	42
	23	High	P-AL	0,2	Loamy Sand	7	Pig Slurry	7,3	22	34
	24	High	P-AL	0,2	Loamy Sand	7	Pig Slurry	7,3	22	21
Pavrage et al. 2015	25	High	P-AL	0,2	Loamy Sand	11	Horse manure	34	11	NA
	26	High	P-AL	0,2	Loamy Sand	11	Horse manure	34	22	NA
	27	High	P-AL	0,2	Loam	26	Horse manure	34	11	NA
	28	High	P-AL	0,2	Loam	26	Horse manure	34	22	NA
	29	Moderate	P-AL	0,2	Peat	nd	Horse manure	34	11	NA
	30	Moderate	P-AL	0,2	Peat	nd	Horse manure	34	22	NA
Svanbäck et al. 2013	31	Low	P-AL	0,2	Silty Clay Loam	30	Dairy manure	NA	30	NA
	32	Low	P-AL	0,2	Silty Clay Loam	30	Dairy manure	NA	30	NA
	33	Moderate	P-AL	0,2	Silty Clay Loam	30	Dairy manure	NA	30	NA
	34	Moderate	P-AL	0,2	Silty Clay Loam	30	Dairy manure	NA	30	NA
	35	Low	P-AL	0,2	Loam	18	Dairy manure	NA	30	NA
	36	Moderate	P-AL	0,2	Loam	18	Dairy manure	NA	30	NA
	37	High	P-AL	0,2	Loam	18	Dairy manure	NA	30	NA
	38	High	P-AL	0,2	Loam	18	Dairy manure	NA	30	NA
	39	Low	P-AL	0,2	Sandy Loam	14	Dairy manure	NA	30	NA
	40	Moderate	P-AL	0,2	Sandy Loam	14	Dairy manure	NA	30	NA
	41	High	P-AL	0,2	Sandy Loam	14	Dairy manure	NA	30	NA
	42	High	P-AL	0,2	Sandy Loam	14	Dairy manure	NA	30	NA
	43	Low	P-AL	0,2	Loamy Sand	7	Dairy manure	NA	21	NA
	44	Moderate	P-AL	0,2	Loamy Sand	7	Dairy manure	NA	21	NA
	45	Moderate	P-AL	0,2	Loamy Sand	7	Dairy manure	NA	21	NA
	46	High	P-AL	0,2	Loamy Sand	7	Dairy manure	NA	21	NA
	47	Low	P-AL	0,2	Silty Clay Loam	48	Dairy manure	NA	21	NA
	48	Low	P-AL	0,2	Silty Clay Loam	48	Dairy manure	NA	21	NA
	49	Moderate	P-AL	0,2	Silty Clay Loam	48	Dairy manure	NA	21	NA
	50	High	P-AL	0,2	Silty Clay Loam	48	Dairy manure	NA	21	NA
Ulén et al. 2013	51	Moderate	P-AL	0,2	Clay	62	Pig Slurry	NA	22	7.1
	52	Moderate	P-AL	0,2	Clay	60	Pig Slurry	NA	22	25.2
	53	High	P-AL	0,2	Clay	52	Pig Slurry	NA	22	62.4

The effect size analysis on all data is presented in figure 1. The results show an overall moderate effect (hg=1.48) on leaching when manure is applied.

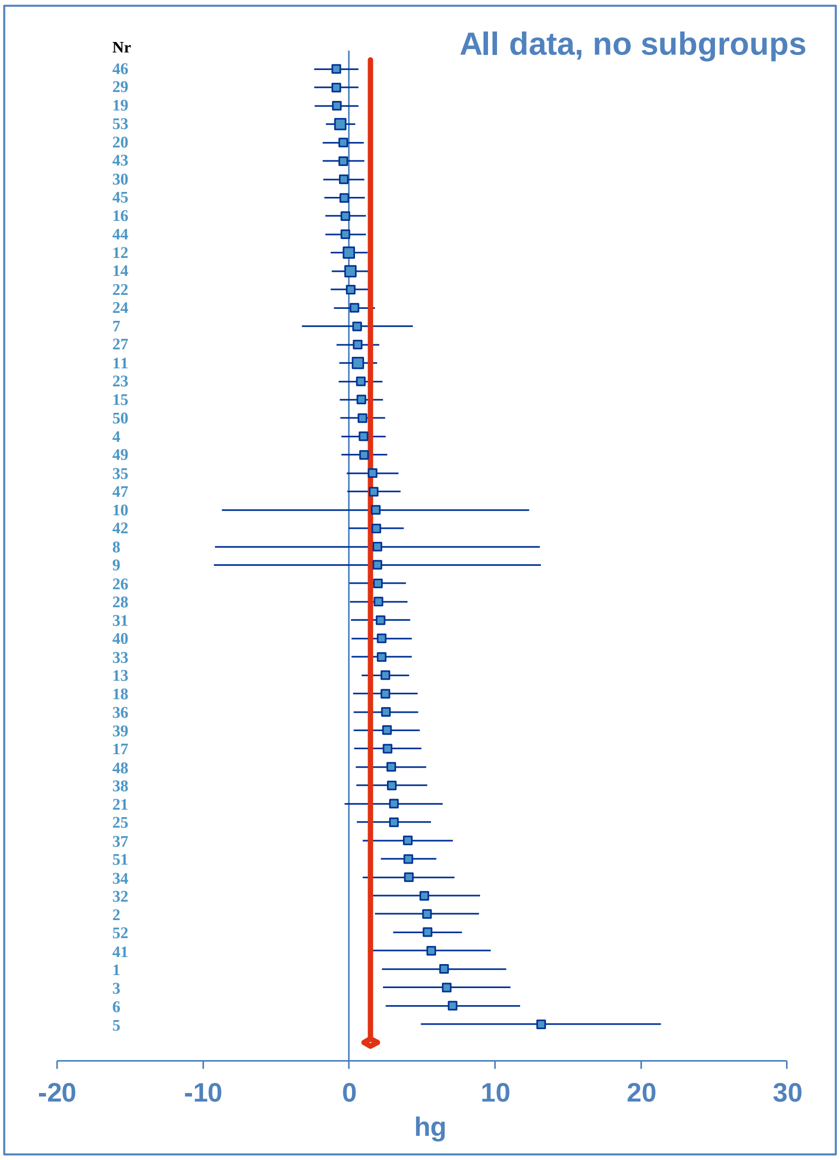

Figure 1
The overall effect of manure application on leaching of phosphorus from agricultural soils. The value for Hedge's g was 1.48, (ci=1.01-1.95), suggesting a moderate effect. In total, 466 replicates are included. The size of the points representing each sub-study represents the relative weight of the sub-study.

Selectivity analysis

Figure 2 shows that there may be publication bias. For an optimal result without bias, the studies should be evenly distributed within the funnel plot. As seen in figure 2, the right side of the funnel is overrepresented, indicating that studies with low precision and effect may not have been published.

