What to do and what not to do about phosphorus in Agro-Manitoba – the science

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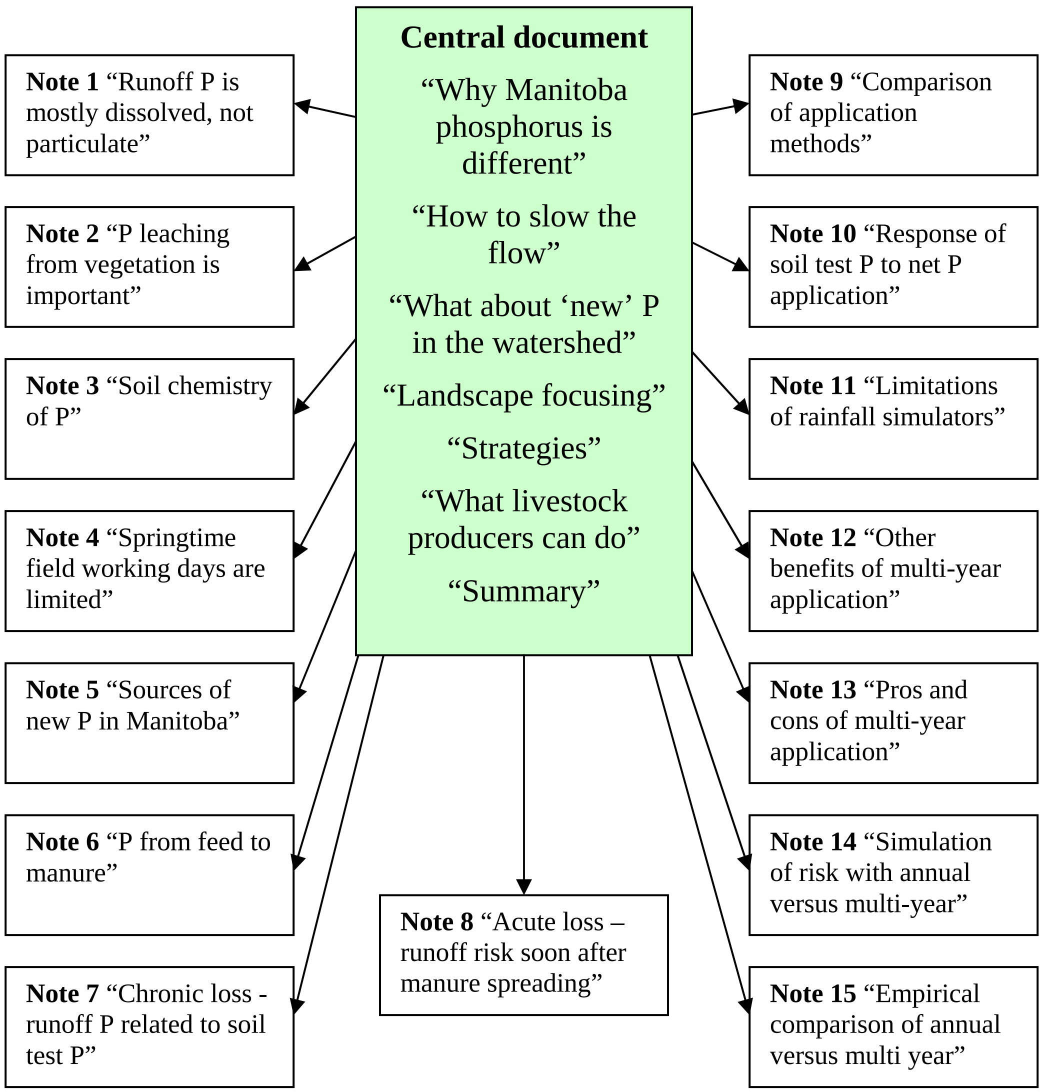
Contents



Reader: This document follows a web structure. The central document provides the main arguments as a dissertation. Some scientific references are given in the central document, but the detailed scientific interpretations and most of the scientific references are given in the Notes. It is anticipated that you would want to read the main document and perhaps a selection of the Notes on topics of special interest to you.

Introduction – why Manitoba phosphorus is different

Phosphorus (P) in Manitoba soils and waters is a Manitoba-specific problem. Despite that P is one of the most studied elements in the agricultural and environmental sciences, there is little universality. Knowledge gained in the southern US, the UK, Ontario and even Alberta does not apply in Manitoba, at least not without careful interpretation. Why?

1. Most of the agro-Manitoban landscape is nearly flat. As a result, water runoff is slow and therefore there is almost no soil erosion. The majority of runoff P in Manitoba is not particle-bound P, it is largely dissolved P (see Note #1). This means that a large percentage of the published literature on P, which is from sloping landscapes, is irrelevant to Manitoba. As an example, vegetated buffer strips are often reported as a best management practice (BMP) to mitigate runoff P, but dissolved P is not retained efficiently in buffer strips and in fact P is readily leached from any vegetation in the flow path, adding to the problem rather than solving it (see Note #2).
2. Due to our relatively dry and cold climate, the majority of water runoff in Manitoba is during spring snowmelt and pre-growth rainfall. Often the soil is still frozen, there is ponding, and rivers, streams and ditches inundate the fields. Summer or autumn rainfall rarely triggers runoff in Manitoba. This has important consequences for how soil, manure and plant P is carried away. Perhaps even more importantly, it means that the flux of P from agricultural lands coincides with high dilution because of the high water flux. As pointed out by Jarvie et al. (2006), eutrophication may be more linked to P flux from urban sources that are continuous even during periods of low flow.

