IMPACT OF AGRICULTURAL ACTIVITIES ON LANDSCAPES WITH SHALLOW BEDROCK

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Abstract
The Nutrient Management Act (NMA) provides a framework for setting clear and consistent standards for managing nutrients on farms. As well as regulating agricultural nutrients like animal manure, the NMA also applies to the land application of other nutrient-rich materials that are not from animal sources, including municipal biosolids, pulp and paper residuals, and other non-agricultural source materials capable of being applied to land for the enhancement of crop growth. One controversial issue, identified during the consultation on regulations, was land application of prescribed materials on areas with thin soil cover over bedrock. The issue was referred to the Provincial Nutrient Management Advisory Committee (PNMAC) for resolution. Outside expertise was required to provide a summary of the current state of knowledge on the impact of nutrient application on landscapes with shallow soils over bedrock, and to provide advice on field research required to fill any significant knowledge gaps. Issues related to livestock wintering yards in areas of shallow soils over bedrock were also included as part of the project.

This paper consists of a summary of a literature review and evaluation of the impacts of nutrient application and livestock wintering yards in areas of shallow soils over bedrock. Specifically, the contaminants of concern were nitrate, ammonium, phosphorus, and microorganisms. The paper identifies critical factors that influence transport of nutrients and microorganisms in shallow soils, discusses the relative importance of matrix and preferential flow in the movement of contaminants through shallow soils to bedrock, identifies differences in bedrock geology, soil type and depth, and assesses the importance of those factors in affecting surface and groundwater quality, identifies knowledge gaps, and proposes experimental design alternatives for study needs.

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Critical Factors that Influence Transport of Nutrients/Pathogens in Shallow Soils

In general, it is understood that in areas of thick overburden, the soil acts as a buffer zone to downward migrating water, effectively filtering contaminants. A shallow soil over bedrock does not allow the opportunity for the chemical interactions, filtration, or retention to occur. Consequently, this leads to a relatively unrestricted flow of water from the surface, which may have negative impacts on groundwater quality (Conboy and Goss, 2000).

Most phosphorus compounds are lost via overland flow and particulate phosphorus can account for 75-90 percent of the total phosphorus transported (McDowell et al., 2002). However, phosphorus transport to groundwater may also occur. Hansen et al. (2002) explained that the movement of phosphorus through the soil profile can be significant for soils that have very low sorption capacity (i.e. soils low in clay, iron and aluminum oxides and carbonates). It is also possible that the leaching of phosphorus may occur via preferential pathways in soils with high clay content. Leaching of phosphorus can also occur when the soil test phosphorus (STP - the amount of soil phosphorus that would be available to a crop during a growing season) is elevated from continuous application of organic wastes to sandy soils, acid organic soils, and soils prone to preferential flow. It has been demonstrated by McDowell and Sharpley (2001) that the concentration of dissolved phosphorus increases with increasing STP concentrations.

Nitrate (dissolved nitrogen, NO₃⁻) is highly soluble and is easily leached to groundwater. It moves freely via advection and diffusion within the soil water. In contrast, nitrogen as ammonium (NH₄⁺) binds to soil particles and so is more prone to be transported via soil erosion, rather than leaching. Nitrate nitrogen is also subject to loss through denitrification, particularly in fine textured soils. The fate of nitrate is strongly affected by factors such as available carbon, soil water content, temperature, cropping practices, and soil properties (Sharpley et al., 1998).