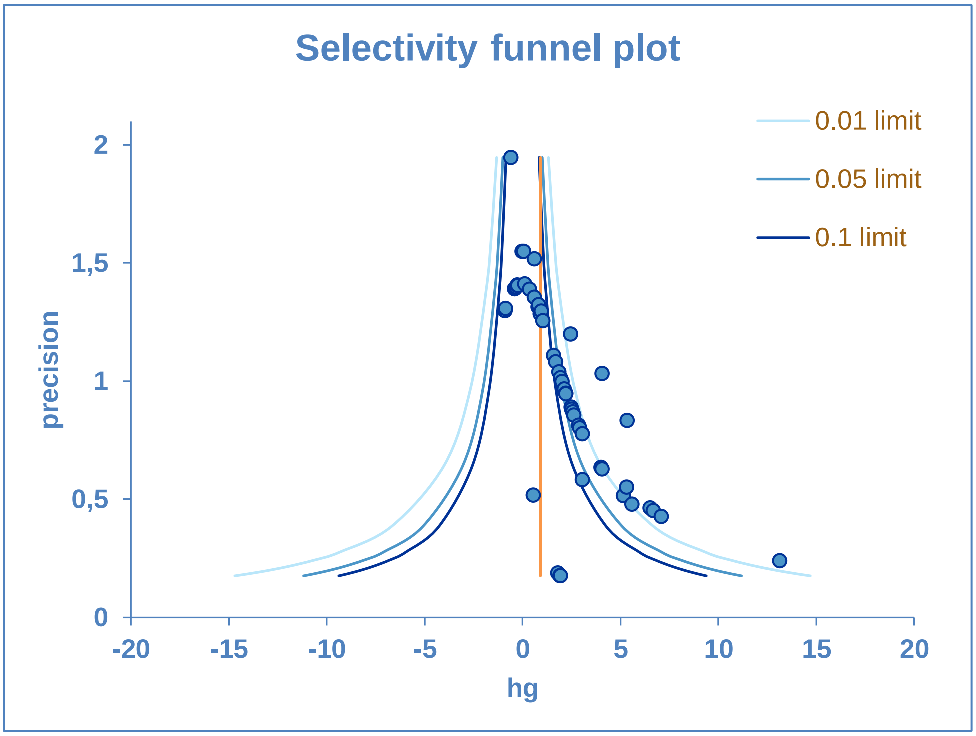

Figure 2
Investigation of publication bias with a selectivity funnel plot. The right side of the funnel is overrepresented. Studies are missing on the left side indicating publication bias.

Subgroup analysis

In order to investigate the role of STP on leaching, the data was grouped into three categories: low, moderate and high STP (figure 3).

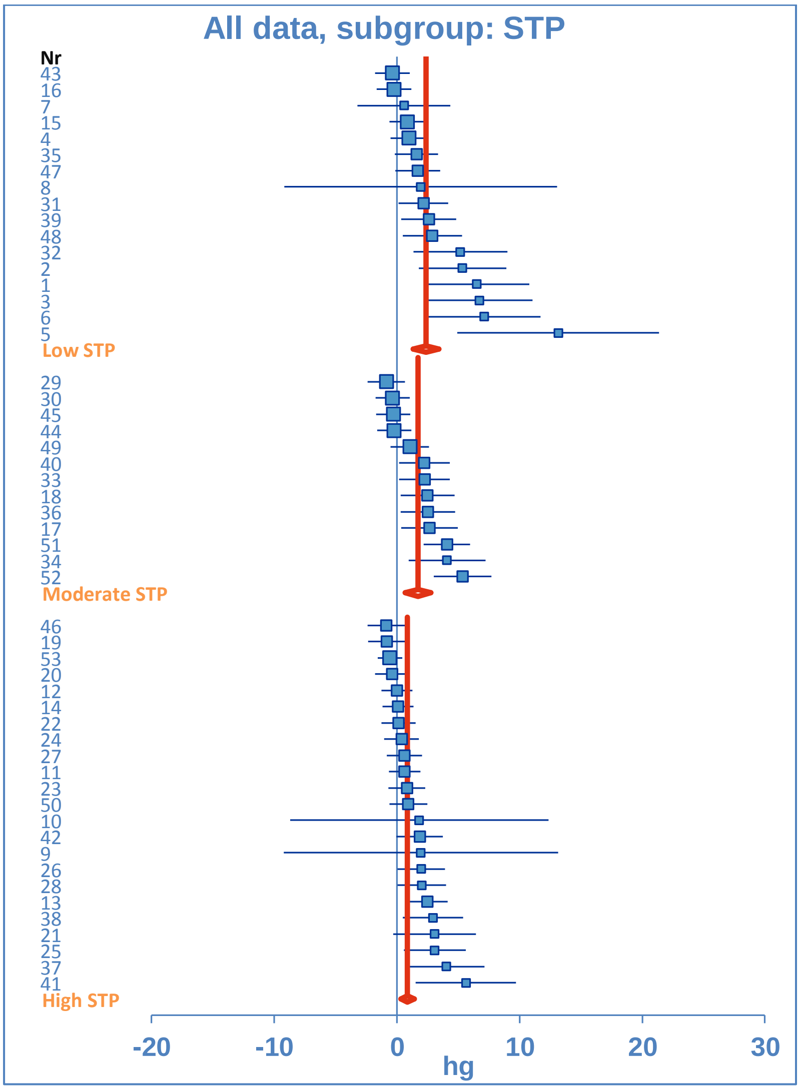

Figure 3

The effect of manure application on phosphorus leaching from soils with different STP (low, moderate, high). The effect was significantly lower in high STP soils compared to low STP soils. The Hedge's g value for the high STP soils was 0.85, suggesting a low effect. No significant difference was found between the low and moderate and the moderate and high STP groups.

In the classing system according to P-AL, classes III and IVa are considered to have moderate STP. The analysis shows that the group with high STP has a lower effect than the group with low STP. While the high STP group showed a low effect, according to the hg value, the low and moderate STP groups showed a moderate effect.

Soils with a potential for moderate or strong preferential flow show a greater effect (hg=2.13, ci=1.57-2.69) than the soils without (hg=-0.12, ci=-0.59-0.36) (Figure 4).

