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Opportunities to implement manureshed management in the Iowa, North Carolina, and Pennsylvania swine industry

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Abstract

The U.S. swine industry is diverse, but opportunities exist to strategically improve manure management, especially given much of the industry's vertical integration. We investigate opportunities for improving manureshed management, using swine production examples in Iowa, North Carolina, and Pennsylvania as a lens into historical trends and the current range of management conditions. Manure management reflects regional differences and the specialized nature of hog farms, resulting in a large range of land bases required to assimilate manure generated by these operations. Selected representative farm scenarios were evaluated on an annual basis; farm-level manuresheds were largest for Pennsylvania sow farms and smallest for North Carolina nursery farms. Compared with nitrogen-based manuresheds, phosphorus-based manuresheds were up to 12.5 times larger. Technology advancements are needed to promote export of concentrated nutrients, especially phosphorus, from existing "source" manuresheds to suitable croplands. The industry is dynamic, as revealed by historical analysis of the siting of hog barns in Pennsylvania, which are currently trending toward the north and west where there is greater isolation to prevent the spread of disease and a larger land base to assimilate manure. Industry expansion should focus on locating animals in nutrient "sink" areas.

1 | INTRODUCTION

Manure management is a central component of swine production, influenced by integration of the industry, physiographic constraints, and the characteristics of individual farm operations. To address concerns ranging from animal health and welfare to off-site nutrient losses, manure management must simultaneously consider a suite of economically viable environmental and production goals. Importantly, manure management can challenge swine operations, from public opposition to siting of swine facilities (e.g., Coleman et al., 2018), to catastrophic impacts of hurricanes on lagoons that affect ecosystem health (e.g., NCDEQ, 2018). Consequently, continual evolution of manure management strategies and tactics are crucial as the U.S. swine industry moves forward.

Abbreviation: MAPHEX, MAnure PHosphorus EXtraction.

The accumulation of nutrients on swine operations and in regions where swine farms are concentrated is well documented (Novak et al., 2000). Here we explore the manureshed at the farm-level scale as introduced by Saha et al. (2018) as well as implications at a larger scale, defined by Spiegal et al. (2020) as a local or regional geographic area surrounding one or more livestock and poultry operations where excess manure nutrients can be recycled for agricultural production. These manuresheds are generally defined by the excess phosphorus (P) generated by farms and the capacity of surrounding croplands to use that P. Although nitrogen (N) and P in manure may both exceed the amount required by crops on swine operations, Spiegal et al. (2020) observed that P excess was the primary concern for counties where swine farms predominate, and in counties with excess N from swine manure, P was also found in excess.

Manuresheds occur at varying scales, from farm to region; the former is more readily addressed by individual producers, whereas the latter requires engagement of industry, government, and other stakeholders. Although every state in the United States has commercial swine operations (USDA National Agricultural Statistics Service [USDA-NASS], 2017), major regional manuresheds are found primarily in the Midwest and Southeast. The states with the greatest number of swine in large operations (over 1,000 head) are Iowa, North Carolina, and Minnesota. These three states housed 55% of the swine in large operations in 2017, and the 10 highest hog-producing states supported 87% of the nation's production (USDA-NASS, 2017). Although expansion continues in many states across the country, growth in North Carolina has been limited since a 1997 moratorium on construction or expansion of swine farms was implemented (General Assembly of North Carolina, 1997). From 1997 to 2017, the U.S. hog inventory increased 133%, whereas the North Carolina inventory declined slightly to 92% of the 1997 inventory. During that same period, hog inventories increased by 157% in Iowa, 150% in Minnesota, and 113% in Pennsylvania (USDA-NASS, 2017).

We seek to elucidate opportunities and challenges of manureshed management in the U.S. swine industry. Following a description of national, local, and farm contexts, we assess key swine manureshed variables. We then focus on case studies to illuminate the dynamic nature of the swine industry (and hence its shifting nutrient footprint) and the role that manure management plays in siting new operations. Comparisons to integrated poultry production are used to highlight strategically important manureshed connections between the industries. We also cover how, despite the challenges of relocating hog manure to areas of high nutrient demand, opportunities do exist to adjust on-farm manure management as well as to integrate manureshed concepts into the long-term expansion of the hog industry.