Many factors, including the soil’s physical and chemical characteristics and the environment in the soil, affect the removal of fecal bacteria and potential pathogens in the soil and prevent their movement into groundwater. The primary factors are filtration, adsorption, and dieoff in the soil (Gerba et al., 1975). Bacteria passing through the soil matrix can be filtered as a result of three processes acting independently or in combination (physical filtration or straining, sedimentation, and "bridging," whereby previously filtered bacteria block or reduce the size of pores through which other bacteria would normally pass) (NRCS, 1999, Unc and Goss, 2004). Other factors influencing transport of microorganisms through the soil include management practices, time of the year, presence or absence of plants, active microbial movement, microbial surface properties, soil water content, and environmental factors. Greater microbial movement takes place in soils having large pore sizes, as compared to those with smaller pore sizes (Unc and Goss, 2003), and it has been observed that removal of bacteria from leachate may occur when the average bacteria cell size is greater than the size of at least 5 percent of soil particles (Warnemuende and Kanwar, 2002). As a general rule, bacteria that are half the size of the pore entrance will move through the soil, but if the average bacteria size is greater than 5 percent of the grain size within the matrix, they will likely be removed by straining.
Relative Importance of Matrix and Preferential Flow in the Movement of Nutrients and Microorganisms

The concept of preferential flow has been recognized as a significant factor influencing the rate of transport of agricultural contaminants. Preferential flow of contaminants can occur through macropores (usually defined from a soil physics perspective as pores with a diameter of 60 micrometres or greater – Brady, 1990). However, at this scale the soil pores will drain under gravity, and there is ample opportunity for interaction within the soil matrix. Preferential flow usually occurs in much larger pores, generally with an effective pore diameter greater than one millimeter (Carter and Ball, 1993), such as fissures and holes created by soil biota (earthworm holes), or by physical processes, such as desiccation cracks, freeze-thaw effects, or tectonic processes (i.e. isostatic rebound), where the opportunity for interaction in the soil matrix is much less. Preferential flow is strongly influenced by rain intensity and duration, and physical properties such as pore size and grain size, while other soil properties seem to be less important (e.g. Kranz et al., 1998).

Preferential flow may occur in well-structured clay and/or peat soils due to the presence of shrinkage cracks. Preferential flow may also occur in non-structured sandy soils due to the development of unstable wetting fronts (Dekker et al., 2001). Uniform or unstructured soils have demonstrated a strong potential for developing preferential flow in the absence of apparent structural voids. Farming practices may influence the development of preferential flow paths in soils (Conboy and Goss, 2000). No-till practices can aid in reducing soil erosion, but may increase the potential for preferential flow paths to develop. In addition, the burrows created by worms remain intact under no till practices, further enhancing preferential flow (Edwards et al., 1989).

Studies have shown that preferential flow is a much greater proportion of the total flow during saturated, rather than unsaturated flow. Preferential flow is strongly influenced by rain intensity and duration, and physical properties such as pore size, and grain size, while other soil properties seem to be less important (Gish et al., 2001, Ryan, 1998, Chinkuyu and Kanwar, 2001).

It has been demonstrated (Ryan, 1998; Bergstr et al., 2001) that phosphorus and ammonium tend to move mainly in the subsurface via preferential flow. Fine-textured soils with large amounts of macropores are particularly prone to this type of transport. McGechan (2001) explained that a large proportion of the area of sorbing surfaces in the soil is on the smallest particles such as clay particles, which become readily detached from the soil matrix, and thus become highly mobile in soil water flows. According to Shirmohammadi et al. (1998), the topsoil is usually the main source of P in subsurface flows, with transportation of P through the soil profile being caused by preferential flow mechanisms through macropores.

Very little nitrate is leached via preferential flow (Ryan, 1998). The literature suggests preferential flow has little impact on the overall leaching of persistent or mobile compounds. Much work has been done to study nitrogen fate and transport in the subsurface since it is one of the most common contaminants found in groundwater and, therefore, there is abundant information on this topic.
Impacts of Nutrient and Contaminant Application in Shallow Soils on Surface and Groundwater Quality

Where animal manure is applied appropriately to agricultural land at acceptable rates, crops can receive adequate nutrients without the addition of commercial fertilizer, and with minimal environmental impact. In addition, manure helps to stabilize soil aggregates and minimize erosion. It also improves the structure of soil, promoting good tilth and water holding capacity. On the other hand, when nutrients and organic matter are present in excess, there may be significant risks to surface water and groundwater (Sharpley, 1999).

