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Review paper

PHOSPHORUS LOSSES AND ON-FARM MITIGATION OPTIONS FOR DAIRY FARMING SYSTEMS: A REVIEW

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ABSTRACT

Phosphorus (P) is an important nutrient in livestock production systems. It together with calcium functions in the skeletal development of animal and also essential for energy metabolism and cell replication within animals. In livestock production, the P requirements are met by feeding animals with both organic and inorganic sources of P.This elementis a major limiting nutrient controlling biological productivity in surface waters. Its excess losses from agricultural systems and from point or diffuse sources can lead to several environmental consequences like eutrophication. On dairy farms non-point source like mineral fertilizer, manure or slurry fertilizer and point sources like grazing with help of overland and subsurface water flow are potential P losses pathways. For efficient mitigation strategy, the quantification of potential P losses is prerequisite e.g., Danish P index. Precise use of P fertilizer with riparian buffer strips, conservation tillage, precise feeding, animal health, exogenous enzymes and rotational grazing are best ways to reduce P losses. Additional to these, manure storage, management and transport can be managed efficiently to reduce P losses from dairy farms.

Key words: Phosphorus, Dairy farms, Point Source, Non-point source, Danish P index, Feeding, Manure management

INTRODUCTION

Phosphorus is an important nutrient in livestock production systems. P together with calcium functions in the skeletal development of animals. It is also essential for energy metabolism and cell replication within animals (Poulsen, 2000). P is an important component of deoxyribonucleic acid (DNA), adenosine triphosphate (ATP), ribonucleic phosphate (RNA) and phospholipids in animals. In livestock production, the P requirements are met by feeding animals with organic sources of P i.e., grassland pastures, clovers and/or inorganic phosphate supplements. However, because P is a major limiting nutrient controlling biological productivity in surface waters, excess losses from agricultural systems, from point and diffuse sources (such as soils, crops residues and animal excreta) can lead to several environmental consequences (McDowell *et al*., 2001; Kebreab *et al*., 2007). High water P content over-stimulates the growth of plants, algae and bacteria, which deplete the available oxygen leading to eutrophication (Steinfield *et al*., 2007). Furthermore, increased growth of microorganisms associated with eutrophication can be detrimental to public health (Steinfield *et al*., 2007).

Among the contributing farming systems to P loss, pastoral land uses, intensive dairy farming have been identified to be a major agricultural practices accounting for P losses leading to environmental deterioration problems in many parts of the world (McDowell and Nash, 2012). A survey conducted by McDowell and Wilcock (2008) in some selected different catchment areas in New Zealand, it was found out that P losses from dairy production sites to surrounding catchments were higher ranging between 1 and 10 kg P ha^{-1} as compared other livestock systems like sheep production. Even though P loss in dairy production may be less when compared to other livestock like pig production systems, the loss could still have significant water quality problem in surface water because P is the major limiting nutrient in freshwater bodies. It is against this background that the present review seeks examine the sources and transport pathways of P losses from dairy farming systems to water bodies and the on-farm mitigation options for reducing these losses.

Potential sources of P loss from dairy systems: There are many potential sources of P loss from dairy farms, either diffuse, which are sources spread around large areas such as fields; or point sources, which are high concentrations of P coming from one source/small area (Steinfield *et al*., 2007). It is believed that diffuse sources contribute more to P losses in comparison to point sources (Sharpley *et al*., 1994; McDowell *et al*., 2009). The major contributor to P loss on farms is application diffuse losses that results from the use of fertiliser (mineral or organic) followed by manure/effluent treatment of crops (McDowell, 2012). Point-source losses include areas where cattle walkways cross streams or where run-off from milking sheds drains directly into waterways (McDowell *et al*., 2009). Finally, the legacy of P in the soil content can alter the contribution of diffuse sources to P losses (Sharpley, 1994; McDowell *et al*., 2009).