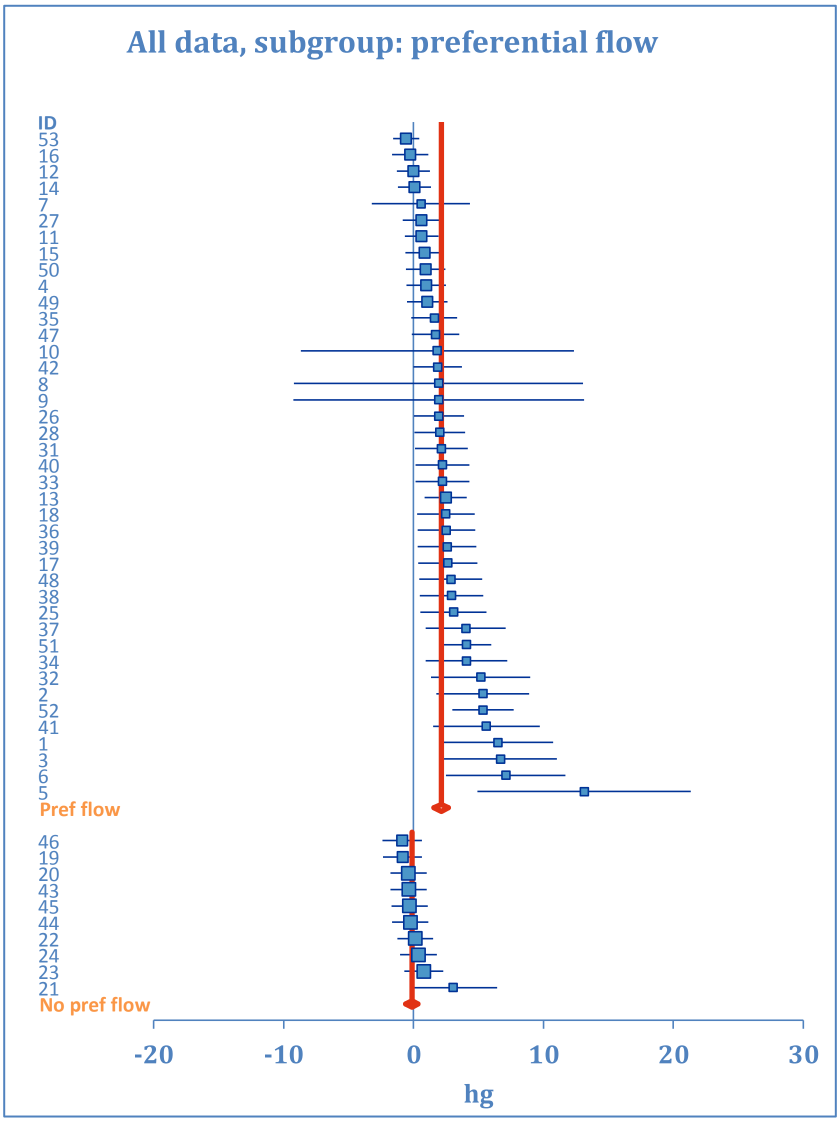

Figure 4
The effect of manure application on leaching of phosphorus from soils with and without potential for preferential flow. Soils with potential for preferential flow have significantly higher effect (hg=2.13, ci=1.57-2.69) than the soils without (hg=-0.12, ci=-0.59-0.36).

The assumption that the effect seen in figure 4 actually is a result of preferential flow was investigated by calculating the ratio between particulate phosphorus and total phosphorus. The result showed that there was a significantly higher ratio between particulate phosphorus and total phosphorus in soils that had potential for preferential flow than in soils without ($p=0.036$). Since all data could not be included, only four out of eight studies presented data on particulate phosphorus, this result is not conclusive. It does, however, show that preferential flow may in fact be the cause of the increased effect.

Figure 5 shows the influence of the application rate on the leaching of phosphorus. The data is grouped into two categories: normal (11-30 kg P/ha) and high (85-128 kg P/ha) application rates. Included data did not contain application rates in between these groups.

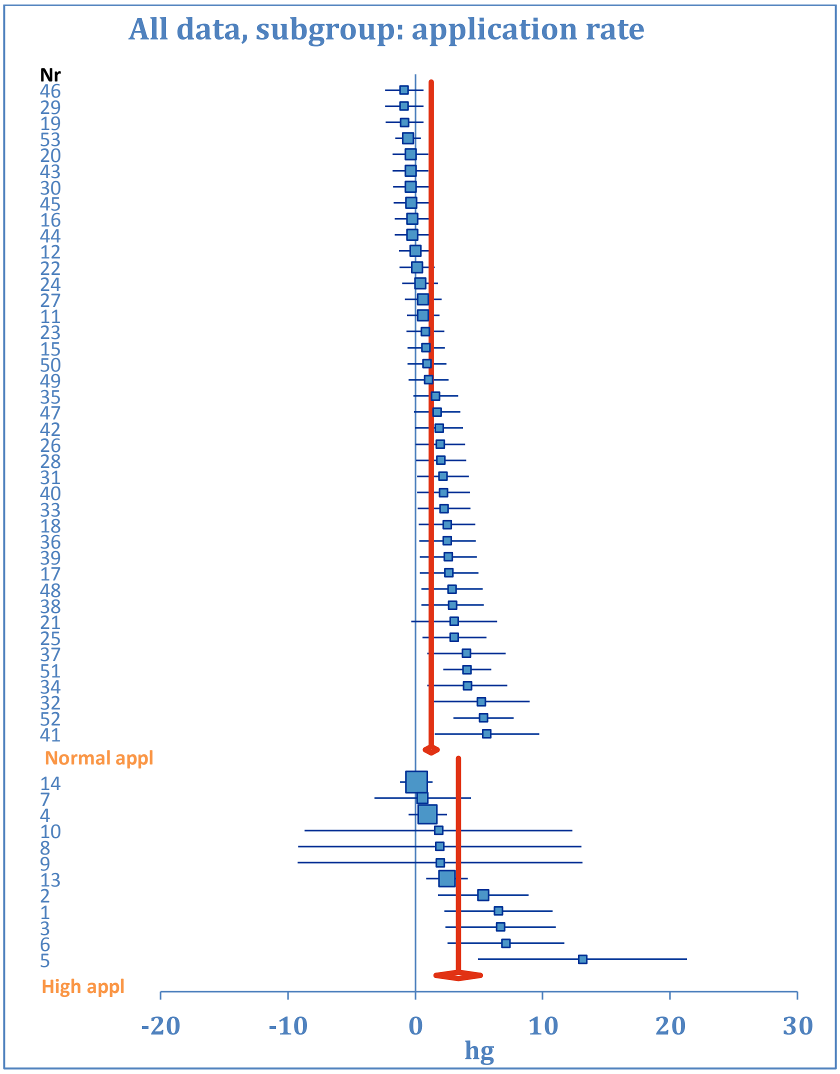

Figure 5
The effect of manure application on leaching of phosphorus from soils depending on application rate. Normal application rate refers to 11-30 kg P/ha, high application rate refers to 85-128 kg P/ha. The high application rate results in significantly higher leaching effect (hg=3.38, ci=1.63-5.12) than the low application rate (hg=1.24, ci=0.77-1.71).

The high application rate significantly increased the leaching effect. The high application rate is approximately the same as the allowed maximum single application according to Swedish manure legislation where 22 kg P per hectare and year as an average over 5 years (Albertsson et al. 2015) which sums up to 110 kg P per hectare.

The influence of lysimeter length is shown in figure 6.