Although considerable research has been conducted on the utilization of animal manures and inorganic fertilizers on cropland, information on the impact of land application of manure or biosolids on shallow soils over bedrock is fairly limited. The available literature can be periodically related to shallow soils, but not necessarily to shallow soils over bedrock. A number of studies were conducted relating to nitrate leaching from monolith lysimeters. The lysimeters were located at the North Appalachian Experimental Watershed (NAEW) in Coshocton, Ohio. The lysimeters had a surface area of 8.1 m² and a depth of 2.4 metres. They were located in shallow soil (well drained silt or sandy loam) over bedrock and constructed in such a way that the overburden soil was not disturbed. Pans were inserted below the lysimeters into the underlying fractured bedrock to measure percolation as it drained from the root zone. Studies conducted by Owens (1987, 1990) and Owens et al. (1999, 2000) using the monolith lysimeters described above concluded that (i) nitrification inhibitors when applied with ammonia fertilizers could potentially reduce nitrate leaching, (ii) incorporation of legumes into crop rotation may help reduce impacts from fertilizers in shallow soils over bedrock, (iii) slow release fertilizers such as methylene urea can reduce the amount of N leaching through the soil profile, and (iv) nitrate transport through shallow soils in any given year is primarily influenced by climatic variations.

A few studies have quantified the movement of nitrate in the soil profile as a function of depth (Chen and Samson, 2002, Shukla et al., 2002, Gupta et al., 2004, Ball-Coelho et al., 2004, etc.), but review of the literature does not allow exact determination of a depth of overburden that would minimize both surface and groundwater contamination related to agricultural activities on shallow soils over bedrock. This is probably due to considerable variation in landscape and specific parameters that influence both surface and sub-surface transport of nutrients and microorganisms, such as manure/biosolids type, application timing and method, tillage practices, cropping systems, soil characteristics, weather variability, etc. One of the most important results of management systems evaluation research was recognition of the widespread inherent soil variability that exists within most fields and even within a given soil type in a field (Power et al., 2001). Also management practices can have a significant impact on the percolation of nitrate through shallow soils. These practices may include the use of slow release nitrogen fertilizers, use of nitrification inhibitors, and incorporation of legumes into crop rotations.

Review of the literature also suggests the following:

1. It is more difficult to control soil nitrate levels in manured soils than in those receiving inorganic fertilizer

2. High rates of manure applications could markedly increase soil nitrate concentrations for ten years or longer
3. Leaching potential is greater in manured soils

4. Residual nitrates in the soil after harvest are often greater for clean tillage than for reduced or no-till methods, increasing the potential for nitrate leaching in groundwater

5. Ridge till systems were effective in controlling erosion and when combined with other best management practices, slowed the rate of nitrification and nitrate movement through the soil

6. No-till systems reduced runoff and increased preferential flow, and therefore allowed greater nitrate movement to deeper soil depths

7. Nitrate concentrations in soil water for reduced and no-till systems are often less than for clean tillage.

Research conducted to examine the effects of biosolids application to shallow soils is fairly limited (Tindall et al., 1994, Richards et al., 1998, 2000). There is indication that nitrate concentrations in groundwater at a biosolids land application site varies with season and rainfall amounts. More recent research that examined the mobility of heavy metals in soils suggested percolate metal concentrations to be a function of both biosolids and soil types (Richards et al., 2000).

Existing guidelines for manure application developed in the U.S. (NRCS, 1999) suggest that manure should not be applied where there is less than 0.25 m of soil over bedrock. Reduced amounts of manure should be applied where the soil is 0.25 to 1.0 m thick over bedrock. Other management practices, such as use of nitrification inhibitors, are suggested where soils are between 0.25 and 0.50 m thick over bedrock. These guidelines seem to have been developed based on observations by field personnel and common sense rather than on scientific studies.