Photo (credit Sheppard, 2005): left - ponding in field, runoff channel and ditch, right – flooded and snow-filled vegetated buffer strip (VBS)

Manitoba soils are neutral to high pH, many are predominantly clay and all were originally low in P (especially in terms of crop production). Even today, 57% of Manitoba soils are below optimal for most crops (Fixen et al. 2010). Thus, P reacts strongly in Manitoba soils to form relatively insoluble chemical species (calcium phosphates, see Note #3), and there is little downward leaching of P (Ajiboye et al. 2008; Idowu et al. 2008; Kashem et al. 2004a,b; Olatuyi et al. 2009).

In addition, the climate and soils of Manitoba impose restraints on agricultural field operations that are unique:

1. The flat landscape and clay soils mean that soil moisture is the single most potent factor restricting farm operations – often too wet (and sometimes too dry). Soils in the critical planting or harvest times can be saturated and will not support equipment for weeks (see Note #4). Therefore, field operations must be few in number and fast, and any operations that can be deferred to a drier time must be deferred. Thus fall application of fertilizer[1] and manure is more common in Manitoba than any other Province (Sheppard et al. 2010a,b). Crop yield decreases linearly with delay in planting (see Note #4), so timeliness in the spring is perhaps the most important management factor – and it cannot always be managed.
2. Crop yield and profit margins are low in Manitoba and to compensate the field sizes are vast. This adds impetus to minimize the number of field operations and to use large multi-tasked equipment.

Where does this leave the 'P problem'? Firstly, it is key to recognize that P movement from land to water is an inevitable, unstoppable process that is primordial in origin. The key transport vectors (carriers) are all downstream. Phosphorus cannot move against the flow. Society could invent a reverse vector if it made it an imperative to harvest P and move it upstream, such as with harvested buffer strips or harvested wetlands (e.g., Cicek et al. 2006; Raty et al. 2009; Uusi-Kamppa and Jauhiainen 2010). Apart from that, we can only slow the downstream flow of P, we cannot stop or reverse it. It is not all gloom, if we can slow the movement of P enough that the watershed can flush itself (i.e., the P goes further downstream to the sea faster than new P is added), the lake P concentrations could decrease. Obviously, in addition to slowing the flow of P it is also important to limit additions of new P to the watershed.

> The 'P problem' is that too much P is transported into Lake Winnipeg, resulting in algal blooms and potential 'death' of the lake. This is not a new problem, in 1640 Lake Winnipeg was known as Ouinipeg or 'Dirty water', it was known as unsafe to drink, and in 1720 the name was attributed to the Cree 'Winnipi' and 'Pacho' meaning 'dirty green water' (Manitoba Conservation 2000). The watershed encompasses several Provinces and States, and is semi-arid so that evaporation concentrates the P in the tributaries. The lake is shallow, so algal productivity is inherently high and burial of P in deep sediment is limited. If it is solvable, it will be a decades-long problem, longer than the similar episode that impacted Lake Erie in the 1960's.

[1] 'fertilizer' in this report is used to mean manufactured mineral products and excludes organic materials such as manure, biosolids or compost.

How to slow the flow

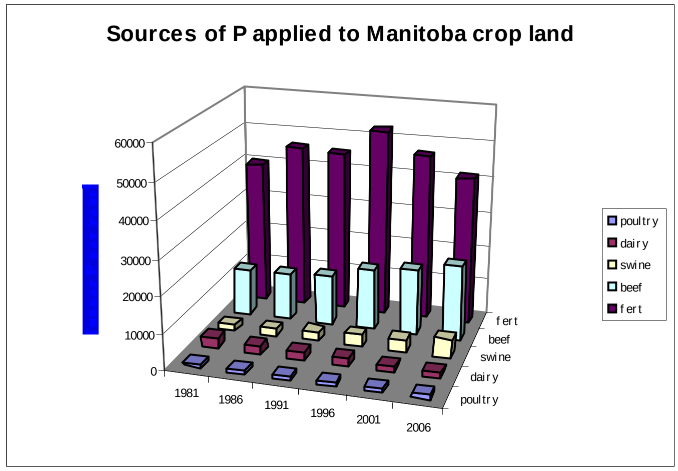
What would slow the movement of P from land to water? Despite common belief and misinterpreted scientific findings, riparian vegetation and vegetated buffer strips are not the answer for Manitoba (see Note #2). Remember that the most runoff happens in spring when plants are not growing, and the P moves off Manitoba fields as dissolved P and so it cannot be entrained with the soil particles held by vegetation. In fact, plants are often detrimental by adding P to the runoff. Plant growth is dependent on the plant's ability to extract P from soil as a key nutrient. This P is moved by the plant from the roots to the shoots, putting it into the runoff flowpath. There has been abundant evidence, for decades now, that P is readily leached from living and dead plant shoots as dissolved P (see Note #2). The leaching is especially strong from dried, dead or frozen vegetation. So plants mine P from the soil and make it more susceptible to runoff. Vegetated buffer strips and riparian vegetation can slow the movement of P if the P is attached to soil particles or runoff happens when the plants are growing – neither applies to Manitoba.