Core Ideas

- Vertical integration of U.S. swine production offers advantages for manureshed management.
- Swine manuresheds vary by region and phase of production (sow, nursery, finisher).
- Swine manuresheds can favorably shift with nutrient relocation and smart expansion.
- Manuresheds are dynamic, as highlighted by Pennsylvania's swine and poultry industries.
- Manure treatment that extracts phosphorus provides opportunity for manureshed management.

2 | SWINE MANURE SOURCES OF P AND N IN THE UNITED STATES

The method used by Spiegal et al. (2020) for conducting a national assessment of P and N sources and sinks identified manure nutrient source counties by animal type. Using those data, a national assessment of P and N sources from the swine industry in aggregate is shown in Figure 1, where swine production is concentrated in the Midwest and North Carolina.

3 | MODERN SWINE FARMS AND THEIR MANURESHEDS

The modern commercial swine industry is generally vertically integrated, supporting highly specialized farm operations that raise hogs at different stages in their life cycle. Historic expansion and integration of the swine industry began in the 1960s, accelerated in the late 1990s, and continues today. Driven by improvements in animal health, increased growth efficiencies, economies of scale, and attainment of favorable returns in commodity markets, these changes included major facility design modifications so that high concentrations of animals could be raised in environmentally controlled, well-ventilated buildings designed for hogs at specific growth stages (Moeller & León Crespo, 2009). Additional benefits are realized with focused labor, specialized equipment, proximity to corn and soybean supplies, and sophisticated feed rations that are specifically designed to meet the requirements at the hog's particular phase of production and stage of growth.

Today's swine industry is complex, with many variations in farm characteristics that reflect the individuality of local markets, production, and environmental factors. Even so, it is useful to delineate the major categories of farms to

