Published online January 13, 2020

Managing Animal Manure to Minimize Phosphorus Losses from Land to Water

Peter J.A. Kleinman,* Sheri Spiegal, Jian Liu, Mike Holly, Clint Church and John Ramirez-Avila

Abstract

Given the expansion of eutrophication in water bodies around the world, the improved management of manure to mitigate phosphorus (P) losses to water has become a global concern. This chapter seeks to frame manure management strategies and practices to minimize P losses to water, with a focus on manure properties, land application, farmstead infrastructure, and farming systems. Although many options exist to better manage manure, and, more specifically, P in manure, doing so requires comprehensive approaches that consider factors far beyond the direct handling of manure and require decisions that may compete or conflict with other priorities, most notably profits and time management.

Eutrophication is the most pervasive concern to freshwater and estuarine water bodies worldwide, with phosphorus (P) pollution continuing to expand the extent of eutrophication, its impacts on aquatic life and its disruption of the benefits of ecosystems to humankind. No sector in agriculture has been more closely tied to the accelerated eutrophication of aquatic systems than animal agriculture, principally as a result of the generation and management of manure. Although P contributions from other sources, agricultural and non-agricultural alike, contribute to the spread of eutrophication globally, the economics and structure of animal production systems, both in modern times and historically, the concentration of P in manure and around animal production zones, and the vagaries of precisely and efficiently using manure resources all compound into myriad opportunities for P to be lost from animal production systems and transferred to the aquatic environment.

Successful manure management strategies must consider aspects of animal production systems that, at first glance, do not appear to connect directly with on-farm manure management practices such as handling, storage, and application. Just as eutrophication manifests itself in water bodies as small as farm ponds and as large as the Baltic Sea, P mitigation opportunities must consider manure management scales that extend well beyond the farm gate. Indeed, successful manure management strategies must be viewed through a comprehensive lens that considers long-term factors as well as the immediate consequences of management decisions. Options to managers are often difficult to implement, because manure

P.J.A. Kleinman, USDA Agricultural Research Service, Pasture Systems and Watershed Management Research Unit, University Park, PA 16802; S. Spiegal, USDA Agricultural Research Service, Range Management Research Unit, Las Cruces, NM 88003; J. Liu, University of Saskatchewan, School of Environment and Sustainability, Saskatoon, SK S7N 5B5; M. Holly, University Wisconsin-Green Bay, Department of Natural and Applied Sciences, Green Bay, WI 54311; C. Church, USDA Agricultural Research Service, Pasture Systems and Watershed Management Research Unit, University Park, PA 16802; J. Ramirez Avila, Mississippi State University, Civil and Environmental Engineering Dept, Mississippi State, MS 39762.

*Corresponding author (peter.kleinman@ars.usda.gov)

doi:10.2134/asaspecpub67.c12

Animal Manure: Production, Characteristics, Environmental Concerns and Management. ASA Special Publication 67. Heidi M. Waldrip, Paulo H. Pagliari, and Zhongqi He, editors.

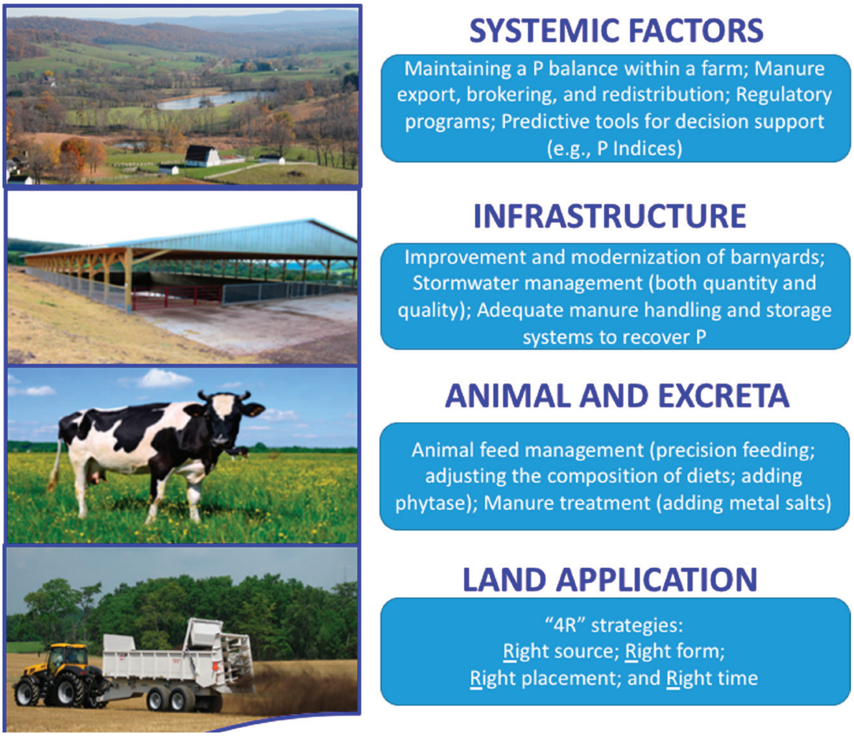

Fig. 1. Managing animal manure across scales to minimize phosphorus losses to water. These scales and their interactions are explored as themes of this chapter.

is a byproduct and not the intended product of animal production and its value, including its potential liabilities (odor, pathogen source, stigma), require management solutions that not only consider social and economic constraints, but take advantage of motivations other than P mitigation to affect change.

This chapter seeks to frame and illustrate the diversity of strategies and practices for manure management that constitute the state of knowledge and the state of the art of managing manures to minimize P losses to water, with a focus on manure properties, land application, farmstead infrastructure, farming systems (Fig. 1). Although examples of manure P management are considered from around the world, there is a noteworthy bias toward manure management in North America (United States and Canada). Further, this chapter does not contain a complete litany of available technologies, even as it strives to highlight recent advances and feature the many dimensions of sustainable manure management. Through the insertion of case studies, we hope to illustrate the opportunities and barriers to manure management options that mitigate P losses to water.

Systemic Factors Affecting Manure Phosphorus, within and among Farms

From the standpoint of manure P, it is appropriate to begin a review of manure management at the level of the animal production system, including not only the farms producing the manure, but the larger networks that provide animal producers with P, be it in fertilizers, grains or forages. A systemic perspective on P cycling helps to differentiate factors that are under the immediate control of producers and those factors outside of a farmer's capacity to manage. It is well-established that the specialization and intensification of modern production systems, vertical integration of certain animal industries (esp. poultry and swine), and consolidation of operations promoted by economies of scale, has wrought great efficiencies in resource flows (MacDonald and McBride, 2009). These economic efficiencies have promoted the uncoupling of nutrient cycles, promoting the export of nutrients from regions with a comparative advantage in producing feeds and forages, and the import of nutrients to areas with a comparative advantage in the production of animals (Lanyon, 2005). Approximately half of the grain produced in the United States is consumed by animals. Despite major improvements in balancing nutrients in feeding regimes, the majority of P fed to animals is not metabolized and therefore destined for manure. As a result, hot spots of manure P are regularly found in regions with high concentrations of animal production (Fig. 2).

Although the benefits of land-applying manure are manifold, it is often difficult to directly substitute manure for synthetic, commercial fertilizers. It is bulky in nature, low in nutrient density, tending toward stoichiometries that are out of balance with crop requirements, unpredictable in nutrient availability to crops, malodorous, a source of pathogens, difficult to store and difficult to handle (Ribaudo et al., 2003; Kleinman et al., 2012). Further, there is a growing number of nutrient management standards that mandate additional paperwork, practices and effort to use manure as a substitute for commercial fertilizers. As a result, manure nutrients are generally undervalued in comparison with commercial nutrient

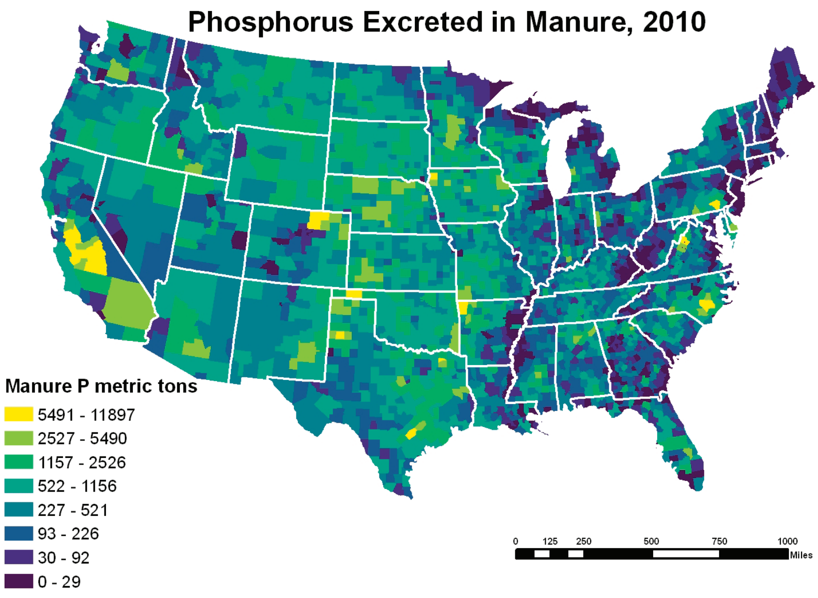

Fig. 2. Estimate of annual excretion of phosphorus in manure in 2010, by county, in the United States. Adapted from Jarvie et al. (2015), based on data from NuGIS (IPNI, 2012).

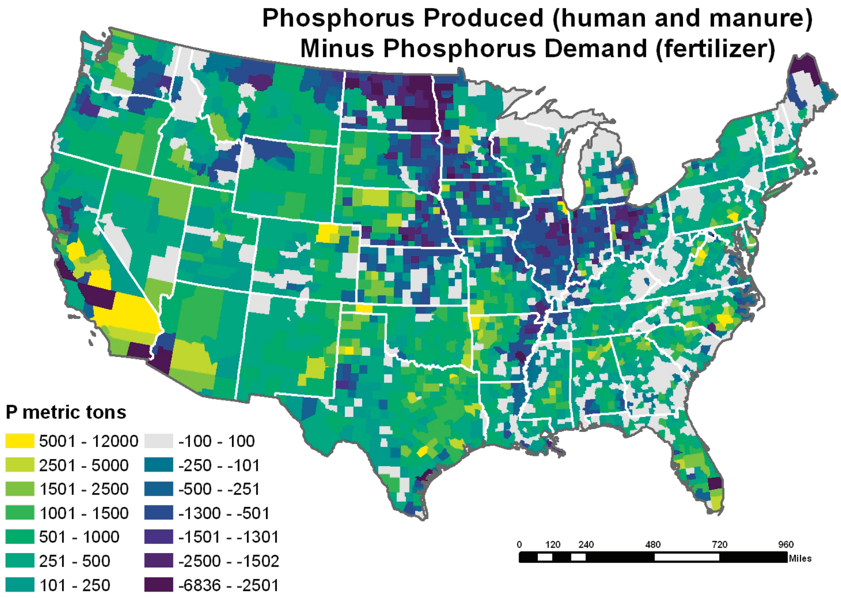

Fig. 3. Comparison of manure and biosolid phosphorus (P) with fertilizer P demand in 2010, by county, in the United States. Adapted from Jarvie et al. (2015).

fertilizers, even if their benefits to crop production are nominally appreciated by farmers and well-documented by science (Magdoff et al., 1997; Beegle, 2014). Unsurprisingly, most manure travels short distances from the barns where it is generated to its point of land application, with ranges of 5 to 20 km often cited as a practical limit (Bartelt and Bland, 2007; Hadrich et al., 2010). Well-constructed manure transport programs can move some manures (e.g., poultry litter) much further, up to 250 kg (Herron et al., 2012). If manure's liabilities could be minimized, many opportunities can be found to substitute manure for purchased fertilizer P (Bosch and Napit, 1992; Carreira et al., 2007). Unfortunately, regions with the most productive cropland, such as the mid-western United States, manifest annual deficits in P on agricultural lands that are currently met by fertilizers, even as other regions reveal theoretical surpluses in P through local generation of manure and its human counterpart, wastewater-treatment-plant biosolids (Fig. 3).

The connection of system-level variables to manure management is particularly evident in farm P budgeting, including connections between manure management and feed use efficiency, fertilizer management, even cropping practices (Rotz et al., 2002; Tarkalson and Mikkelsen, 2003; Plaizier et al., 2014). As illustrated in Fig. 4 for a variety of dairy farming systems in the United States, enterprise P budgets can range widely, even within a single industry. The large accumulations of manure P on some dairy operations reflect a combination of factors, from excess P in dairy rations (e.g., Knowlton et al., 2010), to lesser reliance on forages raised on the farm (Ghebremichael et al., 2008), to unnecessary purchases of commercial P fertilizers (Ketterings et al., 2011), to an inability to export manure from the farm (Van Horn et al., 1994). Notably, from a whole farm budgeting perspective, P losses in runoff, often the driving factor behind manure management regulations, are a minor component of the overall enterprise P balances and almost negligible in dairies of arid regions, even though the impact of these small P losses on the water quality can be great (Sharpley et al., 2003a).

Maintaining a P balance within a farming operation is essential to preventing the accumulation of manure P in farm soils–now referred to as "legacy P" due to its role as a long-term source of P to agricultural runoff–one of the most profound environmental management problems facing agriculture (Sharpley et al., 2013). Increasingly, farm P balances have been promoted for guiding strategic decisions (e.g., Chaperon et al., 2007; Soberon et al., 2015), differentiating between strategies that are suited to enterprises with net P surpluses (export manures, acquire more cropland to use the excess manure nutrients, adjust animal numbers- hence manure generation) and enterprises with net P deficits [targeting manure application to fields with low soil P and potassium (K), avoiding manure application to legumes that don't require the nitrogen (N)]. These farmgate assessments serve as an initial check on the potential for additional manure management practices, such as those described below, to meet production and environmental objectives.