**Impacts of Siting Barn Yards and Outdoor Livestock Confinement in Shallow Soil Areas on Surface and Groundwater Quality**

It has been shown by several studies that a manure/soil seal can effectively reduce salt and nitrate leaching (Mielke et al., 1974, McCullough et al., 2001, Hermanson and Thomason, 1992). However, when manure dries, hydrophilic substances can begin to shrink and crack, and water begins to move rapidly through the surface. Cracks that form due to drying, freeze-thaw cycles, and other activities serve as conduits to increase water infiltration, promoting nitrate leaching (Bodman and Koelsch, 1996).

Investigations of groundwater quality immediately under or adjacent to permanent feedlots have found NO₃-N to vary from 1 to 140 mg/L, NH₄-N from 0.02 to 64 mg/L, P from 0.02 to 2 mg/L, and Cl⁻ from 79 to 664 mg/L. Most of these studies were conducted in Nebraska, Alberta, and Saskatchewan (Mielke et al., 1970, Robertson et al., 1974, Ellis et al., 1975, Arnold and Meister, 1999, Maulé and Fonstad, 2000, 2002, etc.). One study showed that when a feedlot is abandoned, there is great potential for nitrogen mineralization due to drying and cracking of the feedlot surface (Mielke and Ellis, 1976).

There is very limited information available on the impacts of holding pastures for winter-feeding or calving, and loafing lots on surface and groundwater. One study indicated that continuous winter feeding on a pasture located on shallow soil can greatly increase runoff and
erosion (Younos et al., 1998). However, impacts may not last long following a management change (such as removal of cattle from pastures during winter). Other studies that focused on effects of winter feeding areas and mud lots on water quality also suggested management practices can have positive impacts on water quality. The Guide to Environmentally Sound Beef Cattle Manure Management Practices developed by the Québec Federation of Beef Producers, Québec Ministry of Agriculture, Fisheries and Food, and Québec Ministry of Environment (MAPAQ, 1999) recommends similar practices to that investigated by Younos at al. (1998), which involved installation of a grass filter strip as a buffer downslope of a sacrifice lot. This guide suggests the establishment of low and high density areas for minimal wintering housing systems, as well as the use of vegetative filter strip to minimize pollution of surface water, while the system developed in Virginia consists of three grass paddocks to allow the producer to rotate the herd through the lots as needed to maintain a grass cover, and a sacrifice lot. The rotational paddocks are sized to allow 50 to 60 cows per hectare (or about 160 to 200 m²/cow). The sacrifice lot drains towards the grass paddocks, thus minimizing pollution of surface water.

Relatively recent information obtained from field studies on the impact of outdoor wintering on shallow groundwater indicated large increases in soil nitrogen in areas with high manure deposition (e.g. feeding areas) (Majs, 2003). In fact, concentrations of nutrients in soil were found to correspond to bedding and feeding patterns. One study concluded that there was little evidence of nitrogen accumulation underneath the bedded pack. Leaching losses were higher from stockpiled manure than from bedding and feeding areas. Another study evaluated the release of phosphorus from abandoned and active dairy manure impacted soils (Josan et al., 2005). The release of Mg and P was similar in both active and abandoned sites, while release of Ca was less for abandoned dairies than active dairies.

As with the land application of manure or biosolids, there seems to be many variables that need to be taken into account before a depth of overburden can be accurately determined for the siting of barn yards and feedlots on shallow soils over bedrock. Unfortunately, not a single study conducted in Ontario was found under this topic.

Differences in Bedrock Geology, Soil Type and Depth and the Importance of those Factors in Affecting Surface and Groundwater Quality

Clay soils seem to be more prone to developing preferential pathways, which may facilitate movement through the overburden to an underlying bedrock aquifer (Conboy and Goss, 2000). The type of bedrock underlying the soil will affect the transport of contaminants. Some consolidated rocks are much more permeable than others. The majority of wells with a high risk of contamination seem to be located in deposits of limestone, dolostone, shale, and in some sandstone, and either arkose, or gypsum salt. Some factors that influence the permeability of the bedrock include the amount and spacing of joints and fractures, degree of karsting, joint aperture, wall roughness, and infilling.