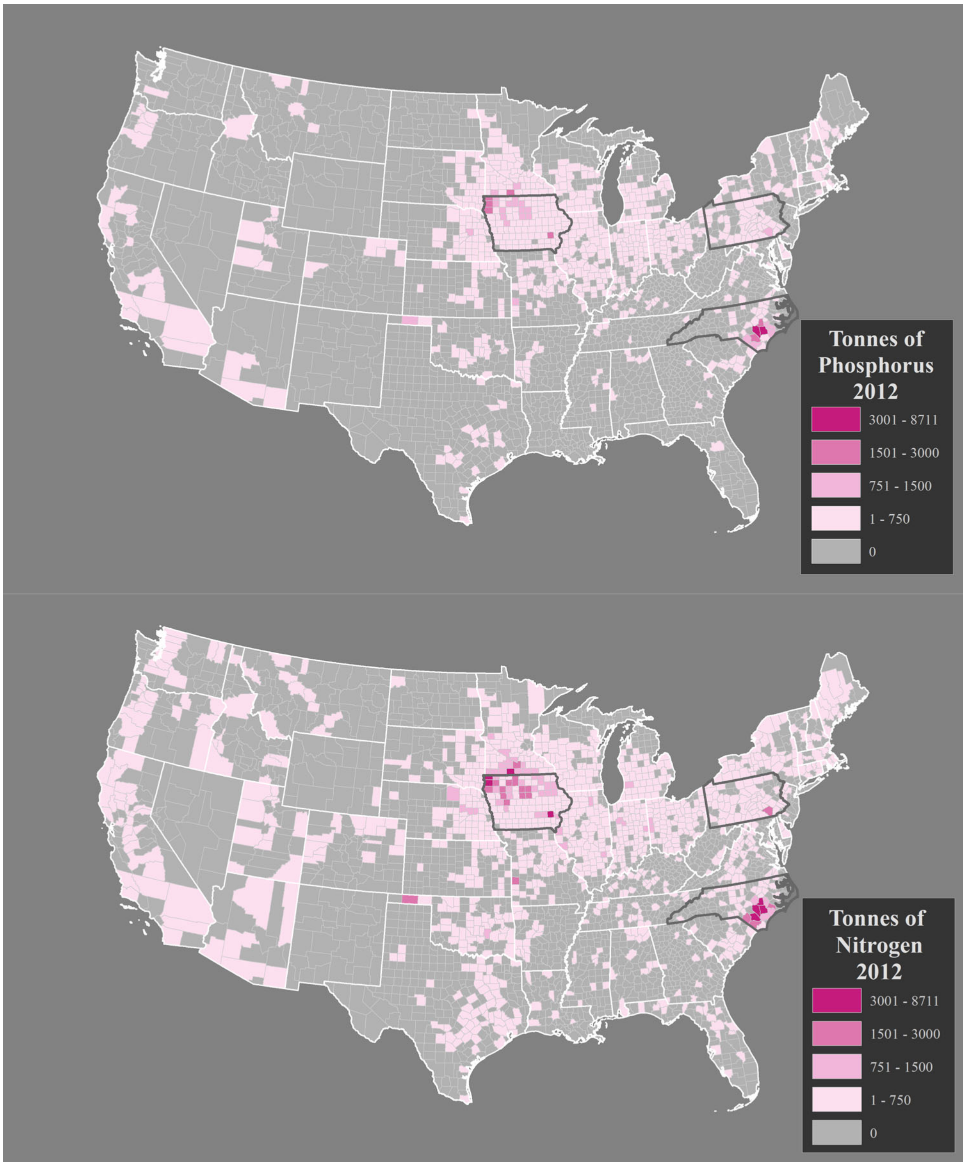

FIGURE 1 Manure P and N from the swine industry in counties across the United States. Obtained by collecting county-level inventory and sales data for Total Hogs from the 2012 United States Census of Agriculture (USDA-NASS, 2014) and applying calculation methods from Kellogg et al. (2014) and Spiegal et al. (2020) to transform inventory to recoverable manure nutrients. Recoverable manure nutrients are those available for use after accounting for losses from collection, spillage, volatilization (N only), and denitrification (N only) in swine systems. States of Iowa, North Carolina, and Pennsylvania are highlighted with black borders

understand how the industry is organized and the potential for manureshed management within existing operations (Estienne et al., 2016; Janni & Cortus, 2019; USDA-NASS, 2017). Here we use three emblematic production scenarios.

1. Farrow-to-wean sow farms: Breeding sow (181–227 kg) productivity dramatically influences manuresheds associated with the swine industry. Due to improved genetics and management, the average number of pigs weaned per litter has increased from 7.36 in 1970 to 11.00 in 2020, and the average sow now produces 22.2 piglets per year, compared with only 10.9 piglets total per year in 1970 (USDA-NASS, 2021). After farrowing (giving birth), sows nurse litters on site for about 21 d, at which time the piglets are weaned and sent to nursery farms. Sows repeat the farrowing cycle as quickly as 140 d and stay on these farms for up to 4 yr.
2. Nursery farms: Weaned piglets are raised on nursery farms from 21 d to 10 wk. During this time, the weight of nursery pigs increases from an average of 6 to 26 kg, and they leave the nursery as “feeder pigs.”
3. Finisher farm: Feeder pigs are moved to a finisher farm where they are raised to market weight at about 26 wk of age. During this final stage, they increase from 26-kg

feeder hogs to 129-kg finished hogs and are moved to a harvest facility (slaughter plant) as “market hogs.”

Modern swine facilities concentrate nutrients because of the import of feed and therefore often have manuresheds that extend beyond the farmgate. However, the industry structure that distributes growing pigs, and their associated nutrients, to new farm locations does assist in manureshed distribution. Using state-specific farm characteristics for swine manure generation and typical manure application and cropping scenarios in that state, we portray differences in manuresheds between swine operations and between three states, Iowa, North Carolina, and Pennsylvania (Table 1; see Supplement S1 for additional information on calculations).

Although many various farm-level manure-handling systems exist in practice, here we describe manure storage and handling practices that exemplify modern swine farms. Manure management on Iowa and Pennsylvania farms follow the common pattern of swine confinement farms in northern latitudes of the United States. Contemporary swine production units in these two states typically store manure in deep pits under fully slatted floors for nursery, finish, and wean-to-finish buildings. Older farms in these states may hold manure in secure outdoor storages. The manure storage systems are emptied one or more times annually when liquid manure is applied to croplands according to state-approved nutrient management plans. In Iowa, manure injection application equipment is widely used to reduce odor and maximize the value of manure nutrients through reduced N volatilization. In Pennsylvania manure is most commonly surface applied.

In contrast, swine farms in North Carolina and the southern United States house animals in systems with shallow underfloor pits that are flushed several times daily to move manure from the barn into outdoor anaerobic lagoon systems. Lagoons are much larger in volume than storages found in northern latitudes. Lagoons are managed to allow distinct stratification of liquid manure layers that form due to anaerobic microbial degradation of manure, long hydraulic retention times, and gravity. The surface layer of liquid manure in a lagoon is very low in solid and nutrient contents (referred to as “liquid” or “supernatant”), and the bottom layer of manure includes settled solids (“sludge”) and nutrients. Supernatant is typically removed for land application annually, whereas sludge may accumulate for 15–25 yr, until it occupies 50% of the lagoon storage capacity (Owusu-Twum & Sharara, 2020; Westerman & Rice, 2008). Thus, manure in a single lagoon is often managed as two separate components and on very different time scales.