There is one process that is somewhat effective to slow the movement of P from land to soil. That is the burial of P into the soil. This does not happen by leaching, P is virtually immobile once in contact with Manitoba soils. Burial can happen by tillage and by what is called 'macro-pore flow', essentially water carrying dissolved P penetrates into the soil through natural cracks, root channels and earthworm burrows (Andraski et al. 2003; Gessel at al. 2004). Obviously, tillage destroys the natural macro-pores – nothing is simple. Again despite many beliefs, tilled land sometimes produces less runoff and markedly lower dissolved P concentrations in the runoff than hayland or reduced-tillage land (e.g., Sturite et al. 2007; Tiessen et al. 2010). Additionally, tillage directly moves P off the soil surface and into deeper layers, away from the runoff flow (Sharpley 2003). In contrast, beneficial natural macro-pores are enhanced by plants (this is one avenue where vegetated buffer strips may help a little in Manitoba), and macro-pores may be enhanced by manure (Adeli et al. 2010; Wortmann and Shapiro 2008; although Eghball 2002 did not see such an effect). These studies and others have shown that runoff is sometimes decreased on manured land, and the explanation seems to be that the soil structure is improved and there are more macro-pore channels. Clearly, this is in the realm of mixed benefits – manure adds P to the landscape but can also alleviate some of the consequences. More on this in the next sections, the message here is simply that getting P deeper into the soil is a delay tactic that may help 'save the lake'.

What about 'new' P in the watershed?

These possible approaches to slow the movement of P from land to water may seem obtuse and difficult to manage, because they are. A much more manageable approach is to limit new sources of P. In the 'death' and revival of Lake Erie, a large source of P was in household products, and removing this source resulted in recovery of the lake within a decade (Koonce et al. 1996, Ludsin et al. 2001, Munawar et al. 2002). The sources of P for Lake Winnipeg are much more diffuse and diverse, but at least some of the P (<15%) comes from agricultural land in Manitoba (Flaten et al. 2003). For such diverse and extensive sources, recovery of the system will probably require more than 50 years (Cherry et al. 2008). The agricultural P from Manitoba can be managed, but not eliminated. A few facts are pertinent:

1. The 'new' P in agro-Manitoba is the P from industrially mined sources that provide fertilizer and mineral feed supplements. Most of the P in livestock feed (and hence manure) is from crop materials grown locally – recycled from the soil and going back to the soil. Manure is not a major source of new P to the Lake Manitoba watershed.



Based on Census of Agriculture animal populations and fertilizer sales records (from the study reported by Sheppard et al. (2010a,b)

2. Fertilizer P is by far the largest source of 'new' P in Manitoba (see Note #5). Fortunately for the environment, P fertilizer is expensive and so is not used vastly in excess of crop needs, and much of it is banded or incorporated (buried) into the soil because that is more efficient to supply crop needs. None the less, it is applied to vast acreages in enormous total amounts.

If taken as a whole, and disregarding mineral feed supplements (see Note #6) for the moment, manure does not add new P to the system, and unless the livestock operations are all closer to the lake than is the crop land, then in theory the impact of livestock operations on the lake would be neutral. The fallacy to this is that crops will be produced regardless of whether they are used in Manitoba for feed, or they are exported. Fertilizer P will be applied in Manitoba regardless. Without doubt, exporting grains and oilseeds abroad would remove far more P from Manitoba soils than does the exporting of meat and animals. Livestock is a value-added form of agriculture – it uses local crops and produces a higher-value product. The holistic picture is simple – if we want value-added agriculture in Manitoba with its economic and employment benefits, the livestock industry is key, but with it we get to keep and deal with more of the P we apply to crop land. This applies to all sectors of livestock, from birds to beef, and it shares the responsibility of the effects of P with the crop producers. One BMP to save the lake is to minimize all livestock production and maximize the export of grains and oilseeds – not a very sustainable, strategic or stable option.

Landscape focusing

There is another aspect of livestock production. Apart from P in mineral feed supplements (which have been markedly lowered in recent years in response to environmental concerns (Note #6 and S. Stott personal communication), livestock operations have the additional unfortunate effect of focusing P in the landscape. Crops are harvested from large areas, and then fed to animals in highly localized facilities. Most (60% to 80%, see Note #6) of the P from the feed is passed to the manure, but manure is too bulky and it is too expensive to transport the manure back onto all the land from which the crops were harvested. Therefore, the P from general cropland is focused (moved) onto the smaller landbase that can be manured. Ideally, these could be located away from large water ways. This is not 'new' P, it is recycled soil-to-soil, and in the total of agro-Manitoba the amount of P removed from soil by feed crops is nearly in balance with what is returned to the soil. This raises several points:

1. Does the creation of livestock 'hotspots' with higher-than-typical soil P contribute disproportionately to lake eutrophication? If the system was simple and linear, the answer would be no – more P would come from the hotspots, but less P would come from the other cropland areas and the total watershed impact would be unaffected by the livestock hotspots. In fact, there is no incontrovertible scientific proof that the hotspots are a greater problem than is the general crop land on a whole-watershed basis, what is pertinent is whether the hot spot is in an area that is critical to overall production of runoff P (Sharpley et al. 2001). None the less, it is prudent to assume the hotspots are a problem.
2. The focusing of P in the landscape creates an opportunity to manage the P. There is no panacea, as stated before: P on land will move to become P in water, the best we can do is slow the process. There are four useful strategies: a) do not apply more P to crop land than can be removed by crops, b) place manure (and fertilizer) P in the soil in the best way to avoid losses in runoff, c) decrease the number and take care in the timing of application operations, and d) remove P from the flowpath by harvesting buffer vegetation.