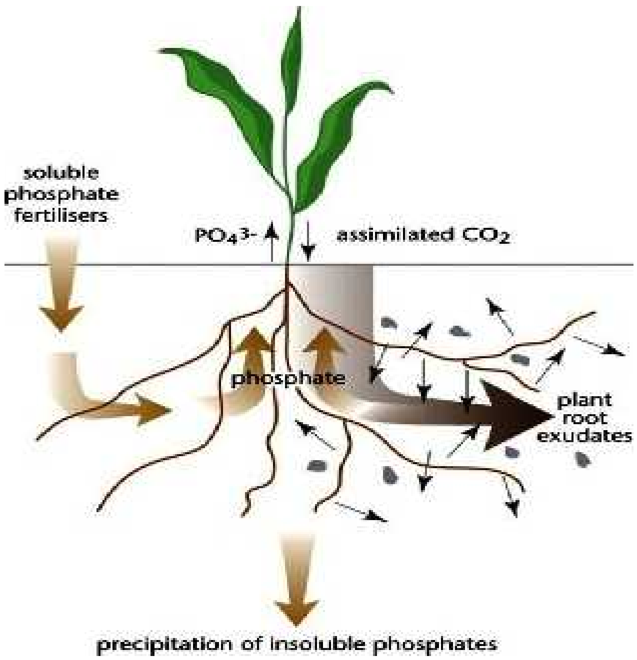

Figure 1: Phosphorus cycle in relation to plant root activity (Manning, 2008).

The P cycle is defined as the interaction of plants with natural and artificial P within a soil. The plant roots take up soluble phosphate from the soil (artificial) and release exudates to convert less soluble P from sources such as feldspars (natural) into more soluble P (Figure 1, Manning, 2008). Insoluble phosphates can be lost into underlying water systems. Similarly, if the accumulation of soluble P in the soil is larger than the uptake by the plant, there is a higher chance of soluble P losses occurring. Since attention has already been given to reducing P loss from industry and human waste (via wastewater treatment), the contribution agriculture makes to this loss has been rising steadily (Kronvang *et al*., 2009). P from various inputs (fertiliser, atmospheric deposition, animal fodder etc.) leaches into the ground or flows from the surface or subsurface and is stored in pools in soil, groundwater, or as sediment in rivers or lakes (Kronvang *et al*., 2009).

Non-Point sources: The main identified source of P loss on farm is from spreading fertilisers on fields, both mineral and manure, which increases the potential for diffuse losses (Manning, 2008).

Mineral fertiliser: The most common artificial mineral fertilisers used are single superphosphate and triple superphosphate. Single superphosphate is made by the combination of phosphate and sulphuric acid, while triple superphosphate is made from organic (and poorly soluble) phosphate rock treated with phosphoric acid (Manning, 2008). These would not be considered sources of P loss on organic farms, since these fertilisers cannot be used in these systems.

Organic mineral fertilisers include phosphate rock, which is naturally occurring and mined for the production of other artificial fertilisers, and struvite, which is produced from wastewaters. These sources are poorly soluble, and require the action of plant root exudates to become accessible to plants (Manning, 2008). Organic farms can use these as fertilisers since they are considered organic, thus phosphate rock and struvite are potential sources of P loss if applied to fields on organic dairy farms or conventional farms.

Manure/slurry fertiliser: Using effluent as fertiliser for paddocks is a very common practice. It is collected from the milking shed and barns and is freely available and considered an effective way of recycling nutrients (Maguire *et al*., 2009). Organic farms especially use manure as a fertiliser, since this is a by-product of production on-farm and is within the regulations of allowed fertilisers. The amount of P in manure varies between species and feeds, if the cow is overfed with P the manure will have a higher P content than a cow fed to her requirements.

If spread over paddocks, it is considered a diffuse source of potential P loss. The way in which manure is applied to paddocks also alters its potential as a P loss source. The straight surface application of manure with no ploughing increasing the chances of losing more P in comparison to ploughing fields after application, or injecting effluent into soils (McDowell, 2012). Furthermore, if animals are allowed to graze freely on paddocks, then manure is spread over a large area but in highly concentrated points, of which more P is lost initially when the manure is wet but as it dries the potential loss of P decreases (McDowell, 2012).

It was quantified that even using best practice methods, the average P loss from fertiliser application amounts to 10% of the total applied (Manning, 2008). In Europe and America only 30% of applied P fertiliser is used in crops. The 60% enters the soil storage pool, contributing to the average 22kg P/ha/year deposition (Steinfield *et al*., 2007). Global use of these fertilisers increased by 38% between 1980 and 2000 and this rapid upward trend is also found in many countries of world (Steinfield *et al*., 2007). In European countries, legislation regarding environmental protection has limited the use of P fertilisers on pastures, nevertheless their application is still very high due to requirements of modern crop (Steinfield *et al*., 2007). On the other hand, studies (Maguire *et al*., 2009) in Denmark show that surplus P in paddocks decreasing from 29kg P/ha/year to 11kg P/ha/year (1980 to 2006) thus there are significant improvements being made.However, this problem is still prevalent on a global scale.