The manure management strategies used in the northern and southern United States lead to very different land requirements to balance swine manure application with crop nutrient demand. Table 1 uses representative contemporary live animal inventories of 5,000 animals at sow farms and 2,000 animals at nursery and finisher farms that were deemed emblematic for each production scenario and chosen for demonstrative purposes. The table uses these inventories in conjunction with representative state-specific swine manure characteristics and cropping scenarios to derive farm-level manureshed sizes based on both N and P, as explained in Supplement S1. Table 1 demonstrates that sow farms in all three states require more land for balanced nutrient utilization than other swine production phases because present-day sow farms often contain high numbers of larger animals and are continuously occupied. This may mean that farrow-to-wean sow farms are more likely to export manure nutrients to balance crop demand on lands not owned or controlled by the producer.

Even within single operations, different manures result in different manuresheds. In lagoon systems, N/P ratio changes are driven by losses of organic and ammonium N fractions from the overlying liquid manure and concentration of P in the settled sludge (Hawkins et al., 2016). Data for North Carolina lagoon systems are divided into liquid and sludge components in Table 1. The table highlights that N loss through volatilization during long-term storage and application decreases land needs for N-based manuresheds in North Carolina compared with Iowa and Pennsylvania. For P, land needs are also lower in North Carolina on an annual basis; however, accumulated settled sludge in lagoons present challenges. For instance, sludge removed after 15–25 yr would significantly multiply the land base needed at the time of sludge application. High demand for N and P in the chosen cropping scenario also contributes to lower manureshed requirements in North Carolina.

Manure application differences contribute to the disparity in ammonia volatilization losses and in manureshed areas between the states. Nitrogen conservation is greatest during application in Iowa, where knife injection conserves 98% of applied N in the field (IA MMP, 2021), and lowest in Pennsylvania, where only 20% of surface-applied manure N is available to the corn crop (Penn State Extension, 2019).

Conservation of N during injection application assists in a more favorable balance between P and N across manuresheds, as demonstrated with the lower ratios between P-based and N-based land requirements in Iowa compared with Pennsylvania. Although the P/N ratio of swine manures varies widely (Estienne et al., 2016; Kleinman et al., 2005), over the long term, N-based application of most swine manures results in an accumulation of P in cropland soils. Phosphorus-based manuresheds are universally larger than N-based manuresheds. The high ratio between P-based and N-based manuresheds highlights the need to cooperatively manage the two nutrients.

TABLE 1 Manure and manureshed characteristics of typical swine farms in Iowa, North Carolina, and Pennsylvania

		Typical hog manure quality			N		P	Typical farm				P/N
Production phase	Manure storage and handling	Solids	Total N	P_2O_5	Crop type and N requirement	Manure N availability factor	Crop P requirement	Animals	Manure produced at typical farm per year	N-based manureshed	P-based manureshed	Ratio of P-based to N-based manureshed size
		%	–kg 1,000 L^{-1}–		kg ha^{-1}		kg ha^{-1}		L	–ha–		
Iowa												
Farrow-to-wean (sows and litters)	underfloor or outdoor storage (liquid)	1.68	3.24	2.76	corn grain, 257	0.98	69	5,000	15,196,775	187.19	610.17	3.26
Wean-to-feeder (nursery)	underfloor storage (liquid)	3.50	4.19	2.40	corn grain, 257	0.98	69	2,000	552,610	8.82	19.29	2.19
Feeder-to-finish (finisher)	underfloor storage (liquid)	3.50	5.99	5.03	corn grain, 257	0.98	69	2,000	3,315,660	75.63	243.10	3.21
North Carolina												
Farrow-to-wean (sows and litters)	anaerobic lagoon (liquid)	0.37	0.29	0.11	bermudagrass, 336	0.5	90	5,000	60,616,775	52.02	72.91	1.40
	anaerobic lagoon (sludge)	10.00	2.44	3.67	Bermudagrass, 336	0.5	90	5,000	1,476,150	10.77 (annually)	60.37 (annually)	5.61
Wean-to-feeder (nursery)	anaerobic lagoon (liquid)	0.37	0.43	0.17	Bermudagrass, 336	0.5	90	2,000	1,445,870	1.86	2.71	1.45