Strategies

With regard to the first strategy, to add no more P to soil than can be removed by the crop is in direct opposition to years of agronomic teaching. For a given crop year, the crop uses less than 40% of the P applied as fertilizer, and even less (~30%) of the P applied in manure (Oberson et al. 2010). The agronomic message was historically: 'never just replace the P the crop takes, unless the soil test P is very high you must add more P'. The reason, of course, is that new P chemically reacts in soils and becomes less plant-available with time. Secondly, crops have the potential to profitably respond to more applied P, even if soil test P levels are exceptionally high. Some of this is the 'starter effect' – fertilizer P placed near the seed will often accelerate early growth, especially in cold soils where root growth is slow (Grant et al. 2001). Finally, all of plant nutrition and crop growth is stochastic – what was too much P to apply one year is too little the next. Economic drivers encourage optimism: to apply enough P for best economic return for at least an average yield, and hope that in the case of yield failure the added P will still be of benefit in the future. The impetus to limit manure P applications to the amount removed by the crop is an ideal solution to help 'save the lake', but in fairness it needs to be applied to all P additions (fertilizer too), and it must be recognized that crop yields will be impacted on soils that do not have high P now. If promulgated as a general policy to all agricultural P applications regardless of soil P levels, it will create a new plateau of crop yield (all other factors equal) that is lower than today (Campbell et al. 2011). This may be a worthwhile societal objective, and it may be economically viable if the market for Manitoba grains and oilseeds allows profitable production with lower yields.

A less stringent version of this first strategy is to still use P application rates based on crop performance, but to allow more P to be added than is removed by the crop until soil P levels reach some predetermined level. This allows farmers to build up the fertility of low-P soils, and requires attention be paid to soil test P levels. Any build-up of soil P will lead to more P in runoff. However, there is a theory that as soil P levels increase, there is a 'break point' below which the P is an added benefit to crops and not too susceptible to runoff, and above which runoff is problematic (Casson et al. 2006, Little et al. 2007, McDowell et al. 2002, Miller et al. 2006, Smith et al. 2001, Weld et al. 2001). This has not been substantiated in Manitoba soils (e.g., Sawka 2009). Such a strategy is clearly a compromise.

The second strategy is to bury any applied P and avoid applying P in runoff-critical areas. For burial, there is already a strong incentive to bury manure by injection or tillage to reduce odor, to conserve ammonium nitrogen and to put the manure where crops have the best opportunity to utilize the nutrients. Slurry manures are well suited for burial, especially with the new injector and aerator designs that have emerged in the last 5 years. The effectiveness of the burial is easily assessed visually, and so can be managed. Injection of slurry is probably the premier Best Management Practice (BMP) for manure application, and is more predominant in Manitoba than in any other Province in Canada (Sheppard et al. 2010a). Once injected, manure P is away from the runoff flow and its effect on runoff is indirectly through its impact on the overall soil P level (see Note #7). It is less easy to avoid applying P in runoff-critical areas, as this requires expert insight and landscape analysis (e.g., Priyashantha et al. 2005), and in the flat Manitoba landscape where soluble P in snowmelt is critical there may be no non-critical areas. None the less, Sharpley et al. (2001) estimated that although these critical areas represent only 25% of the landscape they cause 75% of the P runoff (this conclusion was based on the sloping land of the eastern US, but the concept may also be true in Manitoba).

The third strategy is about timing, on several scales. The greatest potential for excess runoff P is immediately after each application event when manure P has not had time to interact with the soil. The half-time[2] for P in runoff after manure application is about 31 days (see Note #8): if there is no runoff-generating event such as intense rainfall within about 31 days, the potential for environmental impact is markedly lower. Indeed,

[2] 'half-time' is the time required for concentrations to decrease to half of the initial concentration, it implies a first-order kinetic process where rate of loss is proportional to concentration.

light rains even help move the manure P into the soil and away from the runoff flow that will happen in later, heavier precipitation events. Because the concentration of P that can occur in runoff decreases for each day that lapses between when the manure is applied and the runoff occurs, there is some argument that manure should be applied in higher amounts in proportionally fewer times. The argument is essentially based on logistics: if manure can be applied at twice the rate, then it will take less (not quite half) the amount of time to spread it and there is greater likelihood this can be done in the more favorable-weather days. In Manitoba, agronomic practice has established that fall application of fertilizer and manure has a number of advantages, mostly related to the numbers of field-working days available in fall and the top priority of reserving precious spring working days for planting (see Note #4). Manitoba is relatively unique in Canada for the relatively high proportion of fall application of both fertilizer and manure (Sheppard et al. 2010a,b). There are obvious risks to fall application, and these are managed. Injection of both fertilizer and manure is top among the management options, and is especially suited for Manitoba soils that are largely stone-free. Injection of slurry or other methods of incorporation to thoroughly bury manure markedly lower risk of excess runoff P, often to the same risk levels as comparable fields that did not receive manure (see Note #9). Another management opportunity is to spread the fertilizer or manure early in the fall rather than too near freeze-up, and for manure this would be clearly facilitated by being able to spread at multiple-year[3] application rates (because less land and therefore less field time is involved).