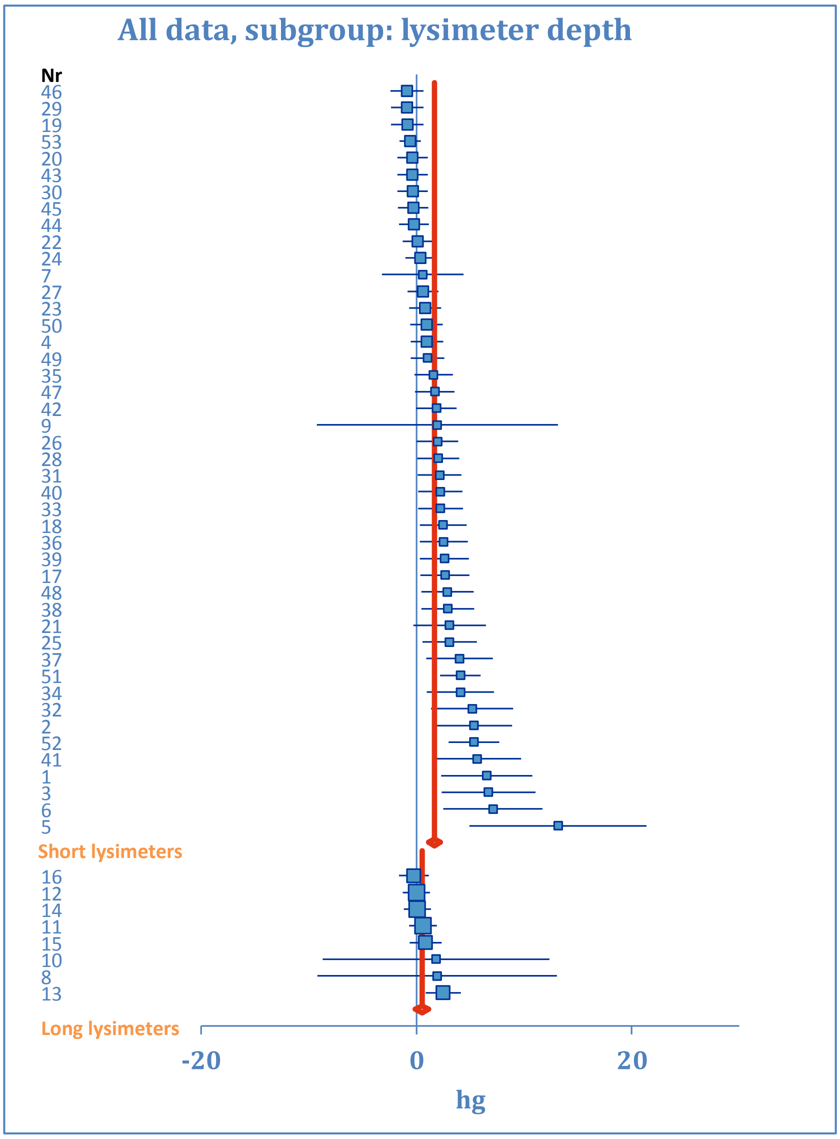

Figure 6
The effect of manure application on phosphorus leaching depending on the length of the lysimeters. Short lysimeters are 0.2-0.3 m long, and are thus investigating leaching from the topsoil. Long lysimeters are 0.5 m long, which includes the subsoil. The leaching from the short lysimeters have a significantly higher effect (hg=1.70, ci=1.15-2.24) than the long lysimeters (hg=0.53, ci=-0.08-1.15).

The results show that long lysimeters are affected significantly less by manure application than the short lysimeters.

The data was also subgrouped depending on DPS value, but no significant difference was found. Furthermore, neither the groups with different dry matter content, nor the groups with different manure type showed any significant differences in leaching effect.

Heterogeneity analysis on subgroups

The change in heterogeneity was analysed in the subgroups that yielded significant differences in order to ascertain if further sub-grouping was needed (Table 6).

Table 6.
Heterogeneity analysis for the performed meta-analyses. *N* refers to total number of replicates in each study. CI is the 95% confidence interval.

Grouping	Subgroups	I^2 (%)	CI (%)	N
All data	-	67	55-75	466
STP	Low STP	67	46-80	136
	Moderate STP	76	60-86	120
	High STP	53	25-71	210
Preferential flow (PF)	PF	63	48-73	372
	No PF	0	0-62	78
Application rate	Normal	65	52-75	366
	High	69	43-83	100
Lysimeter depth	Short	70	59-78	380
	Long	14	0-72	86

I^2 statistics: less than 30% - mild heterogeneity, over 50% - substantial heterogeneity (Higgins & Thompson 2002)

Table 6 shows no significant difference in heterogeneity between subgroups and all data. The effect from soils without potential for preferential flow and long lysimeters show a higher homogeneity, but the confidence interval overlaps the confidence value for the *all data* grouping. These factors are thus not the only reason for the high heterogeneity.

To further investigate if the three factors (potential for preferential flow, application rate, and lysimeter depth) are appropriate for grouping the data, subgroups were divided into additional subgroups. (table 7).

Table 7
Subgroup analyses in subgroups where significant difference was found. N refers to the number of sub-studies, out of the total of 53, in the respective subgroup stated in column 1. PrefFlow refers to grouping by soils with and without potential for preferential flow, Short- and Longlys refers grouping by short and long lysimeters, respectively, and Norm- and HighAppl refers to grouping by normal and high application rates, respectively. *Sig* refers to a significant difference between subgroups, *Not sig* means that there was not a significant difference between subgroups. *NA* refers to lack of data (0 or 1 sub-study).

Subgroups	N	PrefFlow	Lys depth	Appl rate
PrefFlow	43	-	Sig (Short>Long)	Not sig
No Prefflow	10	-	NA	NA
ShortLys	45	Sig (PF>No PF)	-	Sig (High>Normal)
LongLys	8	NA	-	Not sig
NormAppl	41	Sig (PF>No PF)	Sig (Short>Long)	-
HighAppl	12	NA	Sig (Short>Long)	-

Table 7 shows that the subgroups *no preferential flow*, *long lysimeters* and *high application rate* generally did not contain enough data in order to perform the analysis. Two exceptions were found: the data for high application rates could be further subgrouped into long and short lysimeters, and the results show a significant difference, and the data for long lysimeters could be subgrouped into normal and high application rates, although no significant differences were found. Since the number of included sub-studies is substantially lower in the subgroups *long lysimeters* and *high application*, false positives are a possibility (Higgins et al. 2003). Subgroup analysis for lysimeter depth in the group with potential for preferential flow showed that a significant difference could still be found. However, the effect of application rates did not show any significant differences. Subgroup analysis for potential for preferential flow and application rates in the group with short lysimeters showed that both grouping factors still yielded significant differences. Subgroup analysis for preferential flow and lysimeter depth in the group with normal application rates also showed significant differences.

The results indicate that the three selected factors have an impact on the effect of phosphorus leaching when manure is applied. When analysing the data, these factors should therefore be held constant.

Effects of manure application on phosphorus leaching - adjusted data

When the data for short lysimeters, normal application rate and soils with potential for preferential flow was aggregated, 25 sub-studies remained (figure 7).

There was not enough data to perform such an aggregation on the data for long lysimeters, high application rate and soils without potential for preferential flow.

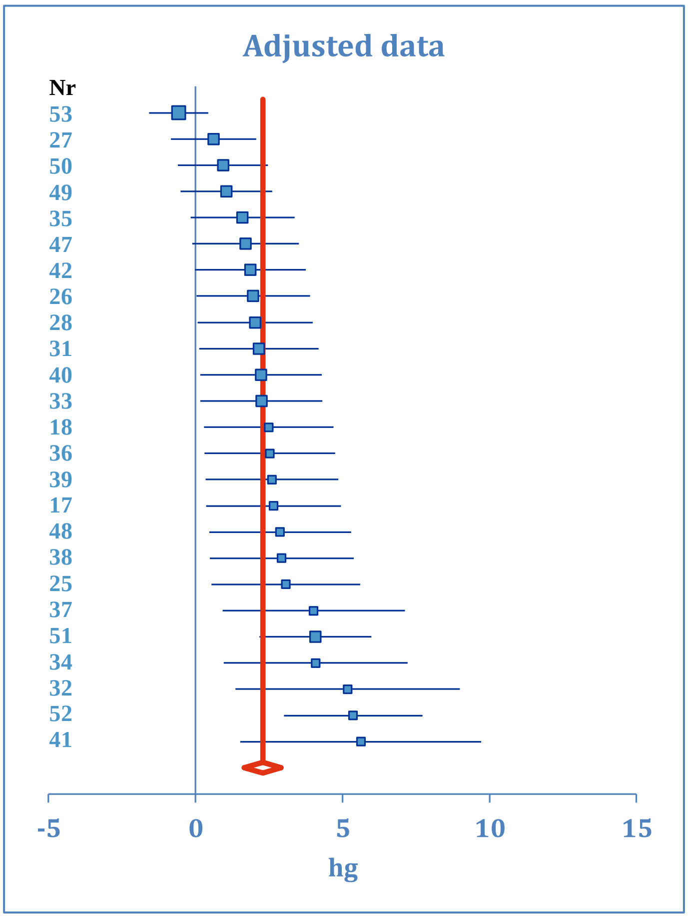

Figure 7
Effects of manure application on phosphorus leaching in soils with potential for preferential flow, that has recieved a normal application rate (11-30 kg P/ha) and that are investigated using short lysimeters (0.2-0.3 m). The hedge's g value of 2.27, (ci=1.64-2.95), suggests a moderate effect. The heterogeneity statistics (I^2=57%, ci=33-72%) is not significantly different from the analysis with all data (Table 6).