(Continues)

TABLE 1 (Continued)

		Typical hog manure quality			N		P	Typical farm				P/N
Production phase	Manure storage and handling	Solids	Total N	P_2O_5	Crop type and N requirement	Manure N availability factor	Crop P requirement	Animals	Manure produced at typical farm per year	N-based manureshed	P-based manureshed	Ratio of P-based to N-based manureshed size
	anaerobic lagoon (sludge)	10.00	2.44	3.67	Bermudagrass, 336	0.5	90	2,000	50,719	0.37 (annually)	2.07 (annually)	5.61
Feeder-to-finish (finisher)	anaerobic lagoon (liquid)	0.37	0.43	0.17	Bermudagrass, 336	0.5	90	2,000	7,017,390	9.03	13.13	1.45
	anaerobic lagoon (sludge)	10.00	2.44	3.67	Bermudagrass, 336	0.5	90	2,000	249,810	1.82 (annually)	10.22 (annually)	5.61
Pennsylvania												
Farrow-to-wean (sows and litters)	underfloor or outdoor storage (liquid)	2.50	2.16	2.16	corn grain, 161	0.2	65	5,000	34,192,744	91.40	1,142.47	12.50
Wean-to-feeder (nursery)	underfloor storage (liquid)	1.50	2.28	0.96	corn grain, 161	0.2	65	2,000	1,353,895	3.82	20.11	5.26
Feeder-to-finish (finisher)	underfloor storage (liquid)	4.00	3.71	2.88	corn grain, 161	0.2	65	2,000	3,171,981	14.60	141.31	9.68

4 | ANIMAL WELFARE, SOCIAL FORCES, AND NUTRIENT MANAGEMENT CONSIDERATIONS INFLUENCE SWINE AND POULTRY MANURESHEDS

In recent years, the Pennsylvania swine industry has co-evolved with the poultry industry. From 2002 to 2017, the hog industry both increased and consolidated: the number of hogs sold increased 130% to 5.5 million, whereas the number of farms declined from 3,785 to 2,878 (76%). During that time span, the number of broilers sold and the number of poultry broiler operations increased from 133 million to 184 million (139%) and from 1,231 to 1,568 (127%), respectively (USDA-NASS, 2017). These historic shifts demonstrate increased farm size and subsequent concentration of animals and nutrients. Between 2007 and 2017, ~84% of statewide swine inventory was found on farms with herds exceeding 2,000 pigs (Shortle et al., 2020).

The interaction of swine and poultry industries, as depicted in odor assessments used to assist with siting of new facility construction, illustrates key facets of the two industries' ability to reach the goals of sustainable manureshed management. Today, most new construction of swine facilities is to the north and west of the traditional, southeastern area of animal concentrations, whereas new poultry facilities continue to be built in the areas where swine is less likely to expand (Figure 2; Supplement S2). A primary driver of this real estate contrast is the short transportation distance of animals required by the poultry industry, whereas hogs are commonly transported longer distances, as evidenced by the location of the harvest facilities of the integrators with the highest participation in the odor site assessments relative to rearing facilities (Figure 2b). The swine harvest facility is in the far southeast corner of the state, far from new swine farm locations, whereas the poultry harvest facility is centrally located to new poultry farms (marked with stars in Figure 2b). There is a substantial manure management consideration in the new construction decisions. Whereas poultry litter is dry (<30% moisture), most swine manures are liquid (>94% moisture, Table 1). In fact, poultry litters in southeastern Pennsylvania may travel long distances (e.g., to New York or eastern Pennsylvania's mushroom industry) due to a developed manure brokering industry that works across many farms (Meinen et al., 2020). Thus, poultry nutrient placement shifts occur by moving manure, whereas swine nutrient shifts are influenced by placing new farms where nutrients are locally deficient.

Contemporary expansion of facilities in the Pennsylvania swine industry is often driven by vertically integrated companies emphasizing animal health as a priority by seeking farm locations that are isolated from other swine facilities to enhance efficiencies that high herd health status provides to production. Additionally, movement of the Pennsylvania swine industry to rural areas with lower densities of human populations assists with the industry's objective to avoid odor conflict with neighbors, thus suggesting that social forces also shape manuresheds.