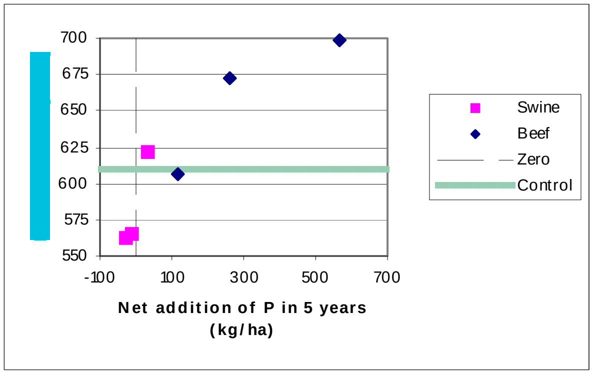
The fourth strategy is to actually harvest the crops, and hence remove the P from the soil as crop offtake (see Note #10). For field crops, this is almost too obvious to state – the crops are grown to be harvested. Where improvements are possible is in the harvest of buffer strip vegetation, including vegetation in rural municipal ditches and engineered wetlands. Some municipalities already encourage (and perhaps financially support) hay production from ditches. It is the only true reverse vector possible in the effort to remove P and lessen the flow of P from land to water. Even if it is not possible to provide incentives to harvest ditches, better management of ditches with regard to P is a missing priority (Kleinman et al. 2007).

What livestock producers can do

The International Plant Nutrition Institute (IPNI) calls it the 'four Rs': right source, right rate, right placement, right timing. In practice, producers do not have a lot of control of the mineral supplements they use, they (appropriately) rely on feed formulation experts. So the source is defined. They can control manure application through right rate, right placement, and right timing.

[3] In this report, a 'multi-year' application schedule means that in the application year, enough manure is applied to a given field to supply the crops on that field for multiple years, perhaps 2 to 5 years, and then there it no other P applied to that field in the intervening or skip years. Multi-year is in contrast to an annual application schedule where a lesser amount of manure is applied to the field every year.

The ‘right rate’ has already been discussed in terms of P: the ideal would be no more P than needed to support optimal crop growth (the agronomic target rate) and for high-P soils a rate that does not exceed expected crop offtake of P. The most pertinent complication to this is the N supply from the manure. To limit manure application to P supply levels means that fertilizer N is also required (the N:P ratio in manure does not match the N:P ratio needed by crops). Even this can be avoided with multi-year P application rates – these are more likely to supply sufficient N in the application year.



The response of total soil P to net additions of P in manure (see Note #10). Net P is the total P applied less the amount removed in grain. The Zero line is zero net addition, and the Control line is the soil P concentrations when there was no manure. Clearly, soil P levels can be changed – up or down.

The ‘right placement’ has also been discussed – bury the manure P by injection or incorporation. There are many scientific papers indicating that with thorough injection or incorporation, the resulting runoff P concentrations are not different from unmanured control plots (see Note #9). Of course, over time the overall soil P level will be higher and this will increase runoff P (unless P application is balanced by crop offtake of P). There are papers that report excess runoff P despite incorporation (e.g., Miller et al. 2011). This is largely because: a) it was solid manure which does not facilitate infiltration of soluble P, b) incorporation was not thorough (Miller et al. used disking which never thoroughly buries manure), and/or c) the measurement of runoff was a worst-case scenario using extreme rainfall intensities immediately after application (Miller et al. used more than a 1-in-50 year rainfall intensity within 6 days of solid manure application, see Note #11). Undoubtedly, small amounts of manure will remain on the soil surface even with the best technologies, but this can be minimized. Conditions that favor thorough burial of manure during application include:

- Use slurry manure because it is most easily injected and contains sufficient water that the soluble P immediately infiltrates the soil (Vadas et al. 2007).
- Develop a system that makes slower, deeper injection economically viable, and a key to this may be allowing multi-year application cycles (see Notes #12 to #15) and fall application (see Note #4).
- Encourage state-of-the-art application methods, and Manitoba has a unique advantage here because it is the leading Province in Canada for commercial manure application (Livestock Farm Practices Survey - Sheppard, personal communication, also the Keystone Organic Nutrient Applicators Association). Because of market competition, these manure applicator companies are especially

adept at conforming to regulation, collecting manure samples as they work, and using the latest equipment (the newest innovation is in-line on-tractor manure analysis coupled to GPS to allow precision application that varies across a field based on previous crop performance data).

The ‘right timing’ for manure application has a slightly different connotation than intended by the IPNI. For fertilizer, the right timing would be at planting or during log-phase (rapid) crop growth. Logistics and environmental concerns change this for the timing of manure application (although slurry application into standing crops such as corn has been done). Timing for manure application is important related to runoff, but how can one predict when a future runoff event will occur? In Manitoba, it will be in the spring during snow melt and within a month thereafter. However, ‘time is money’ in the spring, delayed planting results in a virtually guaranteed yield loss (see Note #4), so a delay in planting to allow manure application later in the spring is problematic. This would be exasperated if only low application rates were possible (i.e., multi-year application rates were not allowed), as this causes a delay in planting on a larger area of land. Thus, post-harvest application has distinct advantages (see Notes #12 and #13), and this implies fall application. The earlier the post-harvest application can occur, the more opportunity there is for good application and incorporation. This again would be facilitated by multi-year application rates because less land and less time are required each year.