For farming systems in which a substantial P surplus exists, manure export is often seen as an essential solution to on-farm accumulation of P, particularly if costs can be absorbed through subsidy or through value added processes that promote the transport of manure off-farm and, preferably, away from local hot spots. Increasingly, in vertically integrated industries with a high degree of strategic coordination (e.g., poultry and swine), new operations are not even designed to land apply manure that is produced and manure export may be required in a contract. Unsurprisingly, manure export programs tend to involve dry manures, either in the form of litters or processed manure solids, which are easier to transport due to their nutrient density (see also discussion below on manure treatment systems). Programs to promote manure export have been very difficult to implement, particularly community programs that involve farm collectives, and, once implemented, equally difficult to sustain (Kleinman et al., 2012). Further, there

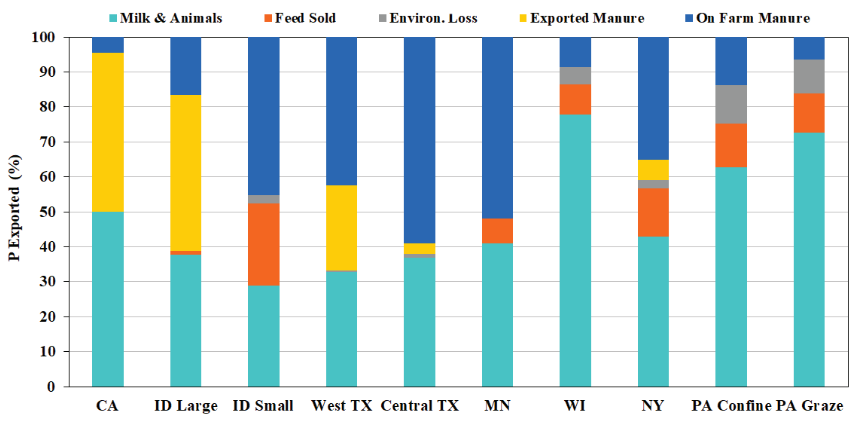

Fig. 4. Enterprise budgets for phosphorus (P) in select dairy farming systems of the United States, showing P distribution in milk and animals sold, feed sold, environmental losses, an on-farm manure accumulation (soil build up), as a percentage of the total quantity of P exported from the farm. Adapted from Holly et al. (2018).

Table 1. Key properties of manures surveyed in the Mid-Atlantic region of the United States. Mean values are followed with standard deviations in parentheses. Nutrient concentrations are expressed on a dry weight equivalent basis. Adapted from Liu et al. (2018a).

	Manure type	No. of samples	pH †	Dry matter	Total P	WEP ‡	WEP/Total P	Total Ca	Total Mg
				%					
Cattle, dairy									
	Manure – All	275	7.53	9.8 (6.8)	0.60 (0.26)	0.28 (0.13)	46.7 (20.8)	2.96 (2.42)	0.84 (0.36)
	– Liquid	29	7.39	2.3 (1.0)	0.91 (0.40)	0.31 (0.13)	34.1 (19.3)	3.95 (1.85)	1.31 (0.43)
	– Slurry	179	7.49	7.9 (1.4)	0.60 (0.20)	0.30 (0.12)	50.0 (21.1)	2.94 (2.06)	0.84 (0.30)
	– Semi-solid	46	7.58	13.1 (2.35)	0.49 (0.17)	0.23 (0.15)	46.9 (21.4)	3.15 (3.87)	0.70 (0.26)
	– Solid	21	7.71	29.5 (6.90)	0.35 (0.10)	0.16 (0.06)	45.7 (12.7)	1.40 (0.56)	0.41 (0.11)
Cattle, beef									
	Manure – All	12	n.d.	23.1 (5.4)	0.52 (0.19)	0.21 (0.13)	40.4 (15.2)	1.51 (0.55)	0.52 (0.24)
	– Semi-solid	3	n.d.	16.8 (3.9)	0.59 (0.25)	0.34 (0.18)	57.6 (13.0)	1.21 (0.16)	0.49 (0.22)
	– Solid	9	n.d.	25.2 (4.1)	0.50 (0.18)	0.17 (0.08)	34.0 (11.5)	1.61 (0.61)	0.53 (0.25)
	Compost	8	n.d.	39.1 (21.6)	0.46 (0.19)	0.11 (0.04)	23.9 (12.3)	2.29 (0.89)	0.62 (0.31)
Swine, farrow to wean or farrow to feeder									
	Manure – All	36	6.63	3.0 (2.9)	2.68 (0.93)	0.56 (0.30)	20.9 (11.6)	4.27 (2.15)	1.75 (0.64)
	– Liquid	31	6.63	2.1 (0.9)	2.51 (0.80)	0.57 (0.33)	22.7 (12.0)	4.02 (1.50)	1.68 (0.58)
Swine, wean to finish or grow to finish									
	Manure – All	35	7.87	4.5 (5.9)	2.37 (0.96)	0.41 (0.19)	17.3 (14.8)	2.62 (0.95)	1.61 (0.52)
	– Liquid	24	7.98	2.0 (0.8)	2.15 (1.02)	0.42 (0.22)	19.5 (16.5)	2.44 (0.78)	1.54 (0.59)
Swine, mixed stages									
	Manure – All	153	7.14	7.5 (5.5)	3.58 (1.38)	0.50 (0.33)	14.0 (15.6)	7.84 (5.62)	2.27 (1.06)
	– Liquid	71	7.09	2.2 (1.1)	2.51 (0.70)	0.70 (0.40)	27.9 (16.8)	3.13 (2.56)	1.44 (0.63)
	– Slurry	21	7.66	8.0 (2.3)	3.97 (1.33)	0.38 (0.08)	9.6 (7.4)	8.01 (5.48)	2.44 (0.97)
	– Semi-solid	60	n.d.	13.2 (1.9)	4.59 (1.09)	0.32 (0.07)	7.0 (4.2)	12.78 (3.4)	3.09 (0.75)
Chicken, layer									
	Solid	30	n.d.	80.3 (11.6)	1.12 (0.66)	0.30 (0.18)	26.8 (15.4)	9.11 (2.91)	0.76 (0.49)
	Compost	2	n.d.	73.7 (9.4)	2.42 (0.25)	0.51 (0.03)	21.1 (3.6)	9.57 (7.92)	0.99 (0.13)
Chicken, broiler									
	Solid	7	7.73	71.5 (8.3)	1.43 (0.36)	0.35 (0.19)	24.5 (11.5)	2.44 (0.68)	0.60 (0.14)
	Compost	4	7.64	67.9 (2.3)	1.82 (0.17)	0.46 (0.08)	25.3 (6.7)	2.52 (0.19)	0.80 (0.13)
Turkey									
	Solid	10	n.d.	66.8 (6.0)	1.94 (0.61)	0.52 (0.13)	26.8 (6.4)	2.99 (0.99)	0.62 (0.21)
Horse									
	Solid	17	n.d.	41.6 (14.2)	0.49 (0.19)	0.27 (0.17)	55.1 (17.8)	1.76 (2.02)	0.43 (0.25)
	Compost	7	n.d.	46.8 (15.1)	0.54 (0.33)	0.19 (0.14)	35.2 (22.0)	1.96 (1.63)	0.58 (0.41)

† n.d. = no data

‡ WEP, water extractable phosphorus.

is a need to ensure that exported manure is used prudently to ensure that the exported manure is used in a sustainable fashion (Liu et al., 2016).

Examples of community programs to promote manure transport in the United States, many of which have faced and sometimes succumbed to existential challenges, include a poultry litter pelletizing, now composting, facility in Delaware (Pipkin, 2017), manure brokering within Chesapeake Bay watershed states (Dance, 2017), a manure-to-energy turkey litter incineration plant in Minnesota (MacDonald, 2006), poultry litter baling and brokering programs in Arkansas (O'Keefe, 2011; Herron et al., 2012), a large scale composting facility in Pennsylvania (Torres, 2010), and a community anaerobic digester for dairies in Wisconsin (USEPA, 2015). Internationally, hopeful futures in community manure processing programs may be found in manure-to-energy for Finland's dairy industry (Uutiset, 2018) and nutrient recovery systems being trialed by Sweden's solid waste industry (EasyMining, 2018). In all cases, regulatory programs, such as those promoting circular economies (Nesme and Withers, 2016), are required to ensure that costs associated with exporting manures from farms and processing them at community facilities do not undermine investment, development and maintenance.

Manure Properties Affecting Phosphorus Availability to Runoff

The connection between agricultural P and manure is profound, with ties to the history of modern agriculture and science alike. Phosphorus was the first element discovered by modern science 350 yr ago, obtained from urine, albeit 5500 L of human urine (Sharpley et al., 2018). Bird and bat guano were once the major sources of fertilizer P in the 19th Century (Giaimo, 2015), as were, briefly, deposits of fossilized dung (Schwarcz, 2017). The relative inefficiency of vertebrates in metabolizing P from food sources, combined with the reactive nature of P, enriches excreta with relatively high concentrations of the element. When these excreta are combined with bedding, water, and other materials to form manure, it is not surprising that manure characteristics vary widely (He et al., 2016).

The nutrient composition of manures (e.g., Total P, Total Ca, Total Mg in Table 1) can be influenced by the biology of the animal as well as by management factors. In a survey of 140 manure samples, Kleinman et al. (2005) reported distinctive differences in total P by animal species when normalized on a dry weight basis: from a low for the major ruminant livestock (0.5% for beef cattle and 0.7% for dairy cattle), to higher concentrations in monogastric species (1.6% for broiler chickens, 2.6% for layer chickens, 2.4% for turkey, and 2.9% for swine). Nutrient compositions in manures are also influenced by animal diets, as well as by manure storage and handling processes (Rotz, 2004). For example, Toor et al. (2005b) reported a 40% decrease in manure P concentrations after reducing total P in dairy diets from 5.1 to 3.6 g kg^{-1}. Eghball (2000) and Preusch et al. (2002) found that composting significantly lowered the N to P ratio in manures, as a result of volatilization of N at the same time that P was conserved.

As factors such as diet and manure management have changed over time, so too have the properties of animal manures. In fact, Liu et al. (2018a) compared properties of manures from the earlier survey of Kleinman et al. (2005) with properties of manures from the same region approximately one decade later (Table 1). They found that while total P in manure of some animals (beef cattle, broiler chickens and turkeys) remained similar at the two points in time, total P in the manure from dairy cattle declined significantly (- 30%), as did total P in layer chicken manure (- 39%) and swine manure (- 46%). In part, these changes are a sign of the recognition of the need for parsimony in dietary P to curtail P in manure (e.g., National Research Council, 2001), in no small part due to efforts to educate animal producers (Applegate and Angel, 2008). Strategies to manipulate animal diets to affect the quantity of P include precisely managing P supplements, adjusting the composition of diets (Dou et al., 2002; Toor et al. 2005a, 2005b), as well as adding phytase to poultry and swine feed or otherwise breaking down organic P forms in feed (Humer et al., 2015). As monogastric animals, poultry and swine lack the phytase generating bacteria found in the anaerobic environment of the rumen in cattle, sheep and goats (Yanke et al., 1998). Phytin, or phytic-acid, is the dominant form of P found in corn and soybeans and must be hydrolyzed to be metabolized. The advent of commercial phytase in the late 1990s led to significant changes in feed formulations in poultry and swine diets, with well documented reductions in the total P content of manure as long as the phytase amendment was tied to a reduction in P supplementation (Smith et al., 2004; Applegate and Angel, 2008).

While total P in manures is an essential metric for P budgets, it is not necessarily a good indicator of the immediate availability of P in land-applied manure to the environment (Moore et al., 1999). Water extractable P (WEP; Kleinman et al., 2007) has been widely used to predict the potential for land-applied manure, particularly manure applied to the soil surface, to directly transfer dissolved forms of P to runoff water (Withers et al., 2001; Kleinman et al., 2002; Brandt and Elliott, 2003). In some areas, WEP is used to adjust environmental recommendations for land application of manure (Elliott et al., 2006), and WEP is an important variable in the most sophisticated computational models for P runoff (Vadas et al., 2009). Just as total P varies widely across animal species, so too does WEP. In the survey of Liu et al. (2018a), WEP ranged by an order of magnitude, with the highest average concentrations found in manures from turkey and swine manure, followed by chickens (layers and broilers), followed by dairy, beef, and horse manures (Table 1). In general, composted manures had lesser WEP concentrations. Water extractable P comprised 11 to 58% of total P in these manures and composts. Notably, Liu et al. (2018a) found WEP to be negatively related to the dry matter content of manures, and positively related to estimates of P sorption saturation (total P/[total Ca + Mg + Fe + Al + Mn]). There was also an indication that increasing pH of dairy and swine manures (from 6.6 to 8.3) reduced WEP. All these relationships point to opportunities to lower manure WEP concentrations through practices that affect manure physical and chemical traits.