The specific capacity of a well (Singer et al., 2003) may be a useful tool to estimate the potential for flow into a bedrock aquifer and, consequently, the ability of surface water and contaminants to infiltrate into the bedrock. Areas where the bedrock water yield is good to fair, coupled with thin soil cover, may indicate areas of potential concern for agricultural impacts on groundwater. Areas that have good-to-excellent water yield in bedrock wells where the bedrock is within 10
metres of ground surface, and that are overlain by sand and gravel may provide a hydraulic connection to the bedrock. Fracturing, dissolution, and karstification of limestone appeared to result in higher potential movement of bacterial contaminants through limestone rock than in any other geological formation (Conboy and Goss, 2000). It should be noted, however, even though the bedrock may be fractured, it does not mean transport will be rapid. The flow of water, and thereby contaminants, depends also on the interconnectedness of the fractures. The age of bedrock is also a factor in contaminant transport, since older material can be very weathered with large solution channels (Conboy and Goss, 2000). Wells susceptible to high contamination risk in Ontario are located most often on sites with older limestone/dolostone overlain by clay or clay loam soil. However, the presence of impermeable metamorphosed igneous rocks may offer some protection from bacterial contamination.

**Study Design Options**

The following knowledge gaps were identified from the literature review (CH2M HILL, 2005):

- Mapping of soil types susceptible to preferential pathways
- Mapping of shallow soils over bedrock
- Modelling of preferential flows at the soil-bedrock interface
- Attenuation of contaminants (nutrients, microorganisms) through shallow soils over bedrock
- Interactions between preferential pathways, soil type/hydrologic soil group & management practices in shallow soils over bedrock
- Interactions between manure/biosolids type, application timing & method, tillage and cropping practices in shallow soils over bedrock and their effect on surface and groundwater
- Contaminant transport from and under barnyards and outdoor livestock confinement areas
- Evaluation of management practices to minimize contamination potential in shallow soils in Ontario

Several study options and experimental designs were proposed and discussed. These include data management and modelling for mapping purposes using GIS, laboratory/pilot scale studies to investigate attenuation of contaminants through shallow soils over bedrock, modelling of preferential flow, and interactions among several contributing factors on surface and groundwater quality, and farm scale studies to investigate or evaluate management practices that have potential to minimize contamination potential in shallow soils over bedrock and contaminant transport from barnyards and outdoor livestock confinement areas.

Development of maps of soil types susceptible to preferential flow and shallow soils over bedrock was estimated to cost between $50,000 and $150,000.

Laboratory/pilot scale studies using simulated shallow soil over bedrock columns were estimated to cost between $50,000 and $150,000 per year for a period of two to three years. Costs will basically be a function of number of treatments and number of samples analysed.
Farm scale studies may be significantly more expensive than laboratory/pilot scale studies due to their long-term nature, and have been estimated to cost between $150,000 to $250,000 per year. Individual farm scale studies were suggested to investigate contamination from barnyards and outdoor confinement areas with cost ranging from $50,000 to $150,000 per study.

Summary and Considerations

There appears to be a good understanding that water quality, as measured by nitrogen and phosphorus concentrations, has declined with land-use changes over the years. It is evident from the literature that impacts of agricultural activities on shallow soil and groundwater are primarily a function of soil type, precipitation, management practices, and contaminant properties. There is limited research on modes of transport within the root zone and there seems to be a lack of understanding of interactions between all the relevant elements and transport processes in landscapes with shallow bedrock.

The literature suggests that soils in temperate regions are most vulnerable to nitrate leaching during the fall, when crop uptake has slowed or ceased, and the soil temperature is still warm. Evaporation decreases while soil moisture and microbial activity increase, resulting in more nitrogen mineralization. Autumn cultivation also enhances mineralization, creating more potential for N to leach from the root and vadose zones over the winter months. However, it should be noted that increases in nitrate leaching from manure applications in the early fall are quite different from a high vulnerability to leaching during this time. Manure application in the early fall increases nitrate concentrations in the soil, predisposing the site to nitrate leaching later in the fall season, when soil moisture is replenished and water moves more readily through the soil profile. This scenario of nitrate leaching later in the fall season is more reflective of conventional wisdom for Ontario situations.