Point sources: Point sources of P loss on farm do not contribute highly to the overall loss of P, since these sources have generally been identified and management practices put in place to decrease losses (McDowell, 2012). However, there are areas where these losses can occur. For example, in organic farms where cattle are required to graze on pasture for a certain amount of time each day, walkways are required to allow access to different fields. If these walkways cross streams/other water sources, then run-off from the walkway can drain directly into the stream, and is considered a point source (Kronvang *et al*., 2009; McDowell *et al*., 2009). Similarly, if drainage of effluent from the milking shed is not managed and if effluent is not stored correctly, these can leak directly into nearby waterways and be point sources of P loss (Kronvang *et al*., 2009; McDowell *et al*., 2009).

Historical P content: Natural soil P content varies depending on location and other factors. The land at the bottom of a hill would contain high soil P than that at the top due to surface run-off from the top land to the bottom. If the P content in soil is already high, then application of fertilisers will increases P losses drastically, since plants only require a certain amount (Sharpley *et al*., 1994). This has been shown experimentally where soils with a high total P content had higher amounts of dissolved P in run-off than those with a lower soil P content (Sharpley *et al*., 1994). The extent to which P is lost from potential sources is dependent on the historical P content of the soil.

P loss pathways in dairy farming systems: The pathways of phosphorus loss in agricultural systems (including dairy production) constitutes important step in the range of mechanisms through which P is transferred to surface water. This has consequences for eutrophication problems because P is the main element that controls major forms of biological activities in surface water systems (Sharpley *et al*., 1994). It must be underscored that similar to all other farming systems, the pathways through which P is lost from a dairy production system are very complex and depend on many factors including hydrology (which serves as the main medium for driving P), slope of landscape, soil characteristics and vegetation (Allen and Mallarino, 2008; Krovang *et al*., 2009; Schouman *et al*., 2013) as well as fertilizer application and management at the farm level. The pathways of P losses could be naturally occurring or could be due to artificial influence (Richard and Steenhuis, 1988). Figure 2 explains the different pathways of P losses from a dairy system under three broad themes: surface or overland losses; subsurface and incidental losses; and how these different pathways interact with different sources of P.

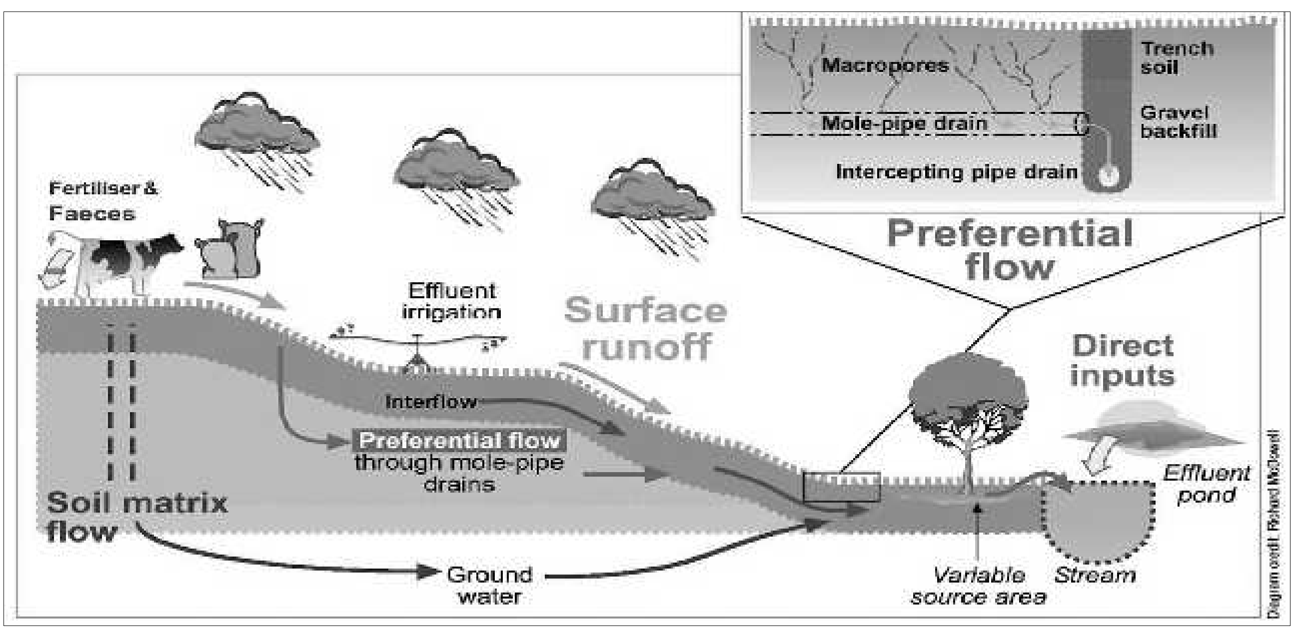

Figure 2: Conceptual diagram of potential sources and processes that transport phosphorus from the dairy pastures to surface water (McDowell and Nash, 2012).