Swine integrators also seek producers who have a need for manure nutrients because such producers are likely to be better stewards of nutrient resources. Because producers often acquire significant financial debt to construct the building, having manure nutrients to offset commercial fertilizer purchases is a great benefit during the years that the farm maintains mortgage payments. Producer desires to replace commercial fertilizers provide opportunity to distribute swine manure close to local cropland manureshed sinks. This is demonstrated in the midwestern United States. Many sow farms from other states ship young pigs to Iowa, where highly productive lands require nutrient inputs. In 2019, 35.8 million feeder hogs were imported into Iowa, with over 1,000,000 of the hogs coming from each of 10 different states (Iowa Pork, 2020). Such infrastructure can distribute manure nutrients into sink areas, and future expansion should consider this important facet.

In areas of Pennsylvania that can act as a manure sink, soil test P is typically low, and soils are more likely to accept manure based on balanced N application rates. Because animal densities in these areas are lower, there is opportunity to apply manure at lower rates across more acres and reap higher aggregate agronomic benefits. Increased adoption of N-conserving technologies, such as manure injection in Pennsylvania, or P-removal technologies, such as those highlighted below, provide opportunity to enhance manureshed characteristics.

5 | TREATING MANURE TO PROMOTE OFF-FARM EXPORT AND MANURESHED MANAGEMENT

Export of swine manure more than a few miles off-farm is hampered by the pervasive generation of liquid manure with dilute nutrient concentrations relative to transport weight. Although manure lagoons generate heavier sludges that accumulate for up to 20 yr or more, the remaining fraction of nutrients in the liquid manure may still be applied at N-based rates that lead to accumulation of P in soils over time. A growing number of options—some established, some in pilot-phase—now exist to concentrate nutrients to support manure nutrient redistribution, and we highlight two recently developed technologies here (Figure 3).

In South Carolina, Vanotti et al. (2005, 2010) developed a full-scale, two-stage system (Figure 3a) for a swine production facility that can treat raw swine manure and could be readily adapted to treat manure supernatant as well. This system uses a nitrification bioreactor to reduce carbonate and ammonium