Multi-year manure application schedules have many logistic advantages and on a watershed scale are not different in environmental consequences than lesser annual applications of the same total amount of P (see Notes #14 and #15). Obviously, in the application year there is potential for greater runoff P from the large single application of manure (which in practice would be mitigated by incorporation). However, this is for one year only. In contrast, if manure application is restricted to a rate based on the annual crop offtake of P, then more land will be manured every year, and averaged over time this will result in the same risk of runoff P as the single larger application (see Note #14).

Photos (credit the Keystone Organic Nutrient Applicators Association): Typical equipment used by commercial manure applicators for slurry manure in Manitoba. Upper two photos are of tanker systems, the lower is an umbilical pipe. All show injection with little or no manure left on the soil surface.

Summary

The P entering Lake Manitoba comes from many sources: at most about 15% comes from agricultural land in Manitoba and only a small portion of this could be attributed to livestock. Even totally removing the Manitoba agricultural sources of P will have little benefit to the Lake, and total removal is impossible. The movement of soil P from land to water is a primordial geological process and is virtually irreversible. However, it is possible to do better with agricultural P than in the past. Already, several very potent BMPs have been adopted, and Manitoba is a leader in Canada with some of these techniques and technologies (e.g., low-P diets, manure injection, low manure application rates).

Manitoba has a different landscape and climate than most other places concerned with P in runoff, and as a result, much of the scientific literature is not directly applicable. There have been misguided initiatives because the unique aspects of Manitoba with respect to P in runoff were not understood (e.g., vegetated buffer strips). Additionally, research that was designed to test worst-case runoff scenarios is sometimes misinterpreted as representative (see Note #11).

Runoff dissolved P concentrations are related to soil P concentrations, and this applies to both manured land and crop land that is only fertilized. By far the largest source of 'new' P in agro-Manitoba is from fertilizer, and the present crop yields in Manitoba are dependent on this P supply. Mandating lower P supply from fertilizer or manure will have a yield impact, especially on soils that are now low in P. There is a societal cost as well as a farm cost to P management. Some of the next most potent BMPs may not be related to farms at all (e.g., harvest of wetland and riparian vegetation).

As a populist analogy, excess soil P shares similarity to being overweight. Adding more P, or calories, is easy, but causes immediate buildup. Decreasing P supply, or calories, is possible and will have an effect, but it is much more difficult. The soil P, or bodyfat, is in chemical forms that are not easily released. It takes longer to lose than to gain, and 'things are not optimal' during the loss phase. In the calorie side of the analogy, sugar intake gives you more energy than burning fat. In the soil P side, crops would respond more effectively to new fertilizer P than to stored soil P, so yields may suffer. In either side of the analogy, total abstinence from P or calories is not an option.

Clearly, the first priority in the management of manure P is the reduction of the addition of 'new' P as mineral supplements to feed, and the optimizing of the total P in the diet to match the animal needs. This has been underway for some time with good success, but there may be scope for more research and improvement. After this, the priorities are optimizing application rates, methods and timing. It is very clear that balancing P application with crop P offtake allows control of soil P levels – it is slow and may cost in terms of yield. It is also clear that any application method that removes manure from the runoff flowpath is beneficial, and this mostly means injection of slurry and incorporation by tillage. Fall manure application facilitates proper incorporation because on average there are more dry field working days in the fall. Finally, timing to allow as much time as possible between application and potential runoff events is critical.

To make optimization of application rates, methods and timing possible in Manitoba, there are some activities that are important but that may appear counter-intuitive. Specifically, as the manure application rates become lower to minimize build-up of soil P, more and more land and more and more application time is required. This expansion in both space and time increases the risk of excess runoff P. A practical option is to apply manure in multi-year rates (which has other environmental and cost benefits as well, see Notes #12 and #13). The concept is simple. If a 2-year cycle is used, twice the amount of manure per hectare is applied once every 2 years. Half the land area and just over half the application time is required. If the application rates are set to match crop offtake, then the net addition to soil P of a 2-year cycle versus annual application is not different (see Note#15), and this should mean that runoff P concentrations will be similarly unaffected. With more time to do the applications, the economics of deep injection and timely incorporation are more favorable, plus more of the spreading can be done in drier conditions. Given these advantages, it would be prudent to allow producers the flexibility to adopt planned multi-year application cycles, and cycles from 2 to 5 years would be suitable.

Recommendations

- encourage research on animal P nutrition to minimize additions of ‘new’ mineral P as dietary supplements.
- encourage Manitoba-relevant research on manure application best management practices with runoff P as the measured outcome.
- consider all lands in Manitoba as sources of P to Lake Winnipeg, and plants as important vectors that put P into the runoff flowpath.
- on soils where P levels are high, use crop offtake of P as the guidance for setting manure and fertilizer P application rates.
- encourage manure application methods that bury the manure, these include but are not limited to deep injection on tilled land, aerator slot injection on perennial crop land, and tillage.
- continue to allow fall application of manure, in return for the anticipated benefit that better incorporation technologies are more likely to be adopted for fall application.
- allow landowners receiving manure applications the flexibility to schedule the applications in multi-year cycles, in return for the anticipated practical benefits and the potential this has to decrease occurrences of excess runoff P.