Overland flow: Overland flow as a pathway of P loss occurs when water moves over the surface of soils following a heavy rainstorm. This type of flow usually results in loss of bio-available soluble P which may be bonded to the soil surface, for example fine clay particles. In dairy production systems, overland flow results in loss of both inorganic and organic P. Organic forms are generally lost through the process of incidental transport when, for instance, manure is applied on pastures which is immediately followed by heavy rainstorm events (Preedy *et al*., 2001). Nevertheless, cattle largely feed on grass pastures, overland loss of P can be reduced because grassland surface minimizes surface flows. However, this can trigger losses of other P forms like Dissolved Reactive Phosphorus (DRP) on grassland (Hahn *et al*., 2012). P loss from dairy productions is also affected by rainfall intensity, type of soil, manure and slurry management (Haygarth and Jarvis, 1997). In conventional dairy systems, losses through overland flow may occur due to fertilizer amendment to fields and grassland pastures. It is important to mention that the degree of loss, especially with regard to inorganic P through overland flow, depends on factors like the sorption and ionic capacity of the soils. Soils with high content of aluminum, iron and calcium have less losses of inorganic P (phosphate ($PO^{3-}{}_4$) because of their high binding capacities (Kronvang *et al*., 2009).

Subsurface flow: Subsurface flow refers to the type of flow that occurs below the soil. It serves as an important conduit through which fractions of P e.g., DRP (which is normally dissolved orthophosphate) is lost to water bodies (Allen *et al*., 2012) leading to surface water eutrophication problems. Also, the fact that P concentration is found to be very rich in the few millimeters below soils (Torbert *et al.*, 2002) signifies that subsurface pathways of P losses are very critical and warrant careful management in dairy farming systems. Subsurface flows are categorized into two sub-forms; lateral and vertical flows. Lateral flow is a collective term given to the horizontal movement of seeped water in soils. It may take forms such as saturated and unsaturated soil flows, interflow and land drainage. In land drainage, water and solute entrained solids are moved from catchment land as a result of drainage practices (Hargarth and Sharpley, 2000). In both conventional and organic dairy farming systems, Particulate Phosphate (PP) can be transferred through drainage practices in livestock barns and/or irrigated crop field leading to P losses to nearby and far water bodies through lateral drainage flows.

The opposite of lateral flow in soil is vertical flow which includes by-pass flow, macropore flow, and matrix flow. These will be examined in details under preferential flow and artificial drainage of channels. Preferential flow constitutes an important subsurface pathway through which P is lost from rich catchment areas to water bodies. According to Simard *et al*. (2000), “preferential flow is the transport pathway by which relatively large amounts of water flow through a small portion of the soil volume”. It has also been defined as vertical flow of soil water through large subsoil pathways such as wormholes and fissures which normally occur in unsaturated soil conditions (Hargarth and Sharpley, 2000). This implies that with this type of flow, water does not pass through all areas of soil matrices but prefers to flow through natural and/or artificially occurring macropores in soils. Natural macropores are formed following long periods of dry conditions in fine textured soils like clay, leading to cracks (Li and Ghodrati, 1997). Natural soil macropores could also be as a result of biological activities that occur in soils, like channels created by plant roots and earthworms. In either of these cases, the presence of naturally occurring macropores could give rise to preferential flows of soil P following temporal saturation of macropores with water before soil matrices (Simard *et al*., 2000). On the other hand, artificial soils macropores are created through anthropogenic farming activities like tilling of fields to grow crop feed for livestock.

Preferential flow can be lateral or vertical and it constitutes the major pathway for P leaching in soils. In agricultural production systems like dairy farming, regular application of mineral P fertilizers and livestock manure on field can constitute a major continuum by which P is preferentially lost through soil macropores (Gächter *et al*., 2004). It is also possible that the hysteresis effects of a long history of desorbed P or immobilized P in soil is mineralized and quickly lost through soil macropores to surface water. This means that even in cases where surface waters are located far away from livestock barns and/or crop fields, it is possible for P, especially PP to get transported preferentially to surface waters through soil macropores without being obstructed. According to Stamm *et al*. (1998), artificial drainage channels deliberately created on agricultural and non-agricultural fields can serve as important pathways through which P is lost to water bodies. This is possible in cases where these channels are directly linked to hydrological system in and around the artificial channels.