A large body of literature documents the potential to reduce manure WEP using various metal salts, borrowing from processes in wastewater treatment plants. Perhaps the best accepted amendment for manures is alum ($Al_2(SO_4)_3$), which is used in the production of over 1 billion broiler chickens in the United States alone. Notably, alum's adoption by the broiler industry reflects its contribution to ammonia conservation and documented improvements in the growth and health of housed birds (Choi and Moore, 2008). Other salts that have been trialed include ferric chloride ($FeCl_3$), ferric sulfate ($FeSO_4$), aluminum chloride ($AlCl_3$), and gypsum ($CaSO_4$), all of which show varying potential to lower WEP in manure but none of which have gained widespread acceptance (Xin et al., 2011). Generally, a reduction in the solubility of P in manure with salt addition does not significantly impact P availability to crops, although the added P sorption capacity from salt amendments in manure can also reduce P solubility in soils, as demonstrated by long-term studies with alum-treated poultry litter (Huang et al., 2016). To address cost, particularly when an amendment does not offer ancillary benefits that would improve profitability of animal production (alum has a benefit to cost ratio of 2 due to aforementioned improvement in chicken health; Moore et al., 2000), waste materials have often been considered (water treatment residuals rich in Al and Fe, Elliott et al., 2002; Ca-, Al- and Fe-rich by-products from coal-fired plants, Dou et al., 2003; Al and Fe residues from treatment of acid mine drainage, Adler and Sibrell, 2003). Notably, in liquid manures, there are acute exposure concerns associated with the use of amendments that include S, due to the potential generation of hydrogen sulfide (H_2S) gas under anaerobic conditions (Fabian-Wheeler et al., 2017).

Farmstead Infrastructure

The management of manure in and around animal production facilities represents one of the greatest opportunities to control acute losses of P from animal production systems. Indeed, modern barns, manure handling and storage systems, and standards for barnyards and drainage system are intended to prevent discharges of manure and its constituents with stormwater. At the core of farmstead manure management strategies is the principal of efficiently isolating and containing manure by preventing the interaction of farmstead stormwater with surfaces and structures where manure is found.

Catastrophic discharges of manure can occur when infrastructure is improperly sited, insufficiently maintained, overwhelmed by extreme storm events, or simply fails (Ogejo, 2009). As climate change accelerates, there is a need for continuous reconsideration of how manure infrastructure is designed and managed (Wright et al., 2013). For instance, 33 swine lagoons discharged manure and six lagoons suffered structural damage in North Carolina as a result of rain and flooding from Hurricane Florence of 2018, despite major changes to the siting, design, and management of lagoons following in the aftermath of Hurricane Floyd in 1999 (NCDEQ, 2018).

Efforts to mitigate manure P losses to the environment due to farm infrastructure are regularly hindered by historical inertia, supported by cultural factors that resist change, as well as the cost of most infrastructure projects. Around the world, past standards (or a lack there-of) and traditional development practices often did not consider water quality implications, and even relied on periodic flooding or direct discharge to waterways as a form of manure management. As late as 2000, an estimated 30 to 70% of China's animal manure was directly discharged to rivers (Strokal et al., 2016). Even when direct discharge to waterways is not a primary factor, inadequate farmstead infrastructure can undermine watershed efforts to mitigate P loss. In a classic case study on this matter, Meals (1993) reported that barnyard improvement strategies on small, New England dairy farms were the most effective practice in mitigating watershed P losses and were essential to the success of watershed management activities around Vermont's LaPlatte River. Similarly, modernization of barnyards on small dairy farms was a principal feature of New York City's successful remediation of P pollution in watersheds serving as the source of its drinking water (USEPA, 2007).

In addition to the modernization of barnyards, a variety of filtration approaches have been used to treat and detain and/or retain stormwater discharge. Traditional practices to remove P from stormwater include vegetated filter strips, detention or

Fig. 5. Examples of on-farm and mobile treatment systems developed in the United States to recover phosphorus from liquid dairy and swine manures.

retention basins, and constructed wetlands (Young et al., 1980; Walker, 1987; Schwer and Clausen, 1989; House et al., 1994; Drizo et al., 1997). Invariably, these filters are overwhelmed by large volumes of stormwater flow and concentrations of P in runoff from farmsteads. While traditional filtration practices can be very effective in controlling particulate P losses from stormwater, assuming they are not undermined by preferential flows (Kim et al., 2006), the capacity of traditional practices to bind dissolved forms of P in runoff from heavily manured sites tends to be overwhelmed by the process of P sorption saturation (Dillaha et al., 1988, 1989; Kleinman, 2017). Indeed, due to the reversibility of sorption processes, heavily P-saturated filters can become sources of dissolved P to runoff. In an extreme example, a constructed wetland used to treat feedlot runoff in Manitoba, Canada eventually became P saturated such that total P concentrations in wetland discharge were 30% greater than concentrations in the feedlot runoff (Pries and McGarry, 2002).

Due to concerns related to the efficacy of traditional runoff treatment practices in mitigating P loss, options to filter stormwater from farmstead areas and other concentrated discharges (e.g., tile and ditch drainage) are growing. Most experience with P filtration out of stormwater with these alternatives remains in the research realm, but a myriad of opportunities exist to implement these systems around older farmsteads that were not developed with modern stormwater management standards (Kleinman et al., 2012). For instance, Bird and Drizo (2010) describe the design of systems to treat milkhouse waste based on residual slag materials, with dissolved P filtration efficiencies up to 76%, with a maximum filter media replacement period of five to six months. In a review of alternative P filtration systems for nonpoint source runoff, Buda et al. (2012) emphasize the extremely high filtration efficiencies (> 60%) of such systems, while Penn et al. (2017) highlight retention time and the sorption properties of the filter media as critical factors in determining filtration efficacy. To compensate for short retention times in stormwater treatment systems, Qin et al. (2018) recommend filter media based on Fe and Al sorption, which is more rapid than precipitation of dissolved P with Ca. Due to cost, most P filters proposed for agricultural settings employ byproduct materials from various industrial processes, although natural P sorbing materials have also been investigated (McDowell et al., 2008; Vohla et al., 2011; Buda et al., 2012), and there is interest in promoting the use of more expensive P sorbing media that would enable the recovery of captured P as a fertilizer product.

Another key consideration in leveraging farmstead infrastructure to minimize P losses to water are manure handling and storage systems. These systems are a principal determinants of manure nutrient properties, particularly when explaining differences within individual species (Table 1). From a qualitative perspective, even manure management strategies aimed at N conservation (e.g., separating urine and feces in dairy barns) have implications to P management as they can substantially alter N/P, and therefore rates of land application, which are frequently driven by crop N demand. Further, systems that generate readily-transportable manures (i.e., dry) or value-added materials (e.g., composts, vermicomposts) are generally needed to promote long-distance transport of manures from their source. However, because P is conserved across the manure handling and storage process, as opposed to N which may suffer significant volatile losses, farm P balances are seldom impacted by handling and storage systems without conscientious effort to engage in manure export. Although potentially self-evident, this is an important distinction because technologies such as anaerobic digesters and solid separators are regularly promoted in watershed mitigation programs (e.g., Kleinman et al., 2012), but their impact on watershed P losses is difficult to enumerate without explicit ties to activities in the field or at the farmgate.

Although P recovery methods are common in municipal wastewater treatment systems, fewer methods exist for livestock manure. A variety of systems have been developed, but their economic viability is still in question (Fig. 5). One of the most common approaches to P recovery from animal manures is to 'force' the formation of struvite (NH_4MgPO_4; Burns and Moody, 2002) by amending the manure with Mg, typically the limiting ion for struvite formation in manures and then removing the struvite. The formation of struvite is sensitive to the ratios of Mg, NH_4, PO_4, and pH, but in liquid swine manures with low solids content (< 2%), the struvite formed can be readily recovered using gravity settling. In one laboratory demonstration, recovery of P in struvite from swine manure slurries was as high as 90% (Burns and Moody, 2002). However, the higher solids content of dairy manures interferes with the gravity settling of struvite, and so, pretreatment to remove manure solids is required. One approach that has been tested uses a fluidized bed reactor to extract P in the form of struvite from anaerobically digested dairy manure liquor. Reported extraction efficiencies for this approach range from 60 to 80% (Fig. 5) (Washington State University, 2018).

Other manure treatment systems have been proposed that recover Ca-P compounds. For instance, in South Carolina, Vanotti et al. (2005, 2010) developed a full-scale, two-stage system for a swine production facility that can treat raw swine manure (Fig. 5). This system uses a nitrification bioreactor to reduce carbonate and ammonium buffers, followed by the addition of $Ca(OH)_2$ to precipitate Ca–P (Vanotti et al., 2005). Manure solids containing about 95% of the P are collected after the treatment process and are exported for end uses in compost or low-solubility fertilizer. Other benefits of this system are the removal of odors and pathogens. Notably, many Ca-based P recovery systems and anaerobic digesters generally volatilize much of the manure N content as they adjust pH to favor Ca-P precipitation unless recovery systems are included to capture NH_3 off-gassed (Karunanithi et al., 2015; Garcia-Gonzales et al., 2016).

Because a substantial amount of P is found in manure solids, liquid–solid separation systems can be used to recover P, albeit in bulk forms that do not readily substitute for commercial fertilizers. Given the costs of bedding, recovery of manure solids, and composting is a common practice on many large dairies, recycling the associated P within the barn rather than applying it to land. Church et al. (2016, 2017) demonstrated that up to 60% of P could be recovered from dairy slurry with liquid–solid separation technologies (screw press followed by centrifugation). When these technologies were combined with chemical treatment, up to 99% of manure P was recovered in various solids, leaving a liquid effluent that preserves more than 90% of the N in the manure (Digested Organics, 2018; Livestock Water Recycling, 2018; Church et al., 2016, 2017, 2018). A mobile version of the solid–separation and chemical treatment system, MAnure PHosphorus EXtraction (MAPHEX), was developed to treat manure slurries on small dairies (Fig. 5) (Church et al., 2016, 2017, 2018).

Land Application of Manure

Globally, animal manure accounts for over 60% of the N and P applied to land each year (Potter et al., 2010), a poignant statistic that, in its magnitude, highlights both the potential for manure to substitute for commercial fertilizer and the imperative that manure be used sustainably in global food production (Magdoff et al., 1997). The tenets of agronomic manure management can be found in the evolving principals of "4 R" nutrient management stewardship (Right *rate*, Right *timing*, Right *placement*, Right *form*) as well as in its predecessor, critical source area management (Sharpley et al., 2003b; Ehmke, 2014). These principals seek to elevate consideration of P use efficiency by crops as well as to curtail the environmental impact of land-applied manure P. While easily stated, crop P use efficiency and environmental protection can be extremely difficult to achieve, largely due to the complex, site-specific interactions of management and environmental factors, but also because P management is but one component of farming and therefore must accommodate other priorities that impinge on the availability of finances, time, technology and land (Syers et al., 2008). Therefore, despite decades of continual improvements in manure management options, it remains the rule that

Table 2. Summary of the effects of different manure application methods on runoff and water quality relative to broadcast application. Adapted from Maguire et al. (2011).†

	Runoff volume		Erosion		Total phosphorus load		Dissolved phosphorus load	
Method	Row cropland	Pasture/ grassland	Row cropland	Pasture/ grassland	Row cropland	Pasture/ grassland	Row cropland	Pasture/ grassland
Chisel Injection								
Chisel with sweep	--	--	--	--	--	--	--	--
Spike/knife	--	--	--	--	94% less	--	--	--
Disk Injection								
Shallow disk	--	3-35% lower	0%	68% less	0-91% less	84% less	71-94% less	--
Tandem disk	--	--	--	--	--	--	--	--
Aerator		0-81% lower		28% more to 69% less	94% less	0-88% less	96% less	13-90% less
Tillage								
by moldboard plow	9-56% lower	--	--	--	90% less	--	84% less	--
by chisel plow	14-66% lower	--	0-97% more	--	90% more to 81% less		0-68% less	
by double disk	20% lower	--	--	--	--	--	--	--

† Data obtained from Ross et al. (1979), Laflen and Tabatai (1984), Andraski et al. (2003), Davarede et al. (2004), Shah et al. (2004), van Vliet et al. (2006), Butler et al. (2008), Franklin et al. (2007), Burcham et al. (2008), Johnson et al. (2011)

land-applied manure P is inefficiently used in crop production, and that historical attitudes toward manure management, while evolving, diminish the value of this important resource and therefore serve as disincentive for changing manure management practices. Thus, as much as the knowledge and management options discussed below can contribute to sustainable management of manure P, education is ultimately at the heart of advancing the agronomic management of manure P (Genskow, 2012).

To understand how different manure application practices affect P fate in the environment, it is useful to characterize manure P losses on the basis of the processes and pathways of P transfer from the soils where it is land applied to the waters where it accelerates eutrophication. Land applied manure contributes P to runoff directly, through the "incidental transfer" or "wash-off" of P in manure, or indirectly, through soils that have accumulated P from past manure applications and now lose that P to runoff through the processes of erosion, desorption, reductive dissolution and mineralization (Buda et al., 2013). The wash-off of manure P from soil is a short-term concern, involving transfers of recently applied manure P during the season in which it is applied and often characterized by severely elevated P concentrations in runoff water (surface and subsurface), whereas soil-mediated losses are persistent, albeit generally lower in concentration. Most notably, the accumulation of P in soil creates so-called "legacy" sources of P that can continue to enrich runoff for years, even decades, after manure application ceases (Kleinman et al., 2011; Sharpley et al., 2013).