Neither the effect (figure 7) nor the heterogeneity (table 8) has changed significantly when the data was grouped according to factors that significantly affected the results. This indicates that there may be additional factors that have been overlooked in this thesis affecting the results. In order to investigate if one of these factors is the STP, the data was grouped and analysed (figure 8).

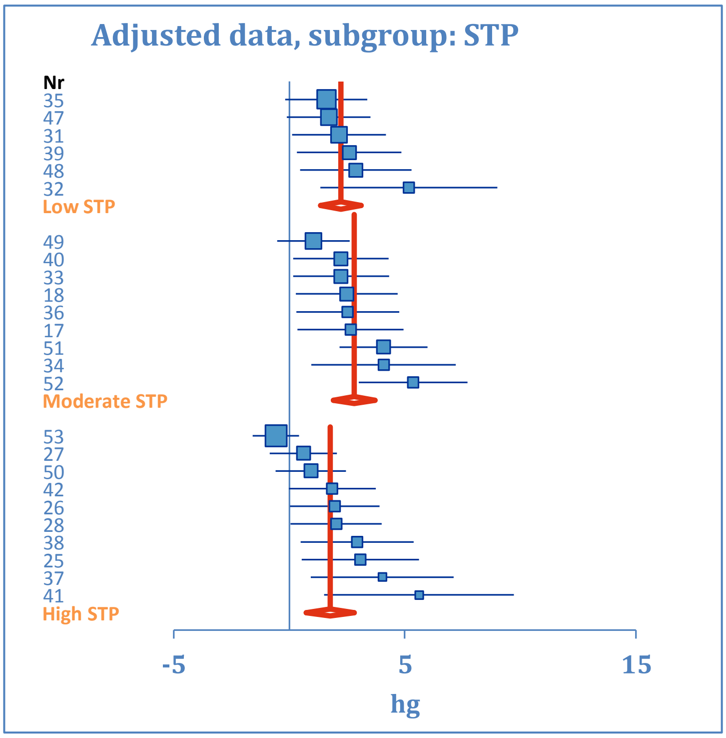

Figure 8
Data for short lysimeters, normal application rate and soils with potential for preferential flow was grouped accordning to P-status. No significant differences were found.

Figure 8 shows no significant difference between with low, moderate and high STP soils. The differences between STP levels seen in figure 3 have thus disappeared when the data was corrected for subgroups affecting the result. Even though a tendency of decreasing heterogeneity can be seen when comparing table 6 and 8, the confidence intervals in table 8 are overlapping the I^2 values in table 6. There are thus no significant differences in heterogeneity when the data have been adjusted.

Table 8

Heterogeneity analysis of the data from short lysimeters, normal application rate and soils with potential for preferential flow. The analysis shows that heterogeneity did not significantly differ when the data was adjusted, compared to when all data was included (table 6). CI is the 95% confidence interval.

Grouping	Subgroups	I^2 (%)	CI (%)	N
All data	-	57	33-72	216
STP	Low STP	0	0-75	48
	Moderate STP	36	0-70	88
	High STP	65	32-82	88

I^2 statistics: less than 30% - mild heterogeneity, over 50% - substantial heterogeneity (Higgins & Thompson 2002)

Leaching of phosphorus from recently unmanured soils

The relationship between background phosphorus leaching from soils that recently had not received phosphorus and phosphorus status in the soil was investigated in the included studies (Table 9). Six studies out of eight were investigating soils that spanned over more than one phosphorus status (low, moderate or high). Three out of six studies showed that increasing STP caused an increase in leaching from soils that had not been recently fertilized, two studies showed no difference, and one study showed an opposite response.

Table 9

Investigation of phosphorus leaching with increasing STP. *Sig* refers to if studies find a significantly higher or lower leaching with increasing STP. *P-status* refers to STP levels in investigated soils, *n* to the number of replicates and *w* to the weight given to the study based on number of replicates.

Author	Sig	P-status	n	w (%)
Glæsner et al. 2011	-	Low	-	-
Kleinman et al. 2005	No	Low - High	8	5
Kleinman et al. 2009	No	Low - High	18	10
Liu et al. 2012a	Yes	Mod < High	31	18
Liu et al. 2012b	-	High	-	-
Pavrage et al. 2015	Yes	Mod > High	12	7
Svanbäck et al. 2013	Yes	Low < Mod < High	80	46
Ulén et al. 2013	Yes	Low < high	24	14

The results in table 9 show that studies supporting the fact that a higher STP leads to a greater phosphorus leaching gets 78% of the weight, while the other studies get 22% of the weight.

The effect of manure application did thus not increase with increasing STP, rather the opposite result was shown. However, the leaching from soils that had recently not received manure did tend to increase with increasing STP.

Investigation on the European manure legislation

Table 10 shows the results from the investigation of manure legislation.

Table 10
Legislation of manure application in Europe.

Country	Restriction – Manure application
Austria	No direct restriction, application is regulated indirectly in the Nitrates Directive. There are recommendations for mineral fertilizers.
Belgium (Walloon)	No direct restriction, application is regulated indirectly in the Nitrates Directive.
Czech Republic	No restrictions of phosphorus application based on STP. Restrictions on nitrogen fertilizers in nitrate sensitive areas. Manure application is regulated indirectly in the Nitrates Directive.
Denmark	No direct restriction, application is regulated indirectly in the Nitrates Directive. Farms that 1) want to expand or change their production unit, 2) drain into Natura 2000 areas overloaded with P and 3) fall under P-class 1, 2 or 3 are subject to additional restrictions. • **P class 0** (drained clay soils, Olsen-P/P-tal < 4): no additional restrictions • **P class 1** (drained clay soils, 4 < Olsen-P/P-tal < 6): phosphorus surplus can increase at maximum by 4 kg P/ha and year • **P class 2** (lowlands with Fe/P mole ratio < 20): phosphorus surplus is at maximum 2 kg P/ha and year • **P class 3** (drained clay soils, Olsen-P/P-tal > 6): no phosphorus surplus is allowed
Estonia	Application of manure phosphorus is restricted to 25 kg P per hectare and year, as an average over 5 years.
Finland	Large livestock farms may be subject to local restrictions of manure application on soils with a high STP, for example if the field drains into a watercourse with poor status. Further restrictions on phosphorus application are placed on farmland if farmers join the voluntary agri-environmental program. Restrictions are based on crop type and STP.

Germany	Phosphorus application must be balanced with crop removal. A surplus of 10 kg P/ha and year, as an average over 6 years, is premitted. If nutrient losses causes negative effects on water ecosystems, further restrictions may be applied. Farmers may be target of penalties if application exceeds crop need. Additional measures include adaptation to weather conditions, STP measurements in order to determine nutrient need, increasing minimum distance to surface waters with increasing slope inclanation, increased manure storage capacity and reporting of manure nutrient status. If farmers join agri-environmental programmes, additional measures are not applied.
Ireland	Phosphorus application by manre is restricted based on STP (Morgan´s P), no phosphorus may be applied on soils with STP considered higher than optimum.
Latvia	No direct restriction, application is regulated indirectly in the Nitrates Directive.
Norway	No restrictions of phosphorus application based on STP. Manure phosphorus application is restricted indirectly by restricting the amount of livestock units per hectare.
Poland	No direct restriction, application is regulated indirectly in the Nitrates Directive.
Romania	No direct restriction, application is regulated indirectly in the Nitrates Directive.
Sweden	Legislation for manure and slurry application states that no more than 22 kg P ha^{-1} yr^{-1} may be applied as manure or slurry, calculated as a mean over 5 years. No general restriction on manure application based on STP. Livestock farms that are large enough to require a permit may get local restrictions on applying manure on P-Al class IV and V-soils.