Incidental flow: Incidental loss of P occurs when soil amended with P fertilizers, especially animal manure or slurry which is followed by a heavy rainfall (Preedy, 2001). This carries away P content in the applied manure to water bodies. However, because of the high binding capacity of mineral fertilizers, for example, phosphate fertilizers as compared to organic P fertilizers, it has been argued that organic P fertilizers are more prone to losses due to incidental flow as compared to mineral P fertilizers. The implication is that incidental loss of P will be high in organic dairy farming, where there is high dependency on manure from livestock as the major source of replenishing soil P nutrient content, as compared to conventional farming where both mineral and organic P fertilizers may be used. In this connection, surface spreading to fields is identified to be very susceptible to higher incidental losses as compared to trailing shore or injection spreading method (McConnell *et al.,* 2013). Table 1 summarizes the various pathways through which P is lost from soil in dairy production systems to surface water as discussed in this section.

Table 1. General and specific pathways of Phosphorus losses from dairy production system.

Term	Scale	Plane	Definition
Surface/overland flow	slope/field	lateral	Movement of water on the surface of soil along down slope during heavy rains
Subsurface flow			
saturated soil flow	soil	lateral	It is a matrix lateral flow
unsaturated flow	slope/field	lateral	It is a preferential flow occurring laterally over capped, compacted or a permeable horizon
matrix flow	soil	vertical	It is a uniform vertical downward movement of water in a very porous media e.g. sandy textured soils
interflow	soil/field	lateral	It is a lateral flow below soil surface
land drainage	subcatchment	lateral	movement of water and solute due to land drainage practices to water catchments
preferential flow	soils	vertical	Vertical water movement along larger subsoil pathways. E.g wormholes

Source: Adapted from Haygarth and Sharpley (2000).

From the forgoing discussion on P losses from dairy production systems, it can be concluded that the pathways of P losses are spatially and temporally variable and are affected by soil and surface characteristics as well as P management practices. This means that integrated measures for controlling these pathway losses will be more effective than measures targeting to control a specific pathway. In the succeeding section, we outline some of the holistic measures of mitigating P losses from dairy production systems.

Assessment and mitigation options for P losses in dairy farms: There are several mitigation options available to decrease the P loss from agricultural point and non-point sources however, it is not always easy to measure where the phosphor loss will be highest mainly due to the legacy of phosphor in the soil. Therefore the concept of the P index can be used to decide where and which mitigation options are the most effective in a particular area.

The Danish P index: The Danish P-index is an empirical index developed from the Pennsylvania P-Index, proposed in USA by Lemunyon and Gilbert in 1993 (Heathwaite *et al*., 2005). The index is modified into Danish conditions (Andersen and Kronvang, 2005) and are still under annual development in Denmark to give more accurate results (Heckrath andAndersen, 2013).

Assessing the risk of P loss includes the identification of source, mobilization, transport and delivery (Heckrath andAndersen, 2013). Each of these factors contributes to a potential critical source area. A critical source area has a high mobile P content, and a high transport potential (Figure 3). The P-Index aims to identify such critical source areas and generates qualitative measures, indexing field vulnerability to P loss. The index does not present physical processes or actual P losses, but the relative difference in risks between two fields or areas.

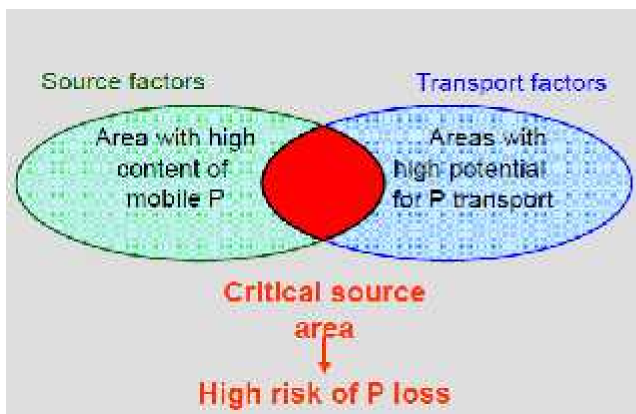

Figure 3: Source and transport factors contributing to the creation of a high risk P loss area (Heckrath and Andersen, 2013).