Manure Application Methods

Surface application of manure by broadcasting, such as with flails, rotors and splash plates, continues to be the most common form of land application. Because surface application of manure leaves ammoniacal forms of manure N vulnerable to

Fig. 6. Examples of low-disturbance manure applicators that improve incorporation of manure into the soil: shallow disk injection, aeration and manure banding, and high pressure injection. The cartoons below the photographs depict the discrete nature of manure (in blue) incorporation into soil.

volatilization (e.g., Dell et al., 2012), it tends to exacerbate N/P imbalances as well as to leave manure P vulnerable to wash-off by runoff. Consequently, a substantial body of research explores alternative methods of application that incorporate manure into soil where chemi-sorption and immobilization of P can be promoted, preferably with minimal disturbance to soils to prevent adverse impacts on soil erosion caused by tillage and to permit manure application to perennial forage crops (Table 2).

Incorporation of manure into soil can be achieved via a variety of low-disturbance technologies, many of which are compatible with soil conservation objectives, some of which are suited to perennial forage crops and all with trade-offs that affect their adoption. A few examples of technologies compared by Johnson et al. (2011) under no-till corn production, as well as the spatial pattern of manure incorporation, are illustrated in Fig. 6. In general, the more manure is removed from the soil surface, the less manure P is available to wash-off processes over the short-term and, where tillage is not used, the less soil P is vertically stratified over the long-term. However, applicators, such as aerators, may also impact rainfall infiltration and therefore runoff volumes, providing dramatic, short-term improvements in infiltration (Table 2).

While both agronomic and environmental benefits can be quantified with these types of technologies (Waldrip et al., 2010; Liu et al., 2016), their adoption by farmers and contract manure applicators can be hampered by a variety of factors, real and perceived. Broadcast applicators tend to employ well-established technologies that are relatively easy to maintain. In contrast, low disturbance manure incorporation technologies can be expensive relative to broadcast technologies, all of the examples in Fig. 6 would replace a simple splash-plate used in broadcasting liquid manure. Injectors and aerators all suffer damage from contact with stones, and their performance can be hampered by antecedent soil conditions (e.g., moisture) as well as a slope. Further, broadcasting applies manure over wide swaths quickly compared with alternative manure application methods that tend to slow down progress toward emptying barns and manure storages–a priority when manure spreading periods are brief. Other factors affecting adoption include interaction of low disturbance incorporation technologies with residue (e.g., the high-pressure system in Fig. 6 tended to rake corn residue and had to be cleaned and reset regularly), impacts on soil surface topography (e.g., mounding of soil by steel ground engagement units), and perceived adverse impacts on crop growth (e.g., potential for salt-burning by concentrated bands of injected manure, although this has not been documented).

Manure Application Rate

Changing manure application rates impacts both the short-term wash-off of manure P and the long-term accumulation of legacy soil P. When manure is applied to the soil surface, there are clear relationships between the rate of application of a particular manure and the loss of dissolved P in runoff in the first few events following application (Kleinman and Sharpley, 2003). This relationship diminishes with time and is modified by factors such as manure properties (concentration of WEP, moisture content) and the rainfall-to-runoff-ratio (Vadas et al., 2004). Wash-off of manure P and the influence of manure application rate are less of a concern when manure is fully incorporated into soil (Maguire et al., 2011).

While the punctuated losses of P in the first runoff events following the surface application of manure can be dramatic, the gradual build-up of soil P that comes with applying manure in excess of crop P uptake can be a more insidious water quality concern over the long-term. Left unchecked, the accumulation of manure P in soils can build legacy P reserves that may require many decades to reverse, creating conditions that undermine watershed mitigation programs (Sharpley et al., 2013). Today, unchecked application of manure is less common than several decades ago, but it is still a concern. For instance, a recent study of over 15,000 soil samples from the top 20 poultry production counties in Mississippi found that average soil test P levels (Mehlich-3) increased from 66 mg kg^{-1} in 2002 to 187 mg kg^{-1} in 2012 (Ramirez-Avila et al., 2017). Given the relatively low N/P of most manures, variable rates of manure nutrient mineralization, and general need to purge manure storages in an expedient fashion, persuading farmers to apply manure at lower rates, especially those corresponding to crop P requirement, can be difficult. As a result, many areas allow manure application rates calculated to meet crop P needs across a longer rotation (e.g., three year rotation of multiple crops), trading off short-term risks of wash-off with long-term balances of soil P.

Manure Application over Subsurface Drainage

Managing manure application over tile drains is a complex subject, fraught with trade-offs that sometimes upend useful generalizations. Subsurface P transport to tile drains is greatest when preferential flow pathways such as biopores and cracks minimize contact between infiltrating water and soil, thereby minimizing dissolved P sorption from leachate. These macropores may also transmit particulate P. When manure is broadcast, tillage prior to manure application may disrupt P leaching via preferential flow pathways, but tillage following manure application may translocate manure to lower depths where it comes in contact with macropores that serve as conduits for preferential flow (Kleinman et al., 2009). Similarly, injection of manure may place highly soluble forms of manure in contact with macropores, although the action of an injector may smear or otherwise destroy macropores around the injection zone (Cooley et al., 2013; Feyereisen et al., 2010). Soil properties can substantially influence P leaching losses, sometimes counterintuitively. Liu et al. (2012) found that incorporation of swine slurry reduced leaching of dissolved P by 64% in a well-structured clay loam soil where P transport was dominated by preferential flow pathways, but had little effect in a sandy soil where P loss was dominated by matrix flow. Since macropores serving as preferential flow pathways to tile drains are only found within a few meters of the tile drain, strategies to avoid manure application in these areas have been proposed, as have strategies that would isolate tillage to areas in closest proximity to drains (Ruark et al., 2009).

Such approaches require knowledge of drainage system layout, technology to perform precision management, and, most importantly, an impetus to instigate efforts that can be time-consuming and costly.

Winter Manure Management

While manure is ideally applied in warm seasons when nutrients can be best used by crops (Ehmke, 2014; IPNI, 2014), manure application in cool seasons of late fall, winter, and early spring is not uncommon in many areas of the U.S. and Canada, due to practical reasons such as the lack of long-term manure storage facilities (Dou et al., 2001), and the unavailability of labors and/or unfavorable (wet) field conditions for manure applications in spring (Lewis and Makarewicz, 2009; Liu et al., 2018b). This, as a result, leads to an elevated risk of P losses, for which winter manure applications on frozen, snow-covered, and water-saturated soils have become a particular concern because of coincidence of manure nutrient sources with active transport pathways (Srinivasan et al., 2006; Williams et al., 2011; Vadas et al., 2017). Furthermore, there are fewer management options that can be implemented to minimize the impacts of nutrient losses associated with winter manure applications. Although the practice of frost injection has been developed, it has only been used at local scales.

Phosphorus runoff associated with winter manure applications is greatly influenced by environmental (e.g., weather, soil, and hydrology) and management (e.g., manure, soil, and crop) factors that interactively determine nutrient runoff characteristics (Steenhuis et al., 1981; Fleming and Fraser, 2000; Srinivasan et al., 2006; Williams et al., 2011, 2012; Liu et al., 2017; Vadas et al., 2017, 2018; Stock et al., 2019). In particular, P runoff is largely dependent on the extent of manure nutrient infiltration in soil prior to and during runoff events, which can be determined by both long-term climatic patterns (Vadas et al., 2017) and short-term weather conditions (Collick et al., 2016). Due to the complex influential factors, studies have reported conflicting nutrient loss trends, with many observing elevated risks of N and P losses following manure application to frozen, snow-covered, or water-saturated soils in winter (Midgley and Dunklee, 1945; Klausner et al., 1976; Young and Mutchler, 1976; Phillips et al., 1981; Maule and Elliott, 2006; Komiskey et al., 2011) but some reporting no impact of winter manure application on water quality (e.g., Young and Holt, 1977; Ginting et al., 1998). To minimize potential P losses, however, mitigation strategies are needed in place wherever winter manure applications are conducted. In a recent study model simulating the efficiencies of a large range of management options on P runoff, Liu et al. (2017) found that although winter and fall manure applications increased P runoff as compared with spring applications, targeting manure applications to low-risk fields (gently sloped fields away from streams) in winter and fall or use of a cover crop could reduce P runoff losses to levels below those resulting from spring application if low-risk fields were not targeted.

Due to the water quality concerns associated with winter manure applications, many countries in the world have developed mandatory regulations or voluntary guidelines to guide manure management in this critical season (Liu et al., 2018b). In the United States and Canada, there are a diverse set of winter manure management directives that vary among states and provinces. The directives range from complete prohibition of manure application during winter months to conditional restriction by law on when, where, how, and what manure is applied to voluntary adoption of conservation practices associated with winter manure applications to no specific directives at all (Liu et al., 2018b). It should be noted that a total of 26 states in the U.S. have stricter directives for large-sized animal operations (i.e., Animal Feeding Operations and Concentrated Animal Feeding Operations) than for small operations as of December 2014, which is due to a greater concern over manure nutrient losses from large operations with higher animal densities than from small operations (Liu et al., 2018b). In general, the policies have been designed to take into account several factors such as their climatic conditions, extents of animal production, and considerations of water quality sensitivity to nutrients. In particular, the sensitivity of water quality to nutrients seems to be the first factor considered when deciding the regulations/guidelines by many. In the Chesapeake Bay region in the United States, for example, regulations and guidelines are found to be more restrictive in Delaware (Delaware Department of Agriculture, 2003) and Maryland (Maryland Department of Agriculture, 2012) that are in close proximity to the Bay, in spite of the milder winter conditions compared with the more distant, northern states of New York (New York Natural Resources Conservation Service, 2013) and Pennsylvania (Pennsylvania Code, 2005; Pennsylvania Department of Environmental Protection, 2011). Similarly, in the Lake Winnipeg basin in Canada, although Saskatchewan and Manitoba have similar climates and production settings, while Saskatchewan allows winter manure applications, Manitoba has banned winter manure applications for many years (for large animal farms since 1998 (Manitoba Environment Act, 1998) and for all animal farms since 2013 (Manitoba Sustainable Development, 2017) due to its close proximity to Lake Winnipeg.

In-field Stacking of Manure

Stacking of dry manure is a common, short-term management practice in which dry manure is staged in the field prior to land application. Although it is recommended that manure should be stored under a permanently roofed structure that prevents litter from exposure to rain (Rasnake et al., 1995; Sylvester, 2007; Ogejo and Collins, 2009; Cunningham et al., 2012), it is still common to stack poultry litter in crop fields in anticipation of spreading that manure during a short time frame. To minimize nutrient runoff from the manure stacked in the fields, most U.S. states and Canadian provinces have developed relevant management guidelines, which require or recommend covering field stacks with plastic sheeting or with a reinforced, ultraviolet-resistant cover (Ogejo and Collins, 2009), having a set-back from environmentally-sensitive areas (streams, water wells, drainage ditches, and sinkholes) (Delaware Code Online, 2015; Pennsylvania Department of Environmental Protection, 2011), and siting the stacks on lands with gentle slopes (Pennsylvania Department of Environmental Protection, 2011). Covering manure stacks with a plastic sheet can be a cost-effective strategy to reduce P and N runoff while better preserving the N value in the manure. While some studies have pointed out concerns related to covering a manure stack under certain circumstances, such as, elevated nutrient leaching by water generated by microorganism respiration under aerobic conditions (Dewes, 1995), most of the studies highlight the benefits of covering the manure stacks (Zebarth et al., 1999; Sommer, 2001; Felton et al., 2007; Nicholson et al., 2010; Doody et al., 2012; Liu et al., 2015). In a field study conducted on poultry litter stacks, for example, Liu et al. (2015) found that although P losses from both covered and uncovered stacks were generally low due to their high capacity to hold precipitation water, covering stacks reduced leachate total P losses by 25 to 100 times such that leachate P losses from covered stacks were similar to that in the controls with no manure stacking. It should be noted, however, that manure stacking could result in the development of P "hotspots" in fields (Doody et al., 2013; Liu et al., 2015). After two years of poultry litter stacking, for example, Liu et al. (2015) observed WEP concentrations in upper 5-cm soils were as high as 120 to 240 mg kg^{-1} under the covered stack and 140 to 250 mg kg^{-1} under the uncovered stack. Therefore, relocating stack sites is needed when field stacking of manure is practiced.

Predictive Tools for Decision Support

A large number of decision support tools have been developed to address P loss from land applied manure, most intending to differentiate between sites and practices that will exacerbate runoff losses of manure P, and many intending to identify manure management options. Decision support tools range from the P Index, to complex watershed models that predict the outcome of different scenarios, to short-term risk forecasts (Kleinman et al., 2017). Most of these tools include input and process information related to source and transport factors (the central construct of the critical source area paradigm), but they differ in their representation of P cycling, fate and transport processes, as well as in their temporal and spatial scales of inference (Radcliffe et al., 2015). These differences are tied to the amount of information needed to set up a tool, its computational demands (processing time and capability), and the required expertise of end-users (Bolster et al., 2017).

No decision support tool for managing manure P has received more attention than the P Index, which has been applied to various conditions around the world to assess site potential for P loss (i.e., fields with greatest vulnerability to P loss in runoff), helping to guide manure and fertilizer management, among other things. The P Index originated in the United States (Lemunyon and Gilbert, 1993), prompted by federal policy, and was rapidly modified into different versions to address the needs of individual states, with up to 47 states identifying this tool as the basis for their P-based management guideline (Sharpley et al., 2003b). While most versions of the P Index focus solely on P losses via surface runoff from agricultural fields, a substantial number of modern P Indices now consider vulnerability to subsurface P loss, principally in relationship to artificial drainage (Shober et al., 2017). With nearly two decades of experience in using the P Index as a site assessment tool, a variety of concerns have been raised, from inconsistency and inaccuracy in its assessment of P loss potential to ineffectiveness in promoting change in manure management (Sharpley et al., 2017). Even so, the P Index remains the best-accepted site assessment tool for P-based manure management, with continuing efforts to improve its performance and utility (Ketterings et al., 2017; Kleinman et al., 2017).