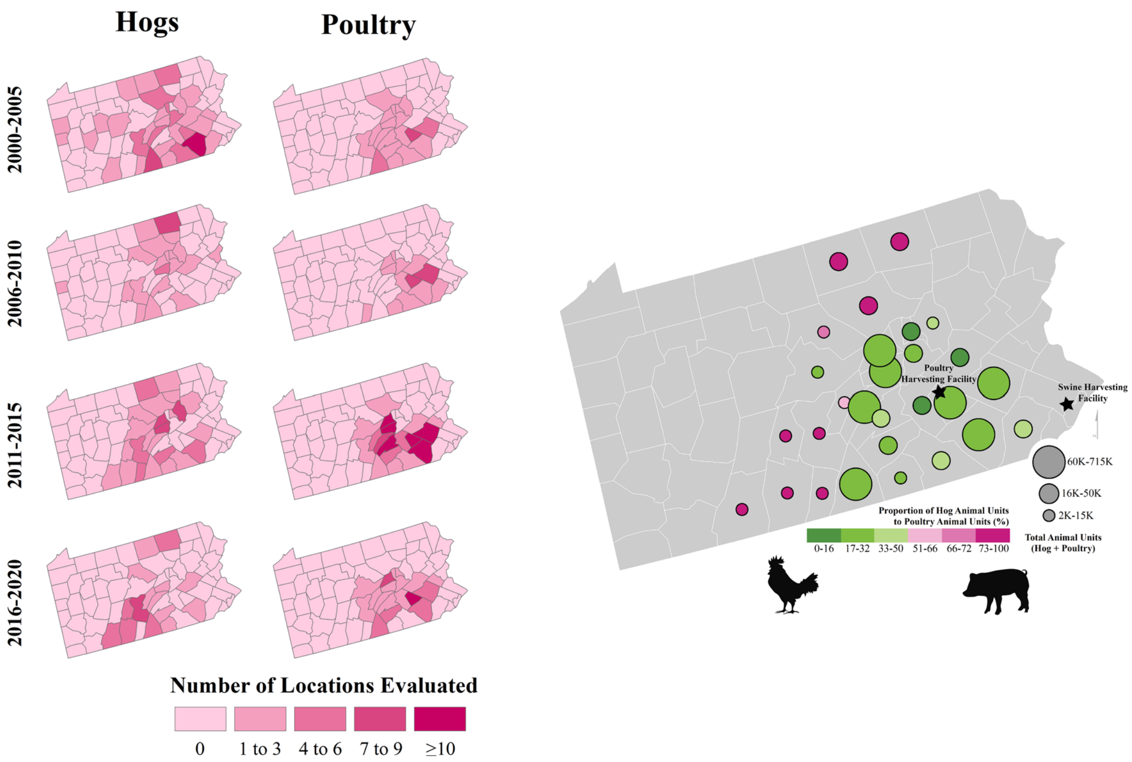

FIGURE 2 Siting and inventory locations by county for Pennsylvania's swine and poultry industries. (a) Farm locations of Penn State University's Odor Site Evaluations, by Pennsylvania county, 2000–2020. Two initial assessments conducted in 1999 were moved to the year 2000 for continuity in this graphic. Details of the Odor Site Evaluation Service are outlined in Supplemental 2. (b) Location of animal units (453 kg live weight) of swine and poultry in Pennsylvania counties (USDA-NASS, 2017), associated with swine and poultry-harvesting facilities. Size of the circle represents the total number of swine-poultry animal units; the color represents the relative contribution of swine vs. poultry. Only counties where the combined swine-poultry animal units totaled 2,000 or more in 2017 were included. The star in the southeast corner of the state is the location of a hog processor, and the more centrally located star is the location of a poultry processor. Both processors participated heavily in the Odor Site Evaluations depicted in (a)

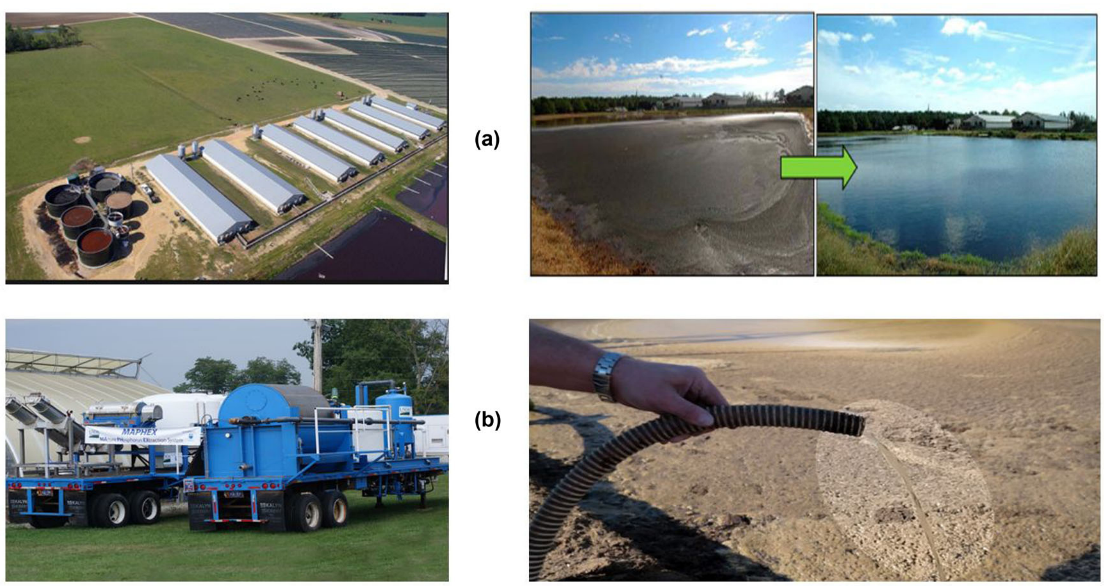

FIGURE 3 Swine manure treatment systems. (a) The South Carolina $Ca(OH)_2$ precipitation system, showing the treatment system (round tanks) beside swine manure barns and the before and after results of swine manure treatment. (b) The Pennsylvania Manure Phosphorus Extraction (MAPHEX) System, showing the mobile treatment system and the before (manure pit, background) and after (hose effluent, foreground) results of manure treatment. (Photos compliments of USDA-ARS)

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 (Garcia-Gonzales et al., 2016; Karunanithi et al., 2015).

In Pennsylvania, Church et al. (2020) showed that the MAnure PHosphorus EXtraction (MAPHEX) System (Figure 3b) removes >96% of the P from a wide range of swine manures. The essentially P-free effluent from this system can be beneficially used for fertigation of N and potassium (K) without further loading the receiving soils with P. Testing of MAPHEX with dairy manure suggests that this system is also effective in eliminating odors and pathogens (Church et al., 2018).