Table 10 shows that Austria, Belgium, Czech Republic, Latvia, Poland and Romania restrict manure application via the European Nitrates Directive. Estonia and Sweden have limits to amounts of manure that may be applied. Norway restricts the maximum amount of livestock per hectare. Finland has legislation that aims to target areas sensitive to nutrient losses coupled with voluntary agri-environmental programs. Germany aims to balance nutrient input with crop removal, coupled with additional measures if surface waters are affected. Furthermore, they encourage farmers to join agri-environmental programs. Ireland is the only country that has implemented general restrictions that does not allow for any manure application on soils with high STP. In Denmark, application must be balanced to crop uptake in sensitive areas and on soils with high STP.

Ireland restricts manure application based on agronomically optimal phosphorus levels (Schulte et al. 2010). The soils are grouped into four classes, where the fourth is considered to have an excess of phosphorus (Coulter & Lalor 2008).

Discussion

Meta-analysis

The results indicate that adjusted phosphorus fertilization will decrease the phosphorus loading to freshwaters and in extension the Baltic Sea. The extent of the effect is, however, not possible to determine. The high heterogeneity of the data material excluded the possibility of using an unstandardized effect size. This meta-analysis is thus not suitable for quantifying the phosphorus loading caused by manure application, but rather to determine when and why loadings increase or decrease.

The initial analysis for heterogeneity of unstandardized data showed that 93% of the variation was not caused by chance, but by differences between the studies or sub-studies. Heterogeneity decreased to 67% when the data was standardized to hedge’s g, indicating that analysis with a standardized effect size was preferable when aggregating and analysing the data.

The top individual sub-studies in figure 1 that show a negative hg value do not have apparent common properties. The soils have different soil test phosphorus levels (STP) and textures. Furthermore, different manure types are applied with different dry matter content with different application rates. The bottom sub-studies (figure 1) (numbers 1, 3, 6, 5) come from the same study with the highest application rate (128 kg P/ha) on soils with low STP. Sub-study number 5 has the highest effect and variance. Glaesner et al. (2011) attributes the strong leaching to the fact that manure was surface applied. This holds true for number 1 and 3 as well, while in number 2, 4 and 6, manure was incorporated into the soil. The strong effect may therefore not only be explained by the application method, but also, according to Glaesner et al. (2011), by the soil texture (loam).

A selectivity analysis revealed that studies with low to moderate precisions and effect sizes were missing in the included studies, suggesting publication bias. The results may also, however, have partly been caused by heterogeneity. Researchers with access to unpublished data may want to repeat this study, if studies are in fact missing, in order to ascertain if publication bias has affected the results.

Subgroup analysis

The results of the analysis when all data was included showed that, when manure is applied, the leaching effect did not increase with increasing STP, compared to unmanured controls. Rather, soils with a high STP seemed to be less affected than soils with low STP. Risk assessment of phosphorus leaching after manuring agricultural lands may therefore not necessarily need to include STP. According to the literature, other factors should play a role in the leaching potential of a soil. Of the investigated factors, preferential flow, lysimeter length and application rate affected the results significantly.

Preferential flow may cause significant phosphorus losses. Soils with preferential flow showed an overall moderate effect on leaching while soils without showed no effect (Figure 4). However, some soils that contributed to the lower effects in the group with potential for preferential flow were investigated using long lysimeters (0,5 m). This may have resulted in that the part of the perforating water that was not transported with preferential flow had longer time to equilibrate with the soil. Although, some sub-studies with long lysimeters did not show at the lower end of the effect spectra (numbers 8, 10 and 13). Another plausible factor that may have contributed to the difference between studies was different application rates. The four sub-studies that showed the highest effects were also receiving the highest application rate, 128 kg P/ha (numbers 1, 3, 5 and 6). It should be noted that one of these sub-studies with 128 kg P/ha is found in the lower effect spectra (number 4). The analysis thus showed that the influence of lysimeter length and application rate did not cause a false positive result for preferential flow.

Increasing application rate caused an increase in the leaching effect, as was expected. The higher leaching from the higher application result supports the guidelines from the Swedish Board of Agriculture (Albertsson et al. 2015) which state that storage fertilization should be avoided due to increased leaching risks.

The fact that long lysimeters had a lower effect on phosphorus leaching than did short lysimeters is supported by the theory. Application of phosphorus causes an increase of STP in the topsoil but may not affect the subsoil. The subsoil therefore has a larger potential for retaining phosphorus, given that the phosphorus solution has time to equilibrate with the soil. The majority of the investigated studies did, however, use short lysimeters. These results suggest that the leaching effect from application of manure may be exaggerated when it is investigated with short lysimeters. It has been argued that short lysimeters are not useful for predicting phosphorus leaching losses from soils, but rather phosphorus movement into the subsoil. Long lysimeters including the subsoil provide an estimate of the leaching from the investigated soils. Short lysimeters may, however, provide crucial insights about how and why phosphorus is moving through the soil profile. Investigation of correlation between leaching of phosphorus and, for example, DPS, PSC and continuous macropores enabling preferential flow will still be valid when investigating the subsoil. If the soil contains macropore structures that allow solutes to leach from the topsoil down to the drainpipes, the influence of the subsoil may not play such a pivotal role. The main problem is that the influence of the subsoil is not regarded when using short lysimeters. The long lysimeters thus provide a better basis for fully understanding phosphorus leaching.

Investigation of manure type, dry matter in manure and soil texture did not show significant differences between subgroups. This result is contradictory to previous research. The fact that these factors do not affect the result may be caused by the fact that preferential flow, lysimeter length and application rate simply affected the results more.

Factors identified and tested in the subgroups could improve the homogeneity of the data material, if differences in said factors yield different effects and thus an increase in heterogeneity. A tendency of decreasing heterogeneity was seen in the subgroups where data from long lysimeters and without potential for preferential flow were included, although there was no significant difference between the two subgroups and other subgroups. The decrease in heterogeneity could be a direct result of a smaller sample size. Because of the small sample sizes in the subgroups with data from long lysimeters, no potential for preferential flow and high application rates, no meta-analysis could be performed.

Background leaching of phosphorus from recently unmanured soils did tend to increase with increasing STP. However, there is no unambiguous evidence in research that a higher STP actually leads to a higher background leaching of phosphorus (Bergström et al. 2008), which is supporting the inconclusive results of this study. The tendency of higher leaching with higher STP in the included studies must therefore be regarded with the possibility that other factors may have influenced the results. Svanbäck et al. (2013) used five different soils with four application rates resulting in different STP concentrations in the soil samples. The increase in leaching with increasing STP concentration from soil columns before manure application therefore presents stronger proof of the relationship than when the investigation is performed on different soils with different properties.

Analysis of adjusted data

After the data was corrected in such a manner that factors proving to influence the result significantly were held constant, the effect of phosphorus leaching from soils with different STP levels disappeared. The effect first seen in figure 1 may thus have been an effect caused by the influential factors.