The P Index has contributed to the development of other tools intended to help animal producer and advisors to comply with state and national nutrient management regulations. Tools such as the Pennsylvania Nutrient Balance Worksheet and the Manure Management Planner (MMP), assist animal producers or advisors in assembling a comprehensive nutrient management plan by entering information about the operation's fields, crops, storage, animals, and application equipment (Effland, 2010). In addition to the P Index, other, more complex, tools have regularly been advanced and advocated for site assessment and manure management guidance by farmers and their advisors, as well as for support of nutrient management and conservation programs. The Annual Phosphorus Loss Estimator (APLE) and its derivative, APLE for Cattle Lots (APLE-Lots), are spreadsheet models that employ empirical algorithms to predict the consequences of manure management options on annual and sediment-bound P loss in surface runoff. The AGricultural Non-Point Source Pollution Model (AGNPS), the Agricultural Policy/Environmental eXtender (APEX) and the Soil and Water

Assessment Tool (SWAT) are highly calibrated, process-based simulation models that predict daily surface and subsurface P losses at field and watershed scales. Although these models apply to different scales of inference, many of them have been adapted to site assessment, either to bolster the P Index, or to replace the P Index (e.g., White et al., 2010). Efforts to further advance the applicability of these models, and other comparable models, to manure management decisions remain an area of active research.

All the tools presented in this discussion have been widely evaluated under different management scenarios, including the use of different manure sources and application methods (Bolster et al., 2017; Collick et al., 2016; Nelson et al., 2017; Osmond et al., 2017; Ramirez-Avila et al., 2012; Yuan et al., 2013). Efforts to corroborate the performance of these decision support tools have demonstrated that the P Index can perform as well as the other, more complex water quality models when assessing field-scale P loss vulnerability (Osmond et al., 2017). Notably, while APEX, SWAT, and AGNPS have been repeatedly used to satisfactorily predict nutrient transport processes, their use in site assessment requires careful calibration to ensure accuracy of their P loss prediction (Baffaut et al., 2017; Ramirez-Avila et al., 2017). Furthermore, none of these models were developed to simulate the unique processes of subsurface P transport (Radcliffe et al., 2015).

The site assessment tools described above all provide strategic support for manure management, as opposed to short-term support for operational decisions that must adapt to weather, changing management priorities, and other dynamic factors. In response to a perceived need for short-term decision support, a new class of tools has been developed that combine short-term weather forecasts with hydrologic modeling techniques to identify when and where manure should be applied. Some tools, such as Wisconsin's Manure Advisory System have been adopted by local nutrient management programs while others remain in development (Easton et al., 2017).

Conclusions

Manure management has profound implications to the biogeochemical cycling of P, both as a result of the specialization and intensification of modern agricultural production systems, and as a result of the many ways in which P can be lost from animal production operations, with little economic consequence to operators. Many options exist to better manage manure, and, more specifically, P in manure, to minimize their impact on water quality. However, doing so requires comprehensive approaches that consider factors far beyond the direct handling of manure and require decisions that may compete or conflict with other priorities, most notably profits and time management.

Increasingly, the connection has been made between manure management and long-term food security, recognizing the finite supply of easily-mined P sources that minimize its cost and therefore the cost of food (Jarvie et al., 2015). Given the large proportion of grain crops, in addition to forages, that support animal production, increases in agronomic use efficiency of manure P should not only be seen as a benefit to the farmer, but to the whole of modern society. It is in this context that the imperative exists to remove the many barriers to P-based manure management.

References

Adler, P.R., and P.L. Sibrell. 2003. Sequestration of phosphorus by acid mine drainage floc. J. Environ. Qual. 32:1122–1129. doi:10.2134/jeq2003.1122

Andraski, T.W., L.G. Bundy, and K.C. Kilian. 2003. Manure history and long-term tillage effects on phosphorus losses in runoff. J. Environ. Qual. 32:1782–1789. doi:10.2134/jeq2003.1782

Applegate, T.J., and R. Angel. 2008. Phosphorus Requirements for Poultry, Purdue Extension, Anim. Sci.-583-W. https://www.extension.purdue.edu/extmedia/as/as-583-w.pdf (Verified 9 Dec. 2018).

Baffaut, C., N.O. Nelson, J.A. Lory, G.M.M.M.A. Senaviratne, A.B. Bhandari, R.P. Udawatta, D.W. Sweeney, M.J. Helmers, M.W. Van Liew, A.P. Mallarino, and C.S. Wortmann. 2017. Multisite Evaluation of APEX for water quality: I. Best professional judgment parameterization. J. Environ. Qual. 46:1323–1331. doi:10.2134/jeq2016.06.0226

Bartelt, K.D., and W.L. Bland. 2007. Theoretical analysis of manure transport distance as a function of herd size and landscape fragmentation. J. Soil Water Conserv. 62:345–352.

Beegle, D. 2014. Nutrient management and the Chesapeake Bay. J. Contemp. Water Res. Educ. 151:3–8. doi:10.1111/j.1936-704X.2013.03146.x

Bird, S.C. and A. Drizo. 2010. EAF steel slag filters for phosphorus removal from milk parlor effluent: The effects of solids loading, alternate feeding regimes and in-series design. Water 2: 484-499. doi:10.3390/w2030484

Bolster, C.H., A. Forsberg, A. Mittelstet, D. Radcliffe, D. Storm, J. Ramirez-Avila, A.N. Sharpley, and D. Osmond. 2017. Comparing an annual and daily time-step model for predicting field-scale phosphorus loss. J. Environ. Qual. 46:1314–1322. doi:10.2134/jeq2016.04.0159

Bosch, D.J. and K.B. Napit. 1992. Economics of transporting poultry litter to achieve more efficient use as fertilizer. J Soil Water Conserv 47: 342-346.

Brandt, R.C., and H.A. Elliott. 2003. Phosphorus runoff losses from surface-applied biosolids and dairy manure. Joint Residuals and Biosolids Management Conference. Water Environmental Federation, Alexandria, VA. doi:10.2175/193864703790898477

Buda, A.R., G.F. Koopmans, R.B. Bryant, and W.J. Chardon. 2012. Emerging technologies for removing nonpoint phosphorus from surface water and groundwater: Introduction. J. Environ. Qual. 41:621–627. doi:10.2134/jeq2012.0080

Buda, A.R., P.J.A. Kleinman, R.B. Bryant, G.W. Feyereisen, D.A. Miller, P.G. Knight, and P.J. Drohan. 2013. Forecasting runoff from Pennsylvania landscapes. J. Soil Water Conserv. 68(3):185–198. doi:10.2489/jswc.68.3.185

Burcham, M., R.O. Maguire, M. Alley, W. Thomason, and B. Jones. 2008. Injecting dairy manure to decrease nitrogen and phosphorous in runoff. SERA17 Annual Conference, Grasonville, MD.

Burns, R.T., and L.B. Moody. 2002. Phosphorus recovery from animal manures using optimized struvite precipitation. Proceedings of Coagulants and Flocculants: Global Market and Technical Opportunities for Water Treatment Chemicals, Chicago, IL. 22–24 May 2002. University of Tennessee, Knoxville, TN. http://wastemgmt.ag.utk.edu/Pubs/floc%20conf%20paper.pdf (Accessed 10 Dec. 2018).

Butler, D.M., D.H. Franklin, M.L. Cabrera, A.S. Tasistro, K. Xia, and L.T. West. 2008. Evaluating aeration techniques for decreasing phosphorus export from grasslands receiving manure. J. Environ. Qual. 37:1279–1287. doi:10.2134/jeq2007.0289

Carreira, R.I., K.B. Young, H.L. Goodwin, Jr., and E.J. Wailes. 2007. How far can poultry litter go? A new technology for litter transport. J. Agric. Appl. Econ. 39:611–623. doi:10.1017/S1074070800023300

Chaperon, C.O.I., V. Girard, and Y. Chorfi. 2007. On-farm phosphorus budget: Model to predict yearly phosphorus contents in manure of dairy herds. Can. Vet. J. 87:407–411.

Choi, I.H., and P.A. Moore, Jr. 2008. Effect of various litter amendments on ammonia volatilization and nitrogen content of poultry litter. J. Appl. Poult. Res. 17:454–462. doi:10.3382/japr.2008-00012

Church, C.D., A.N. Hristov, R.B. Bryant, P.J.A. Kleinman, and S.K. Fishel. 2016. A novel treatment system to remove phosphorus from liquid manure. Appl. Eng. Agric. 32:103–112. doi:10.13031/aea.32.10999

Church, C.D., A. Hristov, R.B. Bryant, and P.J.A. Kleinman. 2017. Processes and treatment systems for treating high phosphorus containing fluids. US Patent 9790.110B2. Date issued 21 Feb.

Church, C.D., A.N. Hristov, P.J.A. Kleinman, S.K. Fishel, M.R. Reiner, and R.B. Bryant. 2018. Versatility of the MAnure PHosphorus Extraction (MAPHEX) System in removing phosphorus, odor, microbes, and alkalinity from dairy manures: A four-farm case study. Appl. Eng. Agric. 34:567–572. doi:10.13031/aea.12632

Collick, A.S., T.L. Veith, D.R. Fuka, P.J.A. Kleinman, A.R. Buda, J.L. Weld, R.B. Bryant, P.A. Vadas, M.J. White, R.D. Harmel, and Z.M. Easton. 2016. Improved simulation of edaphic and manure phosphorus loss in SWAT. J. Environ. Qual. 45:1215–1225. doi:10.2134/jeq2015.03.0135.

Cooley, E.T., M.D. Ruark, and J.C. Panuska. 2013. Tile drainage in Wisconsin: Managing tile-drained landscapes to prevent nutrient loss. Univ. Wisconsin Cooperative Extension publication GWQ064. https://fyi.extension.wisc.edu/drainage/files/2012/06/3-Managing-Tile-Drained-Landscapes-to-Prevent-Nutrient-Loss-DF.pdf (Accessed 28 Jan. 2019).

Cunningham, D.L., C.W. Ritz, and W.C. Merka. 2012. Best management practices for storing and applying poultry litter. The University of Georgia Cooperative Extension Bulletin 1230, Athens, GA. http://extension.uga.edu/publications/detail.cfm?number=B1230 (Accessed 8 Jan. 2019).

Dance, S. 2017. Maryland spends $1M a year to transport chicken litter, to the benefit of the Chesapeake and poultry companies. https://www.baltimoresun.com/features/green/blog/bs-md-manure-export-20170115-story.html (Accessed 11 Jan. 2019).

Daverede, I.C., A.N. Kravchenko, R.G. Hoeft, E.D. Nafziger, D.G. Bullock, J.J. Warren, and L.C. Gonzini. 2004. Phosphorus runoff from incorporated and surface applied liquid swine manure and phosphorus fertilizer. J. Environ. Qual. 33:1535–1544. doi:10.2134/jeq2004.1535

Delaware Code Online. 2015. Title 3–Agriculture. http://delcode.delaware.gov/title3/title3.pdf (Accessed 8 Jan. 2019).

Delaware Department of Agriculture. 2003. Nutrient management regulations. https://agriculture.delaware.gov/nutrient-management/laws-regulations/ (Accessed 27 Jan. 2019).

Dell, C.J., P.J.A. Kleinman, J.P. Schmidt, and D.B. Beegle. 2012. Low disturbance manure incorporation effects on ammonia and nitrate loss. J. Environ. Qual. 41:928–937. doi:10.2134/jeq2011.0327

Dewes, T. 1995. Nitrogen losses from manure heaps. Biol. Agric. Hortic. 11:309–317. doi:10.1080/01448765.1995.9754715

Digested Organics. 2018. Nutrient concentration and water reclamation system. Digested Organics, Farmington Hills, MI. https://www.digestedorganics.com/wp-content/uploads/2015/02/Digested-Organics-NCWR-Flow-Diagram.pdf?0ddc6c&0ddc6c (Accessed 10 Dec. 2018).

Dillaha, T.A., J.H. Sherrard, D. Lee, S. Mostaghimi, and V.O. Shanholtz. 1988. Evalution of vegetative filter strips as a best management practice for feed lots. J. Water Pollut. Control Fed. 60:1231–1238.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Tran ASABE 32: 513-519. doi:10.13031/2013.31033.