The P-Index is a fairly simple risk assessment tool, giving a rough estimate. It requires easy available data input, making it a useful environmental planning tool on a large national scale, because it is relatively cheap to use once the required data has been gathered. The P-Index is made out from the four transport processes described earlier: Erosion, Surface runoff, Matrix leaching and Macropore transport.

Erosion and surface runoff are often the main contributors to the P loss in agricultural land (Heathwaite *et al*., 2005), and they will also be dominating factors in the P-index. The influence of matrix and macropore transport are typically less significant, however when present, one important factor in these two pathways is whether the soil is drained or not. P loss from matrix and macropore transport would increase significantly, if the soil is drained (Heckrath and Andersen, 2013) which will have a high effect on the outcome in the P-index. The P index can be used to create a risk map where the map will present a P loss ranging from low to high risk. Such a risk map can afterwards be used to point out fields that need mitigation for P losses. Thus the P index can be considered an important management tool on national and regional scale.

Mitigation options: Mitigations of P loss should aim to follow the concept of the common best management practices (BMP) (Sims and Sharpley, 2005). The main focus in this section will be on the mechanisms in controlling the P loss, which can be achieved by either mitigating the phosphor sources or the transport processes. Buffer strips and conservation tillage will be presented as two mitigation options that could reduce the P loss from the field.

Management of P sources: Regular basis soil P-testing, management of fertilizer and manure application or mining are the different ways to manage phosphor sources. Management of fertilizers and manure is important since application following heavy rainfall could lead to leeching or runoff from the field (Sims and Sharpley, 2005). These loss processes depends on how the manure are distributed, thus it is important for the farmer to manage the manure properly to get the best cost-effectiveness (McDowell and Nash, 2012).

Management of P transport processes

Riparian buffer strips: A buffer strip is a band of vegetation situated between the agricultural field and the banks of a stream or lake to decrease the nutrient transport into the water bodies, mainly from the runoff process. This includes nitrogen as well as phosphor. For instance in Denmark, it is mandatory for farmers to have a minimum width of 10 meters buffer zones (Retsinformation, 2011). The law about buffer strips is an approach to fulfill the water framework directives aim at 'good ecological status in all water bodies' before year 2015 (Directive 2000/60/EC). The vegetation type of buffer strip is typically grasses, shrubs or trees, which have the ability to uptake nutrients and holdback sediments (Brady and Weil, 2010). Buffer strips decreases P loss by increasing infiltration rate and improving deposition; however they have disadvantages as well as they can be filled quickly with sediment, and they will therefore need some management during the year (McDowell and Nash, 2012).

Conservation tillage: Conservation tillage defined as a soil surface covered with at least 30% plant residues, is an on-farm mitigation option that usually reduces the nutrient runoff from the field (Brady and Weil, 2010). It has been shown that converting from conventional tillage into a no-till management will give a decreased annual runoff concentration of PP however, the total dissolved P in runoff could potentially increase over time (Brady and Weil, 2005; Sims and Sharpley, 2005). Further, the increased infiltration rate due to increase vegetation could result in leaching to the groundwater if the water table is relatively high (Sims and Sharpley, 2005).Therefore, the no-till practices may not be used in areas that have a higher precipitation rate.

Feeding management: P is a key mineral essential to nearly every aspect of metabolism as well as for bone development and growth of dairy cow. P needs to be supplied in sufficient quantity to optimize animal performance. Adequate P nutrition in dairy cattle is dependent upon different interrelated factors, including a suitable ration of Ca to P and the presence of vitamin D (Dijkstra *et al*., 2007). Mitigation of P losses through feed management can be achieved through the different practices i.e., reducing overfeeding, changing the energy status of the cow, using enzymes in feed or grazing rotation management.

Reduce overfeeding: P balance is controlled in the gut by the processes of P absorption and excretion. The concentration of P in milk is constant (0.9 g/kg) and the response of milk P to an increase in P intake is variable. Then, if P is fed in excess of animal requirements a minor part is excreted in urine and the rest in the faeces. A linear relationship link P excreted in faeces with P intake (Figure 4; Dijkstra *et al*., 2007). Therefore, reducing overfeeding is one of the most powerful tools to decrease the P content of the manure. A balance has to be found because there is no benefit when feeding P in excess of the requirements but there is health risk if the level is too low. Reducing the amount of P fed would also benefit the farmer in terms of more profit, as feed costs are reduced (Kebreab *et al*., 2013).