Attempts to reduce nitrate levels in subsurface water have primarily focused on application rate and timing, but this cannot be generalized to all locations. It can be said that nitrate losses from plowed fields are generally higher than from ridged or flat no-till fields, particularly for corn-soybean rotations. In addition, significant reductions in nitrate losses can be realized by switching from row crops to alfalfa or other grass-based crops, and possibly to small grains, that can be successfully planted late in the growing season. As dry matter yield increases, so does the amount of nutrient taken up by the crop, and when harvested, more nutrients are removed from the field. Harvesting is the key in this case, as grazing simply recycles most of the nutrients back into the system. Some studies also show success in minimizing nitrate losses by incorporating solid organic carbon sources below the root zone, to increase denitrification. Some work supports the use of nitrification inhibitors with manure or fertilizer application to reduce nitrate leaching by controlling the nitrification process, but this is not deemed a practical solution for Ontario agriculture. The research also shows that improved nitrogen management practices have limited potential to reduce nitrogen losses, likely only 25 to 30 percent reduction. Reduced tillage and no-till practices have potential for another minor incremental reduction. The use of alternative cropping has the potential to yield major reductions in nitrate losses, but due to economic impact, is least likely to be implemented.

Ammonium and most phosphorus compounds are not subject to leaching, due to strong adsorption to soil particles. Adsorption to soil particles slows the movement of contaminants through the soil profile and subsequently slows the movement of contaminants to groundwater.
However, phosphorus and ammonia movement to groundwater may occur via preferential flow. Similarly, pathogens are more susceptible to transport via preferential flow.

The concept of preferential flow has been recognized as a significant factor influencing the rate of transport of agricultural contaminants, but it is difficult to correlate a particular soil type with the potential for manifesting preferential flow. Farming practices may influence the development of preferential flow paths in soil. For instance, no-till practices can help reduce soil erosion but may increase the potential for preferential flow paths to develop. In addition, earthworm burrows that remain intact under no-till practices further enhance preferential flow. The occurrence of preferential flow is also strongly influenced by precipitation intensity and duration, as well as soil physical properties such as grain and pore size.

Although there is much work available on management practices that limit P movement to surface water, there is limited information about effective practices to reduce P losses to the subsurface. It seems that reducing the potential for P losses likely relates to the combined management of P sources in the agricultural environment and control of the transport of P in the soil environment. Phosphorus is more likely to percolate through the soil column via preferential flow when the soil has high P concentrations. This situation can develop in nitrogen-based nutrient management programs, as these programs usually allow for additions of P beyond crop requirements. In addition, avoiding P additions to soil, whether by manure, biosolids, or fertilizer application, or by grazing, during periods of wet conditions may help reduce P losses, particularly in the early spring. There is some work to show that conservation measures to reduce P losses via overland flow to surface water do not necessarily reduce P concentrations in subsurface pathways. And, while no-till practices can aid in reducing soil erosion and nutrient losses to surface water, they may also increase the potential for preferential flow pathways, thereby contributing to P losses to groundwater. While there are still gaps in the science behind P losses to groundwater, addressing this may not be the best use of limited funds, as P in groundwater is not deemed to have a significant impact to human health.