If the goal of adjusted phosphorus fertilization is to target soils that are susceptible to phosphorus leaching while house-holding with phosphorus, additional factors need to be addressed. From an agronomical point of view, however, soils with excessive STP receiving additional phosphorus constitutes a problem where a valuable resource is wasted, compared to if the manure was used on soils with lower STP. Both approaches are important and thus need to be combined and integrated into a legislative measure.

European manure legislation

The legislation regarding manure application on agricultural soil differs among countries in Europe. The most common measure is to restrict manure application via the Nitrates Directive. By doing so, phosphorus from manure application is only indirectly restricted thus risking to allow application on soils sensitive to phosphorus leaching.

Estonia and Sweden set a maximum allowed amount of phosphorus in manure that may be applied on agricultural soils. In Sweden, the maximum amount of phosphorus in manure that may be applied per year is calculated as a mean over 5 years, meaning that the farmer may apply all manure on a single occasion. The Swedish Board of Agriculture has recommendations not to do so, since it increases the risks of phosphorus losses. The results from this study support the recommendations, why this may be one area where legislative action is needed.

Ireland is the only investigated country that has placed restrictions so that no manure may be applied to soils with an excessive STP. According to the investigation performed by Amery & Schoumans (2014), the Belgian region of Flanders and The Netherlands also enforce restrictions based on STP, but only to reduce the amount of manure applied. Denmark applies further restrictions on farms that want to expand, that drain into Natura 2000 areas and that have high phosphorus content and low Fe/P ratios.

In order to implement a sustainable manure legislation, many factors need to be considered. Phosphorus losses can be detrimental to aquatic ecosystems and must therefore be minimized. Phosphorus is also of utmost importance for food production. Current research suggests that phosphorus levels in soils must be coupled with the ability of the soil to retain phosphorus in order to evaluate leaching.

Important factors for mitigating phosphorus leaching

The results from this thesis suggest that preferential flow and application rates are important to consider. Investigation of leaching from topsoil columns may also overestimate the leaching effect due to the possibility of retention in the subsoil. While the results showed that soils with high STP generally had a higher background leaching from recently unmanured soils, these losses may not be the most urgent to mitigate. Sudden and high losses of phosphorus are more likely when phosphorus has recently been applied followed by a rain event. Furthermore, since the labile plant available pool of phosphorus, which is measured with STP methods, only constitutes some 0.02% of the total phosphorus in soils, a relative increase of, for example, 100% may prove negligible if the phosphorus is left to equilibrate with the soil. Long-term fertilization may however reduce the ability of the soil to remove phosphorus from the free draining solution. Furthermore, increasing to and maintaining a high STP in soils may still cause unnecessary phosphorus losses. If there is no agronomical gain when applying manure, the phosphorus is virtually wasted. Redistribution of manure to areas where phosphorus is indeed needed is an important measure in order to minimize the mining of mineral phosphorus. As mining may result in detrimental environmental effects, such as acid mine drainage, it is vital to minimize such endeavours.

When formulating legislative measures to optimize phosphorus usage while minimizing phosphorus leaching, they should thus in some form include restrictions of application rates and investigations of preferential flow. Preferential pathways can be investigated using dye tracers in undisturbed soil columns (Morris & Mooney 2004). As PSC, DPS, soil pH and manure type also have been identified in previous research as factors that affect phosphorus movement, these factors need to be further investigated with a bigger data set. If these factors are also deemed to have a significant effect on phosphorus leaching, they too should be included in legislative measures. The only investigated country that includes any of the mentioned factors is Denmark, where the ratio between Fe and P, as a measurement of DPS, is taken into account. As current research clearly show that these factors affect the leaching behaviour of phosphorus from soils, legislation measures must adapt.

Cost efficiency and non-target impacts

If manure is to be relocated, the gains need to be weighted against the increased carbon dioxide (CO_2) emissions. Svensson (2009) performed an impact assessment investigating the effects of prohibition of manure application on soils with P-AL class V in Sweden. The impact assessment aimed to investigate the effects on the climate due to increased CO_2 emissions and the economical implications for the farmers. Svensson (2009) concludes that the prohibition will cost the farmers 113-194 million SEK (12-20 million Euro), and will lead to an increased CO_2 emission of 4-6,000 tonnes, depending on how far the manure has to be transported. Since phosphorus levels in soils are decreasing in Sweden, and that a phosphorus deficit is possible during certain conditions despite high STP levels, Svensson (2009) proposes that manure application should be allowed to cover crop uptake. Soils with P-AL class V constitutes 10% of Swedish arable land (Paulsson et al. 2015). Adjusted phosphorus fertilization will also include soils with P-AL class IVb, which constitutes 7% of Swedish arable land (Paulsson et al. 2015). Effects and costs estimated by Svensson (2009) should therefore increased with a factor of 1.7, resulting in a total cost of 192-330 million SEK (20-34 million Euro) and a total CO_2 emission of 6,500-10,000 tonnes. In total, Sweden has 2,400,000 ha agricultural soil, out of which 410,000 ha are classified as P-AL classes IVb-V (Paulsson et al. 2015).

Larsson & Gyllström (2013) performed an analysis on costs versus effects when manure is prohibited on soils with P-AL classes IVb-V. In the investigated area, 3,300 ha were affected by the measure, resulting in a theoretical decrease in phosphorus loss of 327 kg per year at a cost of 522,000 SEK per year (53,000 Euro). If the same reduction potential and costs are extrapolated on all Swedish soil that may be affected by the measure, phosphorus losses will be reduced by 41 tonnes P per year at a cost of 65 million SEK per year (6.6 million Euro). The cost estimation by Larsson & Gyllström (2013) is thus only 34% of the lower end estimation made by Svensson (2009).

There is uncertainty in the estimation of effects and costs of the proposed measure. The measure will, however, come with a cost for farmers. Since soils react differently depending on inherent factors, the effects of a measure targeting a wide range of soils will be difficult to predict. A prohibition of manure application based on STP levels is an uncommon measure, while restrictions based on STP and crop uptake is more common. Such an approach, where phosphorus application is balanced to crop uptake, may prove superior, as it reduces the amount of manure that needs to be transported, results in a lowering of the STP levels while still allowing the farmer to adjust phosphorus input. It is, however, not certain that all soils will show a decrease in STP if phosphorus application is balanced with crop uptake. Those soils need to be identified. Alternatively, application limits may need to be lower than crop uptake. Furthermore, balanced P application will result in a low leaching effect (Svanbäck et al. 2013).

As phosphorus leaching and phosphorus house-holding should constitute the primary targets for mitigating measures, a restriction of phosphorus application based on crop removal could be coupled with additional restrictions on soils that are susceptible for leaching land leach into areas that are sensitive to phosphorus.

Furthermore, voluntary actions to further reduce the excessive fertilization of agricultural soils should be encouraged and subsidized.

Source of errors and further research

In this study, all factors that may affect phosphorus leaching have not been included. Mainly, this is caused by the fact that some important factors, such as soil pH, are not presented in most papers. Furthermore, dependent data was used in order to obtain enough input data for the analysis. As the controls were independent of each treatment, this is not regarded as a major problem. The program used, MIX, does not allow for meta-regression analysis, which would have been useful for identifying the relative impact of the factors affecting the leaching effect.