Different studies showed that a diet with 2.7 g P/kg DM or more was adequate for high yielding dairy cows. The cows were able to retain their milk production with optimum bone desorption to compensate P for production, even with that amount of P in the feed and there was no adverse effect on bone strength (Wu and Satter, 2000; Wu *et al*., 2001; Valk and Sebek, 1999). Another study with a diet with P at 2.3 g/kg DM showed reduced dry matter intake and milk production which may be due to insufficient P feeding level for high yielding dairy cows (Dijkstra *et al*., 2007).

In the USA and Europe, dairy cattle are systematically overfed P because of concern related to fertility despite evidence that excess P supplementation is unnecessary (Sim *et al*., 2005).

Phase feeding could also be done. It could permit to match the requirement of the cows for the different stages of growth, gestation, and lactation. The P requirement of a dairy cow is related to the production level so a significant amount of P can be saved by having level of P supplemented matching the physiological status of the cows (Kebreab *et al*., 2013).

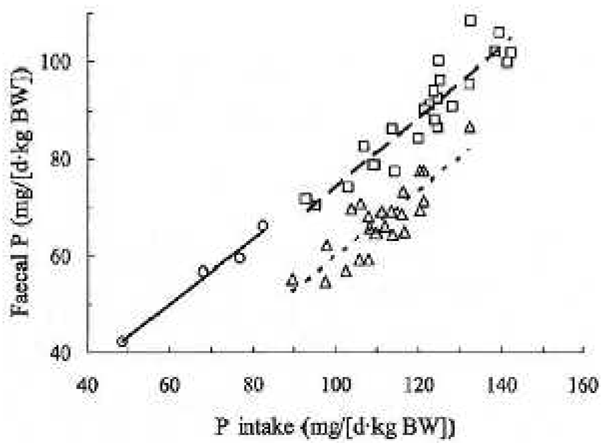

Figure 4: Relationship between P intake and P excretion in faeces (Dijkstra *et al*., 2007)

Moreover, feeding inorganic P to supplement the cows increases the amount of water-soluble P in the manure, which can be as much as 70% of the total P in faeces. This form of P is more susceptible to losses in the environment. Reducing inorganic P supplementation would not only permit more efficient utilisation of P but also have a greater effect on water quality perspective (Kebreab *et al*., 2013). Diet content could also influence the nature and solubility of P in the faeces. Grass silage diets lead to lower water soluble P in faeces than whole crop wheat diets (Kebreab *et al*., 2013).

Energy status of the animals: The type and density of the energy in the feed have a significant effect on P excretion. Cows fed a higher energy diet had significantly improved P efficiency in comparison to those on a lower energy diet (Dijkstra *et al*., 2007). This result could be due to a higher P uptake by the microbes of the rumen which permits a higher conversion of dietary P to milk production and body growth. Kebreab *et al*. (2005) found that cows excrete up to 15% less P when fed slow degradable starch content. The slow release of energy permits a higher utilization of P by rumen microbes.

Enzymes: Phytase is an enzyme often used in monogastric diets to help them to digest plant phytate (contained in mostly in grains). Different studies showed that this enzyme could also be used for ruminants to improve P digestion even if the microbes of the rumen also produce it. Knowlton *et al*. (2007) found an improvement in P digestibility from 7 to 17% when a mix of phytase and cellulose was fed to lactating cows. The use of exogenous enzymes may reduce P losses from manure of dairy cows. Indeed, complete hydrolysis of phytate P does not always occur in the rumen so in these situations the inclusion of dietary phytase in the ration of dairy cows may increase the amount of P available for absorption. In this reference, further research need to be carried out to know enzymes and their use in proper circumstances to improve P utilization in dairy cows.

The use of modified diets that reduce the need to supplement feed with mineral forms of P could also be a solution. It is found that variety of corn and soybean hybrids contain highly available P with lower amounts of phytate-P (Sim *et al*., 2005).

Rotational grazing: Intensifying the use of grassland and improving grazing practices can decrease P losses. Rotz *et al*. (2002) showed that rotational grazing, which involved in brief periods of intensive grazing within a paddock, can increase the productivity of grassland. Thus, the production of forage is more important on the farm which inversely influences the need for concentrate feed. If applied, this results in a reduced amount of mineral P given to the animals.

Grass-based systems also have less erosion than those using cultivation to produce feed for animals (Sim *et al*., 2005). Rotational grazing, compared with other grazing systems reduce total P load in runoff by 64% and improve infiltration and protection of the soil surface from raindrop impact (Kebreab *et al*., 2013). Indeed, in this system cattle graze each paddock for a short time which permits grass growth before the re-grazing and avoids treading and overgrazing resulting in reduced P losses.