One contrast between the South Carolina and MAPHEX systems is that the South Carolina system promotes volatilization of N, whereas the MAPHEX System retains over 90% of the N in the liquid phase. However, both systems generate manure solids that can be (a) economically transported off-site to enable movement around or out of the manureshed; (b) sold to organic farmers or the nursery and mushroom industries; (c) composted, pelleted, and sold in garden centers; or even (d) used as a feedstock for energy generation.

6 | THE POTENTIAL TO IMPLEMENT MANURESHED MANAGEMENT

The swine industry continues to expand with placement of liquid manure systems that often create local surplus manure nutrient balances. Ideally, future migration of manure nutrients from source to sink areas, and subsequent favorable shifts of swine manureshed configurations, result from actions that fall into two broad categories: (a) nutrient (especially P) relocation out of existing manuresheds and (b) encouragement of smart and careful expansion that places new animals and manure nutrients into existing sink areas. Careful planning within the swine industry can shift manuresheds based on nutrient balances, animal health, and public acceptance but should also consider co-existing animal industries and dynamics of combined species manuresheds. Conservation of N can lead to more balanced ratios of crop nutrient demands and manure nutrient content, but this does increase the cropland area needed to accept the manure nutrients.

Although this paper focused largely on Iowa, North Carolina, and Pennsylvania as case studies of swine manuresheds, the outlined concepts are applicable across the United States. Industry-wide similarities are numerous, including availability of animal genetics, feed ration development goals, animal housing models, and management strategies. In-house manure management is also comparable across the industry, with manure contained in one of two broad storage categories (i.e., lagoon and non-lagoon storage) until it is land-applied (Janni & Cortus, 2019). Management in the commodity swine industry is often driven by cumulative small efficiencies that differentiate profitable and nonprofitable operations. Expansion to new locations is carefully evaluated and must prove profitable for both integrators and contracted farmers. The greater disbursement of swine farm expansion in the Pennsylvania case study demonstrates that the industry is already proactively shifting manure nutrients from source to sink areas. The distance that hogs can be transported has limits imposed by economics, animal welfare, and product quality. Similarly, transportation distances of feed to the animals are a key economic consideration. To this end, relocation of feed milling capacity to nutrient sink areas is a strategy that could influence locations of new farms in both the swine and poultry industries.

Opportunities exist to remedy swine manure challenges. These include development of economically viable manure treatment systems that extract P from manure for transportation to lands where the nutrient is needed for crop production. If such treatment systems assist in odor abatement, industry adoption may be accelerated. Increased efficiencies in nutrient utilization through feed formulation, feed nutrient accessibility to the animal, and genetic improvement of animals can also assist in manureshed challenges. Often, innovations in these areas are spearheaded by the industry itself. However, governmental agencies and university researchers must maintain partnerships with the industry to assure industry advancements strive toward the goals of all interests.

Manure treatment and lagoon systems that remove P or separate P into different manure streams can affect land application aspects within manuresheds. When manures have lower P content, the N/P ratios (Table 1) better match crop requirements, leading to slower accumulation of soil P and lower land area demand to achieve balanced nutrient application. When by-product solids or sludges from these systems are land applied, special planning considerations can help direct the nutrient dense manure fraction to cropland where need is high, or loss risk is low. Favorable scenarios may include lands that have low soil test P, are far from environmentally sensitive features, have shallow slopes, have ample ground cover, contain cover crops, contain double cropping rotations, or will be rotated into an unfertilized legume in future seasons so that extra applied P can be assimilated into future crops. It may be economically practical to transport these P-packed manure fractions longer distances to lands that do not receive routine manure application. In this manner, the high-P manure is moved to a nutrient sink area beyond the border of the farm's local manureshed.

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Robert J. Meinen: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing-original draft; Writing-review & editing. Sheri Spiegal: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing-original draft; Writing-review & editing. Peter J. A. Kleinman: Conceptualization; Data curation; Funding acquisition; Investigation; Methodology; Resources; Supervision; Validation; Visualization; Writing-original draft; Writing-review & editing. K. Colton Flynn: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing-original draft; Writing-review & editing. Sarah C. Goslee: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing-original draft; Writing-review & editing. Robert E. Mikesell: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing-original draft; Writing-review & editing. Clinton Church: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Validation; Visualization; Writing-original draft; Writing-review & editing. Ray B. Bryant: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing-original draft; Writing-review & editing. Mark Boggess: Visualization; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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