Doody, D.G., J.S. Bailey, and C.J. Watson. 2013. Evaluating the evidence-base for the Nitrate Directive regulations controlling the storage of manure in field heaps. Environ. Sci. Policy 29:137–146. doi:10.1016/j.envsci.2013.01.009

Doody, D.G., R.H. Foy, J.S. Bailey, and D. Matthews. 2012. Minimising nutrient transfers from poultry litter field heaps. Nutr. Cycling Agroecosyst. 92:79–90. doi:10.1007/s10705-011-9473-x

Dou, Z., D.T. Galligan, C.F. Ramberg, C. Meadows, and J.D. Ferguson. 2001. A survey of dairy farming in Pennsylvania: Nutrient management practices and implications. J. Dairy Sci. 84:966–973. doi:10.3168/jds.S0022-0302(01)74555-9

Dou, Z., K.F. Knowlton, R.A. Kohn, Z. Wu, L.D. Satter, G. Zhang, J.D. Toth, and J.D. Ferguson. 2002. Phosphorus characteristics of dairy feces affected by diets. J. Environ. Qual. 31:2058–2065. doi:10.2134/jeq2002.2058

Dou, Z., G.Y. Zhang, W.L. Stout, J.D. Toth, and J.D. Ferguson. 2003. Efficacy of alum and coal combustion by-products in stabilizing manure phosphorus. J. Environ. Qual. 32:1490–1497. doi:10.2134/jeq2003.1490

Drizo, A., A.C. Frost, K.A. Smith, and J. Grace. 1997. The use of constructed wetlands in phosphate and ammonium removal from wastewater. Water Sci. Technol. 35:95–102. doi:10.2166/wst.1997.0173

Easton, Z.M., P.J.A. Kleinman, A.R. Buda, M.T. Walter, N. Emberston, S. Reed, D. Goehring, P.J. Drohan, J. Lory, and A. Sharpley. 2017. Short-term forecasting tools for agricultural nutrient management. J. Environ. Qual. 46: 1257–1269. doi:10.2134/jeq2016.09.0377

EasyMining. 2018. Ash2Phos. http://www.easymining.se/our-technologies/ash2phos/ash2phos-information/ (Verified 7 Dec. 2018).

Effland, W. 2010. Report on soil information systems of the USDA Natural Resources Conservation Service. USDA-NRCS, Washington, D.C. http://www.fftc.agnet.org/library.php?func=view&id=20110809091556 (Accessed Feb 9, 2019).

Eghball, B. 2000. Nitrogen mineralization from field-applied beef cattle feedlot manure or compost. Soil Sci. Soc. Am. J. 64:2024–2030. doi:10.2136/sssaj2000.6462024x

Ehmke, T. 2014. The 4Rs of nutrient management. Crops & Soils 47(5):4–10. doi:10.2134/cs2014-47-5-1

Elliott, H.A., G.A. O'Connor, P. Lu, and S. Brinton. 2002. Influence of water treatment residuals on phosphorus solubility and leaching. J. Environ. Qual. 31:1362–1369. doi:10.2134/jeq2002.1362

Elliott, H.A., R.C. Brandt, P.J.A. Kleinman, A.N. Sharpley, and D.B. Beegle. 2006. Estimating source coefficients for phosphorus site indices. J. Environ. Qual. 35:2195–2201. doi:10.2134/jeq2006.0014

Fabian-Wheeler, E.E., M.L. Hile, D.J. Murphy, D.E. Hill, R. Meinen, H.A. Elliott, and D. Hofstetter. 2017. Operator exposure to hydrogen sulfide from dairy manure storages containing gypsum bedding. J. Agric. Saf. Health 23:9–22. doi:10.13031/jash.11563

Felton, G.K., L.E. Carr, and M.J. Habersack. 2007. Nutrient fate and transport in surface runoff from poultry litter stock piles. Trans. ASABE 50:183–192. doi:10.13031/2013.22399

Feyereisen, G.W., P.J.A. Kleinman, G.J. Folmar, L.S. Saporito, C.D. Church, T.R. Way, and A.L. Allen. 2010. Effect of direct incorporation of poultry litter on phosphorus leaching from Coastal Plain soils. J. Soil Water Conserv. 65:243–251. doi:10.2489/jswc.65.4.243

Fleming, R., and H. Fraser. 2000. Impacts of winter spreading of manure on water quality: Literature review. Ridgetown College, University of Guelph, Ridgetown, Ontario, Canada.

Franklin, D.H., M.L. Cabrera, L.T. West, V.H. Calvert, and J.A. Rema. 2007. Aerating grasslands: Effects of runoff and phosphorus losses from applied broiler manure. J. Environ. Qual. 36:208–215. doi:10.2134/jeq2006.0012

Garcia-Gonzalez, M.C., M. B. Vanotti, and A. A. Szogi. 2016. Recovery of ammonia from anaerobically digested manure using gas-permeable membranes. Scientia Agricola 73. doi:10.1590/0103-9016-2015-0159 (Accessed 11 Dec. 2018).

Genskow, K.D. 2012. Taking stock of voluntary nutrient management: Measuring and tracking change. J. Soil Water Conserv. 67:51–58. doi:10.2489/jswc.67.1.51

Ghebremichael, L.T., T.L. Veith, J.M. Hamlett, and W.J. Gburek. 2008. Precision feeding and forage management effects on phosphorus loss modeled at a watershed scale. J. Soil Water Conserv. 63:280–291. doi:10.2489/jswc.63.5.280

Giaimo, C. 2015. When the western world ran on guano. Atlas Obscura, Brooklyn, N.Y. https://www.atlasobscura.com/articles/when-the-western-world-ran-on-guano (Verified 9 Dec. 2018).

Ginting, D., J.F. Moncrief, S.C. Gupta, and S.D. Evans. 1998. Corn yield, runoff, and sediment losses from manure and tillage systems. J. Environ. Qual. 27:1396–1402. doi:10.2134/jeq1998.00472425002700060016x

Hadrich, J.C., T.M. Harrigan, and C.A. Wolf. 2010. Economic comparison of liquid manure transport and land application. Appl. Eng. Agric. 26:743–758. doi:10.13031/2013.34939

He, Z., P.H. Pagliari, and H.M. Waldrip. 2016. Applied and environmental chemistry of animal manure: A review. Pedosphere 26:779–816. doi:10.1016/S1002-0160(15)60087-X

Herron, S.L., A.N. Sharpley, S. Watkins, and M. Daniels. 2012. Poultry litter management in the Illinois River Watershed of Arkansas and Oklahoma. Fact Sheet FSA 9535. Cooperative Extension Service, Division of Agriculture, University of Arkansas, Fayettevile, AR. http://www.uaex.edu/Other_Areas/publications/PDF/FSA-9535.pdf (Accessed 26 Apr. 2019).

Holly, M., P. Kleinman, J. Baker, D. Bjorneberg, M. Boggess, R. Bryant, R. Chintala, G. Feyereisen, J. Gamble, A. Leytem, K. Reed, A. Rotz, P. Vadas, and H. Waldrip. 2018. Nutrient management challenges and opportunities across U.S. dairy farms. J. Dairy Sci. 101:6632–6641. doi:10.3168/jds.2017-13819

House, C.H., S.W. Broome, and M.T. Hoover. 1994. Treatment of nitrogen and phosphorus by a constructed upland-wetland wastewater treatment system. Water Sci. Technol. 29:177–184. doi:10.2166/wst.1994.0185

Huang, L., P.A. Moore, Jr., P.J.A. Kleinman, K.R. Elkin, M. Savin, D. Pote, and D. Edwards. 2016. Reducing phosphorus runoff and leaching from poultry litter with alum: Twenty year small plot and paired-watershed studies. J. Environ. Qual. 45:1413–1420. doi:10.2134/jeq2015.09.0482

Humer, E., C. Schwarz, and K. Schedle. 2015. Phytate in pig and poultry nutrition. J. Anim. Physiol. Anim. Nutr. 99:605–625. doi:10.1111/jpn.12258

International Plant Nutrition Institute. 2012. A Nutrient Use Information System (NuGIS) for the U.S. IPNI, Peachtree Corners, GA. http://nugis.ipni.net/About%20NuGIS/ (Verified 6 Dec. 2018).

International Plant Nutrition Institute. 2014. History of the "4Rs". Int. Plant Nutr. Inst., Peachtree Corners, GA. http://www.ipni.net/article/IPNI-3284 (Accessed 5 Jan. 2016).

Jarvie, H., A.N. Sharpley, D. Flaten, P.J.A. Kleinman, A. Jenkins, and T. Simmons. 2015. The pivotal and paradoxical role of phosphorus in a resilient water-energy-food security nexus. J. Environ. Qual. 44:1049–1062. doi:10.2134/jeq2015.01.0030

Johnson, K.N., P.J.A. Kleinman, D.B. Beegle, and H.A. Elliott. 2011. Effect of dairy manure slurry application in a no-till system on phosphorus runoff. Nutr. Cycling Agroecosyst. 90:201–212. doi:10.1007/s10705-011-9422-8

Karunanithi, R., A.A. Szogi, N. Bolan, R. Naidu, P. Loganathan, P.G. Hunt, M.B. Vanotti, C.P. Saint, Y.S. Ok, and S. Krishnamoorthy. 2015. Phosphorus recovery and reuse from waste streams. Adv. Agron. 131:173–250. doi:10.1016/bs.agron.2014.12.005

Ketterings, Q.M., K.J. Czymmek, and S.N. Swink. 2011. Evaluation methods for a combined research and extension program used to address starter phosphorus fertilizer use for corn in New York. Can. J. Soil Sci. 91:467–477. doi:10.4141/cjss10001

Ketterings, Q.M., S. Cela, A.S. Collick, S.J. Crittenden, and K.J. Czymmek. 2017. Restructuring the P Index to better address P management in New York. J. Environ. Qual. 46:1372–1379. doi:10.2134/jeq2016.05.0185

Kim, Y.J., L.D. Geohring, J.H. Jeon, A.S. Collick, S.K. Giri, and T.S. Steenhuis. 2006. Evaluation of the effectiveness of vegetative filter strips for phosphorus removal with the use of a tracer. J. Soil Water Conserv. 61:293–302.

Klausner, S.D., P.J. Zwerman, and D.F. Ellis. 1976. Nitrogen and phosphorus losses from winter disposal of dairy manure. J. Environ. Qual. 5:47–49. doi:10.2134/jeq1976.00472425000500010010x

Kleinman, P.J.A., A.M. Wolf, A.N. Sharpley, D.B. Beegle and L.S. Saporito. 2005. Survey of water extractable phosphorus in manures. Soil Sci. Soc. Am. J. 67. 701-708. doi:10.2136/sssaj2004.0099

Kleinman, P.J.A. 2017. The persistent environmental relevance of soil phosphorus sorption saturation. Curr. Pollut. Rep. 3(2):141–150. doi:10.1007/s40726-017-0058-4.

Kleinman, P.J.A., and A.N. Sharpley. 2003. Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. J. Environ. Qual. 32:1072–1081. doi:10.2134/jeq2003.1072

Kleinman, P.J.A., A.N. Sharpley, B.G. Moyer, and G.F. Elwinger. 2002. Effect of mineral and manure phosphorus sources on runoff phosphorus. J. Environ. Qual. 31:2026–2033. doi:10.2134/jeq2002.2026

Kleinman, P., D. Sullivan, A. Wolf, R. Brandt, Z. Dou, H. Elliott, J. Kovar, A. Leytem, R. Maguire, P. Moore, L. Saporito, A. Sharpley, A. Shober, T. Sims, J. Toth, G. Toor, H. Zhang, and T. Zhang. 2007. Selection of a water extractable phosphorus test for manures and biosolids as an indicator of runoff loss potential. J. Environ. Qual. 36:1357–1367. doi:10.2134/jeq2006.0450

Kleinman, P.J.A., A.N. Sharpley, L.S. Saporito, A.R. Buda, and R.B. Bryant. 2009. Application of manure to no-till soils: Phosphorus losses by sub-surface and surface pathways. Nutr. Cycling Agroecosyst. 84:215–227. doi:10.1007/s10705-008-9238-3

Kleinman, P.J.A., A.N. Sharpley, A.R. Buda, R.W. McDowell, and A.L. Allen. 2011. Soil controls of phosphorus runoff: Management barriers and opportunities. Can. J. Soil Sci. 91:329–338. doi:10.4141/cjss09106

Kleinman, P., D. Beegle, K. Saacke Blunk, K. Czymmek, R. Bryant, T. Sims, J. Shortle, J. McGrath, D. Dostie, R. Maguire, R. Meinen, Q. Ketterings, F. Coale, M. Dubin, A. Allen, K. O'Neill, M. Davis, B. Clark, K. Sellner, M. Smith, L. Garber, and L. Saporito. 2012. Managing manure for sustainable livestock production in the Chesapeake Bay Watershed. J. Soil Water Conserv. 67:54A–61A. doi:10.2489/jswc.67.2.54A

Kleinman, P.J.A., A.N. Sharpley, A.R. Buda, Z.M. Easton, J.A. Lory, D.L. Osmond, D.E. Radcliffe, N.O. Nelson, T.L. Veith, and D.G. Doody. 2017. The promise, practice, and state of planning tools to assess site vulnerability to runoff phosphorus loss. J. Environ. Qual. 46:1243–1249. doi:10.2134/jeq2017.10.0395

Knowlton, K.F., D.K. Beede, and E. Kebreab. 2010. Phosphorus and calcium utilization and requirements in farm animals. In: D. Vitti and E. Kebraib, editors, Phosphorus and calcium requirements of ruminants. CAB International. doi:10.1079/9781845936266.0112

Komiskey, M.J., T.D. Stuntebeck, D.R. Frame, and F.W. Madison. 2011. Nutrients and sediment in frozen-ground runoff from no-till fields receiving liquid-dairy and solid-beef manures. J. Soil Water Conserv. 66:303–312. doi:10.2489/jswc.66.5.303

Laflen, J.M., and M.A. Tabatabai. 1984. Nitrogen and phosphorus losses from corn-soybean rotations as affected by tillage practices. Trans. ASAE 27:58–63. doi:10.13031/2013.32735'

Lanyon, L.E. 2005. Phosphorus, animal nutrition and feeding: Overview. In: J.T. Sims and A.N. Sharpley, editors, Phosphorus: Agriculture and the environment. Agronomy Monograph. American Society of Agronomy, Madison, WI. p. 561–586.