References

Adeli, A.; Tewolde, H.; Sistani, K., and Rowe, D. Comparison of broiler litter and commercial fertilizer at equivalent N rates on soil properties. Communications in Soil Science and Plant Anaylsis. 2010; 41(20):2432-2447.

Ajiboye, B.; Akinremi, O. O.; Hu, Y., and Jurgensen, A. XANES speciation of phosphorus in organically amended and fertilized vertisol and mollisol. Soil Science Society of America Journal. 2008; 72(5):1256-1262.

Andraski, T. W.; Bundy, L. G., and Kilian, K. C. Manure history and long-term tillage effects on soil properties and phosphorus losses in runoff. Journal of Environmental Quality. 2003; 32(5):1782-1789.

Campbell, C. A.; Lafond, G. P.; van den Bygaart, A. J.; Zentner, R. P.; Lemke, R.; May, W. E., and Holzapfel, C. B. Effect of crop rotation, fertilizer and tillage management on spring wheat grain yield and N and P content in a thin Black Chernozem: A long-term study. Canadian Journal of Plant Science. 2011; 91(3):467-483.

Casson, J. P.; Bennett, D. R.; Nolan, S. C.; Olson, B. M., and Ontkean, G. R. Degree of phosphorus saturation thresholds in manure-amended soils of Alberta. Journal of Environmental Quality. 2006; 35(6):2212-2221.

Cherry, K. A.; Shepherd, M.; Withers, P. J. A., and Mooney, S. J. Assessing the effectiveness of actions to mitigate nutrient loss from agriculture: A review of methods. Science of the Total Environment. 2008; 406(1-2):1-23.

Cicek, N.; Lambert, S.; Venema, H. D.; Snelgrove, K. R.; Bibeau, E. L., and Grosshans, R. Nutrient removal and bio-energy production from Netley-Libau Marsh at Lake Winnipeg through annual biomass harvesting. Biomass and Bioenergy. 2006; 30(6):529-536.

Eghball, B. Soil properties as influenced by phosphorus- and nitrogen-based manure and compost applications. Agronomy Journal. 2002; 94(1):128-135.

Fixen, P. W.; Bruulsema, T. W.; Jensen, T. L.; Mikkelsen, R.; Murrell, T. S.; Phillips, S. B.; Rund, Q., and Stewart, W. M. The fertility of North American soils, 2010. Better Crops. 2010; 94(4):6-8.

Flaten, D.; Snelgrove, K.; Halket, I.; Buckley, K.; Penn, G.; Akinremi, W.; Wiebe, B., and Tyrchniewicz, E. Acceptable phosphorus concentrations in soils and impact on the risk of phosphorus transfer from manure amended soils to surface waters. 2003: 216 pages.

Gessel, P. D.; Hansen, N. C.; Moncrief, J. F., and Schmitt, M. A. Rate of fall-applied liquid swine manure: Effects on runoff transport of sediment and phosphorus.

Journal of Environmental Quality. 2004; 33(5):1839-1844.

Grant, C. A.; Flaten, D. N.; Tomasiewicz, D. J., and Sheppard, S. C. The importance of early season phosphorus nutrition. Canadian Journal of Plant Science . 2001; 81(2):211-224.

Idowu, M. K.; Ige, D. V., and Akinremi, O. O. Elution of inorganic and organic phosphorus from surface-applied organic amendments. Canadian Journal of Soil Science. 2008; 88(5):709-718.

Jarvie, H. P.; Neal, C., and Withers, P. J. A. Sewage-effluent phosphorus: A greater risk to river eutrophication than agricultural phosphorus? Science of the Total Environment. 2006; 360(1-3):246-253.

Kashem, M. A.; Akinremi, O. O., and Racz, G. J. Extractable phosphorus in alkaline soils amended with high rates of organic and inorganic phosphorus. Canadian Journal of Soil Science. 2004; 84(4):459-467.

Kashem, Md. A.; Akinremi, O. O., and Racz, G. J. Phosphorus fractions in soil amended with organic and inorganic phosphorus sources. Canadian Journal of Soil Science. 2004; 84(1):83-90.

Kleinman, P. J. A.; Allen, A. L.; Needelman, B. A.; Sharpley, A. N.; Vadas, P. A.; Saporito, L. S.; Folmar, G. J., and Bryant, R. B. Dynamics of phosphorus transfers from heavily manured Coastal Plain soils to drainage ditches. Journal of Soil and Water Conservation. 2007; 62(4):225-235.

Koonce, J. F.; Busch, W.-D. N., and Czapla, T. Restoration of Lake Erie: Contribution of water quality and natural resource management. Canadian Journal of Fisheries and Aquatic Sciences. 1996; 53(SUPPL. 1):105-112.

Little, J. L.; Nolan, S. C.; Casson, J. P. , and Olson, B. M. Relationships between soil and runoff phosphorus in small Alberta watersheds. Journal of Environmental Quality. 2007; 36(5):1289-1300.