Manure management

Manure export: Reducing nutrient surpluses by re-locating animal manures to farm with P deficient soil can decrease the risk of P pollution. It can also prevent excessive levels of manure nutrients in soils. Although manure export is an interesting solution for both sides is not easy to do. The cost for the transport of the manure does not permit to make large distances, so land application is often limited to the neighbourhood. The situation is most problematic for liquid and semi-solid manures. De-watering can be a solution to reduce the transport cost and improve the value as a fertilizer (Sim *et al*., 2005).

Manure storage: Appropriate positioning of housing for livestock and storage of manure is important to minimize the risk of contamination of water sources (Dijkstra *et al*., 2007). Inadequate storage capacity is a common problem and often leads to land application of manure during periods when crops are not growing or when the ground is frozen (Sim *et al*., 2005). Storage also provides opportunities for treatment of manure.

Manure treatment: Manure treatment can be done in different ways, as separation of liquid and solid fractions, composting or chemical treatment.

On-farm manure composting does not affect the forms of P contained in manure. Liquid-solid separation systems results in separated liquid fractions containing a greater amount of organic, inorganic and hydrolysable P than the solid part. Anaerobic digestion of manure does not affect the amount of different forms of P in digested manure. The separated solid manure from the two systems not only results in soil P immobilization but also increased soil test P to greater amount than raw manure. New studies should be conducted to confirm the results as it could be a solution to minimize environmental pollution of P (Pagliari and Laboski, 2013).

Chemical treatment of manure could also be a solution. For instance, Brennan *et al.* (2011) found that the chemical amendment of slurry using aluminium, iron or calcium based compound reduced P solubility in manure as well as P in runoff. Chemical amendments decreased the incidental P losses by a combination of the formation of stable metal-phosphorus precipitates and flocculation of the particles in the slurry to form larger ones, which decrease the risk of erosion. Poly-aluminium chloride hydroxide and alum are the most effective chemical amendment that reduced different forms of P. These amendments also change the pH of the slurry, mostly by lowering it. It results in a reduction of NH_3 emissions from slurry.

Chemical amendment could therefore be an interesting tool to reduce farm P losses. The cost of chemical amendments in comparison to other treatment methods as transport to other farms, anaerobic digestion, separation or composting is likely to be the most significant factor in the future implementation of chemical amendments.

Before the use at farm level, more research must examine the long-term effect of amendments on P loss to runoff, gaseous emissions, plant availability of P, metal build-up in the soil and microbial communities.

Conclusions: The diffuse sources of P loss contribute more to the issue of eutrophication than point sources as already there are management practices in place to prevent loss from the latter. The main diffuse sources are mineral fertilizers (super phosphate and rock phosphate) and manure (spread on fields). The diffuse sources of P may be lost through several pathways, which are broadly categorised into surface flow, subsurface flow and incidental flow. It must be underscored that these pathways are more integrated with one another and therefore require more holistic mitigation options to reduce the problems of P in surface water bodies.

P index is made as an assessment tool to find out the critical areas for P losses. So the P index can be used as a risk assessment tool to find out where to mitigate catchment areas. In dairy farming system, two main types of mitigation options could be identified, namely, field and animal management. In case of field management, the specific strategies are using buffer strips, conservation tillage practices and manure application management. The importance of using buffer strips lies to the fact that it is able to increase the infiltration and deposition of P. Conservation tillage can be used to reduce the runoff of P. However, the increased infiltration rate could increase the leaching of P in ground water. In terms of feed management, there are different strategies which includes reduced over feeding, utilization of high energy content diet, the use of enzymes for better digestion of phytate and the rotation grazing to use less inorganic P. Other mitigation options are manure management, through export of manure to farms with P-deficient soils, manure storage to prevent land application in inappropriate period. Also different manure treatments can be used to create more stable forms of P which has less risk of losses to the environment.

From the foregoing discussion, it could be said that P losses from dairy farming system, just like all other diffuse sources, are complex and follow different pathways. However, the best mitigation option could be difficult to define as it depends on the situations such as how specific mitigation option affects the productivity of the farm and the impact on environmental pressures coming from phosphor. Choosing wisely between the mitigation tools available would create a balance between the concept of the best management practices and the financial and environmental goals set by the farmer and municipality.

It should also be mentioned that one mitigation option for P could have an impact on other nutrients as well. Mitigation of nutrient losses should be considered together, because one mitigation option could decrease the loss of one nutrient and may increase the loss of another.

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