Lemunyon, J.L., and R.G. Gilbert. 1993. The concept and need for a phosphorus assessment tool. J. Prod. Agric. 6:483–486. doi:10.2134/jpa1993.0483

Lewis, T.W., and J.C. Makarewicz. 2009. Winter application of manure on an agricultural watershed and its impact on downstream nutrient fluxes. J. Great Lakes Res. 35:43–49. doi:10.1016/j.jglr.2008.08.003

Liu, J., H. Aronsson, L. Bergström, and A.N. Sharpley. 2012. Phosphorus leaching from loamy sand and clay loam topsoils after application of pig slurry. Springerplus 1:53. doi:10.1186/2193-1801-1-53

Liu, J., P.J.A. Kleinman, D.B. Beegle, J.L. Weld, A.N. Sharpley, L.S. Saporito, and J.P. Schmidt. 2015. Phosphorus and nitrogen losses from poultry litter stacks and leaching through soils. Nutr. Cycling Agroecosyst. 103:101–114. doi:10.1007/s10705-015-9724-3

Liu, J., P.J.A. Kleinman, D.B. Beegle, C.J. Dell, T.L. Veith, L.S. Saporito, K. Hun, D.H. Pote, and R.B. Bryant. 2016. Subsurface application enhances benefits of manure redistribution. Agric. Environ. Lett. 1:150003. doi:10.2134/ael2015.09.0003

Liu, J., T.L. Veith, A.S. Collick, P.J.A. Kleinman, D.B. Beegle, and R.B. Bryant. 2017. Seasonal manure application timing and storage effects on field- and watershed-level phosphorus losses. J. Environ. Qual. 46:1403–1412. doi:10.2134/jeq2017.04.0150

Liu, J., J.T. Spargo, P.J.A. Kleinman, R. Meinen, P.A. Moore, Jr., and D.B. Beegle. 2018a. Water extractable phosphorus in livestock manures and composts: Quantities, characteristics and temporal changes. J. Environ. Qual. 47:471–479. doi:10.2134/jeq2017.12.0467

Liu, J., P.J.A. Kleinman, H. Aronsson, D. Flaten, R.W. McDowell, M. Bechmann, D.B. Beegle, T.P. Robinson, R.B. Bryant, H.B. Liu, A.N. Sharpley, and T.L. Veith. 2018b. A review of regulations and guidelines related to winter manure application. Ambio 47:657–670. doi:10.1007/s13280-018-1012-4

Livestock Water Recycling. 2018. https://www.livestockwaterrecycling.com/the-system.html (Accessed 10 Dec. 2018).

MacDonald, P. 2006. Poultry litter to power. Manure Manager, Simcoe, ON. https://www.manuremanager.com/poultry/poultry-litter-to-power-1219 (Verified 7 Dec. 2018).

MacDonald, J.M., and W.D. McBride. 2009. The transformation of U.S. livestock agriculture. Scale efficiency, and risks. U.S. Department of Agriculture Economic Research Service, Washington, D.C. www.ers.usda.giv/publications/eib43 (Accessed 28 Jan. 2019).

Magdoff, F., L. Lanyon, and W. Lieghardt. 1997. Nutrient cycling, transformations, and flows: Implications for a more sustainable agriculture. Adv. Agron. 60:1–73. doi:10.1016/S0065-2113(08)60600-8

Maguire, R.O., P.J.A. Kleinman, C. Dell, D.B. Beegle, R.C. Brandt, J.M. McGrath, and Q.M. Ketterings. 2011. Manure management in reduced tillage and grassland systems: A review. J. Environ. Qual. 40:292–301. doi:10.2134/jeq2009.0228

Manitoba Environment Act. 1998. Livestock manure and mortalities management regulation. Government of Manitoba, Winnipeg, MB. https://web2.gov.mb.ca/laws/regs/current/_pdf-regs.php?reg=42/98 (accessed 28 Jan. 2019).

Manitoba Sustainable Development. 2017. Restriction on winter application of nutrients. Province of Manitoba, Winnipeg, MB. https://www.gov.mb.ca/sd/waterstewardship/wqmz/pdf/vary_spring_nutrient_application_dates.pdf (accessed 28 Jan. 2019).

Maryland Department of Agriculture. 2012. Nutrient application requirements. Maryland Nutrient Management Manual Section 1. Nutrient recommendations. Maryland Department of Agriculture, Annapolis, MD. http://mda.maryland.gov/resource_conservation/Documents/nm_manual/1-D1-1-1D1-6.pdf (Accessed 28 Jan. 2019).

Maule, C., and J. Elliott. 2006. Effect of hog manure injection upon soil productivity and water quality. Part II. Elstow site 2000-2005. ADF Project 98000094. Saskatoon, Canada.

McDowell, R.W., A.N. Sharpley, and W. Bourke. 2008. Treatment of drainage water with industrial by-products to prevent phosphorus loss from tile-drained land. J. Environ. Qual. 37:1575–1582. doi:10.2134/jeq2007.0454

Meals, D.W. 1993. Assessing nonpoint phosphorus control in the LaPlatte River watershed. Lake Reservoir Manage. 7:197–207. doi:10.1080/07438149309354271

Midgley, A.R., and D.E. Dunklee. 1945. Fertility runoff losses from manure spread during the winter. University of Vermont, Agricultural Experiment Station Bulletin 523:1–19.

Moore, P.A., Jr., T.C. Daniel, and D.R. Edwards. 1999. Reducing phosphorus runoff and improving poultry production with alum. Poult. Sci. 78:692–698. doi:10.1093/ps/78.5.692

Moore, P.A., Jr., T.C. Daniel, and D.R. Edwards. 2000. Reducing phosphorus runoff and inhibiting ammonia loss from poultry production with alum. J. Environ. Qual. 29:37–49. doi:10.2134/jeq2000.00472425002900010006x

National Research Council. 2001. Nutrient requirements of dairy cattle: Seventh revised edition. The National Academies Press, Washington, D.C. doi:10.17226/9825

Nelson, N.O., C. Baffaut, J.A. Lory, G.M.M.M. Anomaa Senaviratne, A.B. Bhandari, R.P. Udawatta, D.W. Sweeney, M.J. Helmers, M.W. Van Liew, A.P. Mallarino, and C.S. Wortmann. 2017. Multisite evaluation of APEX for water quality: II. Regional parameterization. J. Environ. Qual. 46:1349–1356. doi:10.2134/jeq2016.07.0254

Nesme, T., and P.J.A. Withers. 2016. Sustainable strategies towards a phosphorus circular economy. Nutr. Cycling Agroecosyst. 104:259–264. doi:10.1007/s10705-016-9774-1

New York Natural Resources Conservation Service. 2013. Conservation practice standard: Nutrient management (Ac.) Code 590. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_027006.pdf (Accessed 28 Jan. 2019).

Nicholson, F., A. Rollett, and B. Chambers. 2010. Review of pollutant losses from solid manures stored in temporary field heaps. Project WT1006 Report. UK Department of Environment, Food and Rural Affairs (DEFRA), London, U.K. http://www.defra.gov.uk (Accessed 8 Jan. 2019).

North Carolina Department of Environmental Quality. 2018. DEQ Dashboard, Animal Operations-Swine Lagoons. https://deq.nc.gov/news/deq-dashboard#animal-operations—swine-lagoon-facilities (Verified 12 Dec. 2018).

Ogejo, J.A. 2009. Poultry and livestock manure storage: Management and safety. Virginia Cooperative Extension Publication 442-308, Blacksburg, VA. http://pubs.ext.vt.edu/content/dam/pubs_ext_vt_edu/442/442-308/442-308_pdf.pdf (Verified 12 Dec. 2018).

Ogejo, J.A., and E.R. Collins. 2009. Storing and handling poultry litter. Publication 442-054. Virginia Cooperative Extension, Blacksburg, VA. http://pubs.ext.vt.edu/442/442-054/442-054.html (Accessed 8 Jan. 2019).

O'Keefe, T. 2011. Baling makes poultry litter portable. WattAgNet, Rockford, IL. https://www.wattagnet.com/articles/8486-baling-makes-poultry-litter-portable (Accessed 7 Dec. 2018).

Osmond, D., C. Bolster, A. Sharpley, M. Cabrera, S. Feagley, A. Forsberg, C. Mitchell, R. Mylavarapu, J. Larry Oldham, D.E. Radcliffe, J.J. Ramirez-Alva, D.E. Storm, F. Walker, and H. Zhang. 2017. Southern Phosphorus Indices, water quality data, and modeling (APEX, APLE, and TBET) results: A comparison. J. Environ. Qual. doi:10.2134/jeq2016.05.0200

Penn, C.J., I. Chagas, A. Klimeski, and G. Lyngsie. 2017. A review of phosphorus removal structures: How to assess and compare their performance. Water 9:583. doi:10.3390/w9080583

Pennsylvania Code. 2005. Act 38 Nutrient Management Regulations. Penn State Extension, College Station, PA. http://extension.psu.edu/plants/nutrient-management/act-38/act-38-nutrient-management-regulations (Accessed 28 Jan. 2019).

Pennsylvania Department of Environmental Protection. 2011. Land application of manure: A supplementary to manure management for environmental protection. Manure Management Plan Guidance 361-0300-002. http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-86014/361-0300-002%20combined.pdf (Accessed 8 Jan. 2019).

Phillips, P.A., J.L.B. Culley, F.R. Hore, and N.K. Patni. 1981. Pollution potential and corn yields from selected rates and timing of liquid manure applications. Trans. ASAE 24:139–144. doi:10.13031/2013.34213

Pipkin, W. 2017. Perdue turns to composting to get more poultry waste off farm fields. Ches. Bay J. https://www.bayjournal.com/article/perdue_builds_compost_facility_to_get_more_poultry_waste_off_farm_fields (Accessed 7 Dec. 2018).

Plaizier, J.C., G. Legesse, K. Ominiski, and D. Flaten. 2014. Whole-farm budgets of phosphorus and potassium on dairy farms in Manitoba. Can. J. Anim. Sci. 94:119–128. doi:10.4141/cjas2013-089

Potter, P., N. Ramankutty, E.M. Bennett, S.D. Donner. 2010. Characterizing the spatial patterns of global fertilizer application and manure production. Earth Interactions 14: 1-21. doi:10.1175/2009EI288.1

Preusch, P.L., P.R. Adler, L.J. Sikora, and T.J. Tworkoski. 2002. Nitrogen and phosphorus availability in composted and uncomposted poultry litter. J. Environ. Qual. 31:2051–2057. doi:10.2134/jeq2002.2051

Pries, J., and P. McGarry. 2002. Feedlot stormwater runoff treatment using constructed wetlands. Archive of Agri-Environmental Programs in Ontario, Ottawa, ON. http://agrienvarchive.ca/bioenergy/download/WEAO_2001_Pries.pdf (Verified 20 Dec. 2018).

Qin, Z., A. Shober, K.G. Scheckel, C.J. Penn and K.C. Turner. 2018. Mechanisms of phosphorus removal by phosphorus sorbing materials. J. Environ Qual 47: doi:10.2134/jeq2018.02.0064

Radcliffe, D.E., D.K. Reid, K. Blomback, C.H. Bolster, A.S. Collick, Z.M. Easton, W. Francesconi, D.R. Fuka, H. Johnsson, K. King, M. Larsbo, M.A. Youssef, A.S. Mulkey, N.O. Nelson, K. Persson, J.J. Ramirez-Alva, F. Schmieder, and D.R. Smith. 2015. Applicability of models to predict phosphorus losses in drainage fields: A review. J. Environ. Qual. 44:614–628. doi:10.2134/jeq2014.05.0220

Ramirez-Avila, J.J., S.L. Ortega-Achury, and W.H. McAnally. 2012. Application of the APEX model to determine water quality assessments in agricultural fields in the Mississippi Delta. Research Report. Geosyst. Res. Inst., Mississippi State Univ. Starkville, MS.

Ramirez-Avila, J.J., D.E. Radcliffe, D. Osmond, C. Bolster, A. Sharpley, S.L. Ortega-Achury, A. Forsberg, and J.L. Oldham. 2017. Evaluation of the APEX model to simulate runoff quality from agricultural fields in the southern region of the United States. J. Environ. Qual. 46:1357–1364. doi:10.2134/jeq2017.07.0258

Rasnake, M., T. Pescatore, and D. Overhults. 1995. Proper handling and storage of poultry litter. University of Kentucky Poultry Extension. http://www2.ca.uky.edu/agc/pubs/id/id117/id117.htm (Accessed 9 Jan. 2019).

Ribaudo, M., N. Gollehon, M. Aillery, J. Kaplan, R. Agapoff, L. Christensen, V. Breneman, and M. Peters. 2003. Manure management for water quality: Costs of animal feeding operations of applying nutrients to land. Agricultural Economic Report 824. USDA Economic Research Service, Washington, D.C.

Ross, I.J., J.P. Sizemore, J.P. Bowden, and C.T. Haan. 1979. Quality of runoff from land receiving surface application and injection of liquid dairy manure. Trans. ASAE 22:1055–1062. doi:10.2134/jeq2015.09.0498

Rotz, C.A. 2004. Management to reduce nitrogen losses in animal production. J. Anim. Sci. 82(E. Suppl.): E119–E137. doi:10.2527/2004.8213_supplE119x

Rotz, C.A., A.N. Sharpley, L.D. Satter, W.J. Gburek, and M.A. Sanderson. 2002. Production and feeding strategies for phosphorus management on dairy farms. J. Dairy Sci. 85:3142–3153. doi:10.3168/jds.S0022-0302(02)74402-0

Ruark, M.D., J.C. Panuska, E.T. Cooley, and J. Pagel. 2009. Tile drainage in Wisconsin: Understanding and locating tile drainage systems. University of Wisconsin Extension publication GWQ054. University of Wisconsin-Madison, Madison, WI. http://learningstore.uwex.edu/Assets/pdfs/GWQ054.pdf (Accessed 28 Jan. 2019).