Ludsin, S. A.; Kershner, M. W.; Blocksom, K. A.; Knight, R. L., and Stein, R. A. Life after death in Lake Erie: Nutrient controls drive fish species richness, rehabilitation. Ecological Applications. 2001; 11(3):731-746.

Manitoba Conservation. 2000. Geographical Names of Manitoba, National Library of Canada (Ottawa) and Manitoba Conservation (Winnipeg), ISBN 0-7711-1517-2.

McDowell, R.; Sharpley, A., and Withers, P. Indicator to predict the movement of phosphorus from soil to subsurface flow. Environmental Science and Technology. 2002; 36(7):1505-1509.

Miller, J. J.; Olson, E. C. S.; Chanasyk, D. S.; Beasley, B. W.; Larney, F. J., and Olson, B. M. Phosphorus and nitrogen in rainfall simulation runoff after fresh and composted beef cattle manure application. Journal of Environmental Quality.

2006; 35(4):1279-1290.

Miller, J. J.; Chanasyk, D. S.; Curtis, T. W., and Olson, B. M. Phosphorus and nitrogen in runoff after phosphorus- or nitrogen-based manure applications. Journal of Environmental Quality. 2011; 40(3):949-958.

Munawar, M.; Munawar, I. F.; Dermott, R.; Niblock, H., and Carou, S. Is Lake Erie a resilient ecosystem? Aquatic Ecosystem Health and Management. 2002; 5(1):79-93.

Oberson, A.; Tagmann, H. U.; Langmeier, M. ; Dubois, D.; Mader, P., and Frossard, E. Fresh and residual phosphorus uptake by ryegrass from soils with different fertilization histories. Plant and Soil. 2010; 334(1):391-407.

Olatuyi, S. O.; Akinremi, O. O.; Flaten, D. N., and Crow, G. H. Solubility and transport of phosphate and the accompanying ions as influenced by sulphate salts in a model calcareous soil system. Canadian Journal of Soil Science. 2009; 89(5):589-601.

Priyashantha, K. R. S.; Maule, C. P., and Elliott, J. A. Impact of slope position and hog manure injection on soil P and N distribution in an undulating landscape in Saskatchewan, Canada: ASAE Annual International Meeting; 2005.

Raty, M.; Uusi-Kamppa, J.; Yli-Halla, M.; Rasa, K., and Pietola, L. Phosphorus and nitrogen cycles in the vegetation of differently managed buffer zones. Nutrient Cycling in Agroecosystems. 2009; 86(1):121-132.

Sawka, C. A. D. Relationship between chemical analysis of P in soil and P loss in simulated runoff. MSc Thesis, Dept. Soil Sci., Univ. Manitoba. 2009.

Sharpley, A. N. Soil mixing to decrease surface stratification of phosphorus in manured soils. Journal of Environmental Quality. 2003; 32(4):1375-1384.

Sharpley, A. N.; Kleinman, P. J. A., and McDowell, R. W. Innovative management of agricultural phosphorus to protect soil and water resources. 2001; 32, 1071-1100.

Sheppard, S. C.; Bittman, S., and Bruulsema, T. W. Monthly ammonia emissions from fertilizers in 12 Canadian Ecoregions. Canadian Journal of Soil Science. 2010a; 90(1):113-127.

Sheppard, S. C.; Bittman, S.; Swift, M. L. , and Tait, J. Farm practices survey and modelling to estimate monthly NH_3 emissions from swine production in 12 Ecoregions of Canada. Canadian Journal of Animal Science. 2010b; 90(2):145-158.

Smith, K. A.; Jackson, D. R., and Withers, P. J. A. Nutrient losses by surface run-off following the application of organic manures to arable land. 2. Phosphorus. Environmental Pollution. 2001; 112(1):53-60.

Sturite, I.; Henriksen, T. M., and Breland, T. A. Winter losses of nitrogen and phosphorus from Italian ryegrass, meadow fescue and white clover in a northern temperate climate. Agriculture, Ecosystems and Environment. 2007; 120(2-4):280-290.

Tiessen, K. H. D.; Elliott, J. A.; Yarotski, J.; Lobb, D. A.; Flaten, D. N., and Glozier, N. E. Conventional and conservation tillage: Influence on seasonal runoff, sediment, and nutrient losses in the Canadian prairies. Journal of Environmental Quality. 2010; 39(3):964-980.

Uusi-Kamppa J. and Jauhiainen, L. Long-term monitoring of buffer zone efficiency under different cultivation techniques in boreal conditions. Agriculture, Ecosystems and Environment. 2010; 137(1-2):75-85.

Vadas, P. A.; Gburek, W. J.; Sharpley, A. N.; Kleinman, P. J. A.; Moore Jr., P. A.; Cabrera, M. L., and Harmel, R. D. A model for phosphorus transformation and runoff loss for surface-applied manures. Journal of Environmental Quality. 2007; 36(1):324-332.

Weld, J. L.; Sharpley, A. N.; Beegle, D. B., and Gburek, W. J. Identifying critical sources of phosphorus export from agricultural watersheds. Nutrient Cycling in Agroecosystems. 2001; 59(1):29-38.

Wortmann, C. S. and Shapiro, C. A. The effects of manure application on soil aggregation. Nurtient Cycling in Agroecosystems. 2008; 80(2):173-180.