Since the transport of pathogens to groundwater, like the transport of P, occur primarily via preferential flow, management practices used to minimize P leaching are likely to have a positive effect in reducing pathogen movement to fractured bedrock and groundwater. For example, avoiding manure or biosolids application to wet soils, or during periods of rainfall, will minimize the potential for movement via preferential flow. Significant work is needed in this area to draw definitive conclusions. Another option is to utilize some form of manure treatment, similar to the biological treatment phase for sewage biosolids, which can reduce the concentrations of pathogens prior to land application. Some work alludes to the fact that longer storage times could assist in reducing pathogen levels before land application, but this requires more investigation. Composting, when properly administered, may also be a viable treatment option to reduce pathogen levels in manure, while reducing availability of nitrogen, thereby reducing potential N losses at the same time. Mesophilic and thermophilic anaerobic digestion is another option to be considered for pathogen reduction in manure prior to land application. However, it would be prudent to conduct further work to determine if pathogen transport to groundwater via fractured bedrock is, indeed, a problem prior to investigating treatment alternatives strictly for pathogen reduction.

Both permanent feedlots and temporary wintering areas contribute to ground and surface water contamination. Information obtained from field studies indicated large increases in soil nitrogen in areas with high manure deposition, with concentrations of nutrients in soil corresponding to bedding and feeding patterns. However, as with land application of manure, there are many
variables to be taken into account. The use of wintering areas, where animal concentration and traffic are high, has the potential to cause more pollution than permanent feedlots. Assuming manure sealing is developed at the soil surface while livestock are in the area, there is a high potential for nutrient losses through the soil profile once the animals are removed, as the manure seal dries and cracks, thus facilitating infiltration. One study cited in this review found that losses from beneath the bedded pack were significantly less than from stockpiled manure. Another study showed similar release of P and Mg from both active and abandoned sites. Clearly, more investigation is required in this area.

These findings create a bit of a dichotomy overall – which contaminant do we manage for and within which soil zone? A successful result likely lies in site-specific management, and the further investigation of the identified knowledge gaps. For the purposes of this report, an attempt has been made to generalize the findings and draw some conclusions relevant to Ontario agriculture. While these suggestions are qualitative in nature, they stem from the research conducted to-date, and provision of more quantitative recommendations will require further field investigation. The following considerations are put forth for further investigation.

**Nitrogen Management:**

- Split nutrient applications, to provide nutrients closer to the timing of plant uptake, thereby reducing the time when high concentrations of nitrate are in the soil and subject to loss.
- Use a “knife” approach to nitrogen banding, to help seal the band of nitrogen in the soil environment from easily percolating to groundwater.
- Incorporate straw or other organic carbon source below the root zone to minimize N losses from fall-applied manure.
- Plant a cover crop, such as winter rye, to sequester mineral nitrogen from the soil in the fall, and thereby reduce nitrate leaching to groundwater.
- Consider eliminating early fall application of manure, except when a cover crop and/or organic carbon source are added.
- Consider grass-based or grain crops as part of the crop rotation, where possible.
- Investigate contaminant mitigation options for wintering yards and seasonal feedlots.

**Phosphorus Management:**

- Balance N management with P management, and reduce P applications beyond crop requirements.
- Minimize manure/nutrient applications to wet soils or during times of high rainfall potential.

**Pathogen Management:**

- Minimize long-term no-till practices in soils prone to preferential flow and where manure or biosolid applications are planned.
- Investigate manure treatment techniques that minimize pathogen levels prior to land application (i.e. anaerobic digestion, composting, longer storage times).
As previously discussed, an understanding of N mineralization is essential for the development of management practices that better utilize N, and minimize groundwater impacts. The considerations above relating to nitrogen management are based upon developing this enhanced understanding of N mineralization. The impact of P in groundwater, and subsequently to human health, should be carefully considered prior to implementing stringent management practices to limit P losses to groundwater. Similarly, since the literature reviewed in this study does not prove unequivocally that pathogen movement to groundwater is a problem, more investigation is required to evaluate the benefit of managing pathogen movement.

Soil-manure/biosolids interactions constitute a complex set of relationships that depend on the soil environment, microbial populations, and the chemical and physical properties of the soil and material being applied. Decomposition of manure and other organic material in soil is dependent upon a number of factors including the type of material, animal feeding ration, animal age, animal housing, and how the material is handled.

References