Schwarcz, J. 2017. England's coprolite rush had big effect on world. McGill University Office for Science and Society Newsletter, Montreal, QC. https://www.mcgill.ca/oss/article/environment-health-history-quirky-science/joe-schwarcz-englands-coprolite-rush-had-big-effect-world (Verified 8 Dec. 2018).

Schwer, C.B., and J.C. Clausen. 1989. Vegetative filter treatment of dairy milkhouse waste water. J. Environ. Qual. 18:446–451. doi:10.2134/jeq1989.00472425001800040008x

Shah, S.B., J.L. Miller, and T.J. Basden. 2004. Mechanical aeration and liquid dairy manure application impacts on grassland runoff water quality and yield. Trans. ASAE 47:777–788. doi:10.13031/2013.16109

Sharpley, A.N., T. Daniel, T. Sims, J. Lemunyon, R. Stevens, and R. Parry. 2003a. Agricultural phosphorus and eutrophication, 2nd ed. ARS–149. U.S. Department of Agriculture, Agricultural Research Service, Washington, D.C.

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, Jr., and G. Mullins. 2003b. Development of phosphorus indices for nutrient management planning strategies in the U.S. J. Soil Water Conserv. 58:137–152.

Sharpley, A., H.P. Jarvie, A. Buda, L. May, and P. Kleinman. 2013. Phosphorus legacy: Overcoming the effects of past management practices to mitigate future water quality impairment. J. Environ. Qual. 42:1308–1326. doi:10.2134/jeq2013.03.0098

Sharpley, A., P. Kleinman, C. Baffaut, D. Beegle, C. Bolster, A. Collick, Z. Easton, J. Lory, N. Nelson, D. Osmond, D. Radcliffe, T. Veith, and J. Weld. 2017. Evaluation of phosphorus site assessment tools: Lessons from the USA. J. Environ. Qual. 46:1250–1256. doi:10.2134/jeq2016.11.0427

Sharpley, A., H. Jarvie, D. Flaten, and P. Kleinman. 2018. Celebrating the 350th anniversary of phosphorus discovery: A conundrum of deficiency and excess. J. Environ. Qual. 47:774–777. doi:10.2134/jeq2018.05.0170

Shober, A.L., A.R. Buda, K.C. Turner, N.M. Fiorellino, A.S. Andres, J.M. McGrath, and J.T. Sims. 2017. Assessing coastal plain risk indices for subsurface phosphorus loss. J. Environ. Qual. 46:1270–1286. doi:10.2134/jeq2017.03.0102

Smith, D.R., P.A. Moore, Jr., C.V. Maxwell, B.E. Haggard, and T.C. Daniel. 2004. Reducing phosphorus runoff from swine manure with dietary phytase and aluminum chloride. J. Environ. Qual. 33:1048–1054. doi:10.2134/jeq2004.1048

Soberon, M., Q. Ketterings, K. Czymmek, S. Cela, and C. Rasmussen. 2015. Whole farm nutrient mass balance calculator for New York dairy farms. Cornell Field Crops newsletter. http://blogs.cornell.edu/whatscroppingup/2015/03/25/whole-farm-nutrient-mass-balance-calculator-for-new-york-dairy-farms/ (Verified 6 Dec. 2018).

Sommer, S.G. 2001. Effect of composting on nutrient loss and nitrogen availability of cattle deep litter. Eur. J. Agron. 14:123–133. doi:10.1016/S1161-0301(00)00087-3

Srinivasan, M.S., R.B. Bryant, M.P. Callahan, and J.L. Weld. 2006. Manure management and nutrient loss under winter conditions: A literature review. J. Soil Water Conserv. 61:200–209.

Steenhuis, T.S., G.D. Bubenzer, J.C. Converse, and M.F. Walter. 1981. Winter-spread manure nitrogen loss. Trans. ASAE 24(2):436–441. doi:10.13031/2013.34270

Stock, M.N., F.J. Arriaga, P.V. Vadas, and K.G. Karthikeyan. 2019. Manure application timing drives energy absorption for snowmelt on an agricultural soil. J. Hydrol. 569:51–60. doi:10.1016/j.jhydrol.2018.11.028

Strokal, M., L. Ma, Z. Bai, S. Luan, C. Kroeze, O. Oenema, G. Velthof, and F. Zhang. 2016. Alarming nutrient pollution of Chinese rivers as a result of agricultural transitions. Environ. Res. Lett. 11:024014. doi:10.1088/1748-9326/11/2/024014

Syers, J.K., A.E. Johnston, and D. Curtin. 2008. Efficiency of soil and fertilizer phosphorus use: Reconciling changing concepts of soil phosphorus behaviour with agronomic information. U.N. Food and Agriculture Organization Plant Nutrition Bulletin 18. http://www.fao.org/3/a-a1595e.pdf (Verified 10 Jan. 2019).

Sylvester, P. 2007. Poultry manure field stockpiling. University of Delaware Kent County Cooperative Extension, Dover, DE. http://extension.udel.edu/kentagextension/2007/11/27/poultry-manure-field-stockpiling/ (Accessed 8 Jan. 2019).

Tarkalson, D.D., and R.L. Mikkelsen. 2003. A phosphorus budget of a poultry farm and a dairy farm in the Southeastern U.S. and the potential impacts of diet alterations. Nutr. Cycl. Agroecosyst. 66:295–303. doi:10.1023/A:1024435909139

Toor, G.S., B.J. Cade-Menun, and J.T. Sims. 2005a. Establishing a linkage between phosphorus forms in dairy diets, feces, and manures. J. Environ. Qual. 34:1380–1391. doi:10.2134/jeq2004.0232

Toor, G.S., J.T. Sims, and Z. Dou. 2005b. Reducing phosphorus in dairy diets improves farm nutrient balances and decreases the risk of nonpoint pollution of surface and ground waters. Agric. Ecosyst. Environ. 105:401–411. doi:10.1016/j.agee.2004.06.003

Torres, C. 2010. Oregon dairy organics opens its doors to the public. Lancaster Farmer, Ephrata, PA. https://www.lancasterfarming.com/news/main_edition/oregon-dairy-organics-opens-its-doors-to-the-public/article_02bc642b-5d12-53c8-ad38-bbd907cf70b4.html (Verified 7 Dec. 2018).

U.S. Environmental Protection Agency. 2007. Restoration and protection activities in the Upper Branch of the Delaware River protects New York City's drinking water supply. Section 319 nonpoint source protection success story: New York. U.S. Environmental Protection Agency, Washington, D.C. https://www.epa.gov/sites/production/files/2015-11/documents/ny_wbde.pdf (Verified 19 Dec. 2018).

U.S. Environmental Protection Agency. 2015. Dane County Community Digester–Waunakee, WI. U.S. Environmental Protection Agency, Washington, D.C. https://www.epa.gov/sites/production/files/2016-05/documents/dane_county_agstar_site_profile_final_508_093015.pdf (Verified 7 Dec. 2018).

Uutiset. 2018. Finland to probe potential of cattle manure for energy production. Uutiset, 10 July. https://yle.fi/uutiset/osasto/news/finland_to_probe_potential_of_cattle_manure_for_energy_production/10297989 (Verified 7 Dec. 2018).

Vadas, P.A., P.J.A. Kleinman, and A.N. Sharpley. 2004. A simple method to predict dissolved phosphorus in runoff from surface applied manures. J. Environ. Qual. 33:749–756. doi:10.2134/jeq2004.7490

Vadas, P.A., L.W. Good, P.A. Moore, Jr., and N. Widman. 2009. Estimating phosphorus loss in runoff from manure and fertilizer for a phosphorus loss quantification tool. J. Environ. Qual. 38:1645–1653. doi:10.2134/jeq2008.0337

Vadas, P.A., L.W. Good, W.E. Jokela, K.G. Karthikeyan, F.J. Arriaga, and M. Stock. 2017. Quantifying the impact of seasonal and short-term manure application decisions on phosphorus loss in surface runoff. J. Environ. Qual. 46:1395–1402. doi:10.2134/jeq2016.06.0220

Vadas, P.A., M.N. Stock, G.W. Feyereisen, F.J. Arriaga, L.W. Good, and K.G. Karthikeyan. 2018. Temperature and manure placement in a snowpack affect nutrient release from dairy manure during snowmelt. J. Environ. Qual. 47:848–855. doi:10.2134/jeq2017.12.0464

Van Horn, H.H., A.C. Wilkie, W.J. Powers, and R.A. Nordstedt. 1994. Components of dairy manure management systems. J. Dairy Sci. 77:2008–2030. doi:10.3168/jds.S0022-0302(94)77147-2

Van Vliet, L.J.P., S. Bittman, G. Derksen, and C.G. Kowalenko. 2006. Aerating grassland before manure application reduces runoff nutrient loads in a high rainfall environment. J. Environ. Qual. 35:903–911. doi:10.2134/jeq2005.0266

Vanotti, M.B., A.A. Szogi, and P.G. Hunt. 2005. Wastewater treatment system. U.S. Patent 6893,567 B1. Date issued: 17 May.

Vanotti, M.B., A.A. Szogi, and L.M. Fetterman. 2010. Wastewater treatment system with simultaneous separation of phosphorus and manure solids. U.S. Patent 7674,379 B2. Issued 25 Dec.

Vohla, C., M. Koiv, H.J. Bavor, F. Chazarenc, and U. Mander. 2011. Filter materials for phosphorus removal from wastewater in treatment wetlands– A review. Ecol. Eng. 37:70–89. doi:10.1016/j.ecoleng.2009.08.003

Waldrip, H.M., Z. He, and S. Erich. 2010. Effects of poultry manure amendment on phosphorus uptake by ryegrass, soil phosphorus fractions and phosphatase activity. Biol. Fertil. Soils. doi:10.1007/s00374-011-0546-4

Walker, W.W., Jr. 1987. Phosphorus removal by urban runoff detention basins. Lake Reserv. Manage. 3:314–326. doi:10.1080/07438148709354787

Washington State University. 2018. Livestock nutrient management: Struvite extraction. Washington State University, Pullman, WA. https://puyallup.wsu.edu/lnm/struvite-extraction/ (Accessed 11 Dec. 2018).

White, M.J., D.E. Storm, P. Busteed, M.D. Smolen, H. Zhang, and G. Fox. 2010. A quantitative phosphorus loss assessment tool for agricultural fields. Environ. Model. Softw. 25:1121–1129. doi:10.1016/j.envsoft.2010.03.017

Williams, M.R., G.W. Feyereisen, D.B. Beegle, and R.D. Shannon. 2012. Soil temperature regulates phosphorus loss from lysimeters following fall and winter manure application. Trans. ASABE 55:871–880. doi:10.13031/2013.41529

Williams, M.R., G.W. Feyereisen, D.B. Beegle, R.D. Shannon, G.J. Folmar, and R.B. Bryant. 2011. Manure application under winter conditions: Nutrient runoff and leaching losses. Trans. ASABE 54:891–899. doi:10.13031/2013.37114

Withers, P.J.A., S.D. Clay, and V.G. Breeze. 2001. Phosphorus transfer in runoff following application of fertilizer, manure and sewage sludge. J. Environ. Qual. 30:180–188. doi:10.2134/jeq2001.301180x

Wright, P., J.L. Rennells, A.T. DeGaetano, and C. Gooch. 2013. Impacts of climate change in the Northeast on manure storage. Waste to worth: Spreading science and solutions, Denver, CO. 1-5 Apr. 2013. Livestock and Poultry Environmental Learning Community, University of Nebraska, Lincoln, NE. https://articles.extension.org/pages/67643/impacts-of-changing-climate-in-the-northeast-on-manure-storage (Verified 12 Dec. 2018).

Xin, H., R.S. Gates, A.R. Green, F.M. Mitloehner, P.A. Moore, Jr., and C.M. Wathes. 2011. Environmental impacts and sustainability of egg production systems. Poult. Sci. 90:263–277. doi:10.3382/ps.2010-00877

Yanke, L.J., H.D. Bae, L.B. Selinger, and K.J. Cheng. 1998. Phytase activity of anaerobic ruminal bacteria. Microbiology 144:1565–1573. doi:10.1099/00221287-144-6-1565

Young, R.A., and C.K. Mutchler. 1976. Pollution potential of manure spread on frozen ground. J. Environ. Qual. 5:174–179. doi:10.2134/jeq1976.00472425000500020013x

Young, R.A., and R.F. Holt. 1977. Winter applied manure: Effects of annual runoff, erosion, and nutrient movement. J. Soil Water Conserv. 32:219–222.

Young, R.A., T. Hutrods, and W. Anderson. 1980. Effectiveness of vegetative buffer strips in controlling pollution from feedlot runoff. J. Environ. Qual. 9:483–487. doi:10.2134/jeq1980.00472425000900030032x

Yuan, Y., M.A. Locke, R.L. Bingner, and R.A. Rebich. 2013. Phosphorus losses from agricultural watersheds in the MS delta. J. Environ. Manage. 115:14–20. doi:10.1016/j.jenvman.2012.10.028

Zebarth, B.J., J.W. Paul, and K. Chipperfield. 1999. Nutrient losses to soil from field storage of solid poultry manure. Can. J. Soil Sci. 79:183–190. doi:10.4141/S98-050