In order to identify soils susceptible of phosphorus leaching, further research is needed. Factors identified need to be controlled and the relative impact of each factor needs to be estimated. A meta-analysis is a useful tool in order to investigate and summarize the research on phosphorus leaching. As this study shows, there is great heterogeneity in the studies used, indicating that important factors may be missing from the study. Although, there is a chance that the heterogeneity shown is simply a result from testing a complex environment, and thus it is expected. The strength of using standardized effect sizes is that different types of effects may be compared and combined. In order to further investigate phosphorus leaching risks, field studies and studies investigating phosphorus leaching with mineral fertilizers should be included in the input data, thus increasing the number of studies and widening the investigative grasp. Studies using disturbed soil columns should, however, not be included since they cannot be used in order to investigate solute transport pathways. In order to ascertain in what extent different factors influence phosphorus leaching when manure is applied to a soil, a multivariable meta-regression analysis should be performed.

As phosphorus losses do not only constitute of leaching but also of runoff losses, the investigation of one without the other will result in an incomplete analysis. Runoff research should be included in the meta-analysis in order to describe the total losses of phosphorus and identify soils susceptible to losses. The factors affecting phosphorus losses should also be controlled and updated. If more factors can be included when the data material grows, the analysis has a higher chance of providing an answer to where, when and why phosphorus losses occur.

Conclusions

Restricting manure application on soils with high STP will reduce phosphorus leaching and STP levels. However, the results show that high STP soils do not leach more phosphorus when manure is applied compared to lower STP soils. The measure will reduce the background leaching of phosphorus, but the amount phosphorus that leach from these events may be negligible compared to recently manured soils.

The meta-analysis revealed that application rate, preferential pathways and the ability of the subsoil to retain phosphorus is important when investigating phosphorus leaching. These factors need to be included in legislative measures if soils with high potential for phosphorus leaching are to be targeted.

The European manure legislation mainly focuses on restricting manure application via the Nitrates Directive. Other measures include setting a maximum application rate, balancing phosphorus application with crop removal and voluntary subsidized actions. Ireland is the only country to prohibit the application of manure based on STP.

Phosphorus movement through soil can be divided into two distinct groups: soils with potential for substantial preferential flow and soils without. In soils with preferential flow, the main task is to disrupt the continuous pathways, thus increasing the mixing of water with soil and allowing for longer equilibration time. In soils without preferential flow, PSC and DPS seem to determine phosphorus adsorption and desorption. Legislation that takes these factors into account has a higher probability of targeting soils with high risks of phosphorus leaching.

Since the measure may result in higher costs for the farmers and higher CO_2 emissions, compromises may be needed. Application of manure where phosphorus is balanced to crop removal coupled with additional restrictions in areas sensitive to phosphorus leaching may prove more effective than restriction based on STP. Additional measures may be based on investigations of preferential pathways, PSC and DPS, while also include a maximum application rate.

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Appendix 1

Table 11
Mean values, standard deviations and number of replicates in the included studies.

Artikel	nr	T mean	T SD	T n	C mean	C SD	C n
Glæsner et al. 2011	1	0,1019	0,0093	3	0,0556	0,0046	6
	2	0,0833	0,0046	3	0,0556	0,0046	6
	3	0,1759	0,0278	3	0,0602	0,0046	6
	4	0,0694	0,0139	3	0,0602	0,0046	6
	5	0,2500	0,0185	3	0,0926	0,0046	6
	6	0,1296	0,0046	3	0,0926	0,0046	6
Kleinman et al. 2005	7	0,442	0,42	2	0,132	0,12	2
	8	1,38	0,468	2	0,192	0,164	2
	9	0,644	0,215	2	0,126	0,005	2
	10	0,181	0,049	2	0,068	0,01	2
Kleinman et al. 2009	11	0,25	0,13	3	0,17	0,12	12
	12	0,17	0,21	3	0,17	0,12	12
	13	0,5	0,15	3	0,17	0,12	12
	14	0,18	0,07	3	0,17	0,12	12
	15	0,29	0,18	3	0,15	0,13	6
	16	0,12	0,03	3	0,15	0,13	6
Liu et al. 2012a	17	2,764	1,21	4	0,15	0,081	4
	18	1,385	0,604	4	0,15	0,081	4
	19	0,17	0,057	4	0,231	0,069	4
	20	0,203	0,059	4	0,231	0,069	4
Liu et al. 2012b	21	0,404	0,032	3	0,307	0,016	3
	22	0,599	0,186	4	0,568	0,214	4
	23	0,491	0,125	4	0,405	0,041	4
	24	0,157	0,034	4	0,143	0,029	4

Pavrage et al. 2015	25	0,045	0,008	4	0,02	0,006	4
	26	0,083	0,039	4	0,02	0,006	4
	27	0,833	0,337	4	0,649	0,156	4
	28	1,186	0,286	4	0,649	0,156	4
	29	1,868	1,591	4	3,403	1,479	4
	30	2,709	1,921	4	3,403	1,479	4
Svanbäck et al. 2013	31	0,995	0,509	4	0,098	0,048	4
	32	1,072	0,211	4	0,157	0,051	4
	33	2,232	0,952	4	0,475	0,159	4
	34	3,336	0,549	4	1,046	0,418	4
	35	0,207	0,124	4	0,046	0,007	4
	36	0,236	0,092	4	0,045	0,006	4
	37	0,370	0,085	4	0,090	0,012	4
	38	0,332	0,101	4	0,090	0,012	4
	39	1,333	0,610	4	0,046	0,010	4
	40	1,347	0,683	4	0,107	0,026	4
	41	2,911	0,513	4	0,513	0,111	4
	42	2,790	1,187	4	0,901	0,387	4
	43	0,073	0,022	4	0,095	0,069	4
	44	0,106	0,029	4	0,123	0,079	4
	45	0,333	0,126	4	0,394	0,215	4
	46	0,725	0,207	4	1,019	0,357	4
	47	0,288	0,169	4	0,053	0,018	4
	48	0,640	0,206	4	0,151	0,034	4
	49	2,224	0,316	4	1,782	0,414	4
	50	2,885	0,768	4	2,142	0,607	4
Ulén et al. 2013	51	0,42	0,0546	8	0,23	0,0299	8
	52	1,25	0,1625	8	0,54	0,0702	8
	53	1,93	0,2509	8	2,09	0,2717	8

Appendix 2

Table 12
Countries and contact information for the investigation of European manure phosphorus legislation.

Country	Contact	Organization
Austria	Paul Schenker <Paul.Schenker@bmlfuw.gv.at>	Federal ministry of agriculture, forestry, environment and water management
Czech Republic	Ministry of the Environment of Czech republic <neodpovidat@helpdesk.cenia.cz>	Ministry of the Environment of Czech republic
Denmark	Wibke Christel <wibch@mst.dk>	Environmental Protection Agency – Ministry of Environment and Food
Estonia	Enn Liive <Enn.Liive@envir.ee>	Ministry of the environment – Water department
Finland	Kulmala Airi <Airi.Kulmala@mtk.fi>	Central Union of Agricultural Producers and Forest Owners (MTK)
Germany	Amelie Bauer <Amelie.bauer@lwk-niedersachsen.de>	Chamber of Agriculture - Niedersachsen
Ireland	Per-Erik Mellander <PerErik.Mellander@teagasc.ie>	Agricultural Catchments Programme, Johnstown Castle Environmental Research Centrem, Ireland
Latvia	Aiga Krauze <aiga.krauze@lvgmc.lv>	Latvian Environment, Geology and Meteorology Centre, Inland Waters division
Norway	Marianne Bechmann <Marianne.Bechmann@nibio.no>	NIBIO – Miljø og naturressurser
Poland	Andrzej Szymański <a.szymanski@cdr.gov.pl>	The Agricultural Advisory Centre
Romania	Birou Presa ANAR <birou.presa@rowater.ro>	National Administration of Romanian Waters

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