CARD Policy Brief
Iowa State University
Center for Agricultural and Rural Development

October 2024
24-PB 43

Economic Benefits of Swine Manure: Regional Differences and Opportunities

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Published by the Center for Agricultural and Rural Development, 578 Heady Hall, Iowa State University, Ames, Iowa 50011-1070; Phone: (515) 294-1183; Fax: (515) 294-6336; Web site: www.card.iastate.edu.

Acknowledgements
This project was supported by the National Pork Board grant, A Systems-Approach to Understanding the Nutrient Cycle Across the Pork Ecosystem.

Executive Summary

Commercial fertilizer prices increased dramatically from 2020 to 2022 and remain at elevated levels compared to the last decade. Manure, a co-product of livestock and poultry production, is a substitute for commercial fertilizer. Its characteristics vary by species and production practices. Swine manure has a higher nutrient availability than cattle and poultry manures, making it attractive as a fertilizer. Opportunities for fertilizer and non-fertilizer use depend on local crop production and storage method. Hence, a regional analysis of business cases is warranted. Regions are adopted to conform to ongoing water quality initiatives. Using publicly available data from the United States Department of Agriculture's 2022 Census of Agriculture, we evaluate three business cases for swine manure for each region. These include cost savings from use as fertilizer, sale as manure or manure products, and reduced greenhouse gas emissions. Operations with commercial swine production are most likely to benefit from cost savings through same-farm fertilizer use. Operations with smaller-scale production may benefit from local sale of manure for high value or organic crops. Anaerobic digestion can be cost effective at commercial scale or with subsidies.

Commercial fertilizer prices were two to four times higher in 2022 than in 2020 (Crespi et al. 2022). Comparing the US Department of Agriculture (USDA) biweekly Iowa Production Cost Report, published jointly by the Agricultural Marketing Service Livestock, Poultry and Grain Market News and the Iowa Department of Ag Market News, the last two weeks of May 2022 and May 2020 show a 222% increase in anhydrous ammonia, a 150% increase for urea, a 185% increase for liquid nitrogen (32%), a 154% increase in monoammonium phosphate (11-52-0), and a 146% increase for potash (red) (0-0-60).[1]

When input prices rise, farmers look for lower cost, often imperfect, substitutes. One such substitute for commercial fertilizer is swine manure, which can offer both economic and environmental benefits for users and help alleviate pressures on the commercial fertilizer market (Fleming et al. 1998; Honeyman 1991; Huffstutter et al. 2022). Swine production and, hence, manure production varies by location in the United States. The structure of the swine industry and its manure management practices have evolved over time (Key et al. 2011). Our goal is to provide, within the limitations of current knowledge, an economic assessment of the use of swine manure as a fertilizer (cost savings), the potential sale of fertilizer products, and the potential value greenhouse gas (GHG) reductions could have based on further development of carbon markets. Within this assessment, we consider nutrient losses from runoff, leaching, and volatilization, and returns to manure use as a fertilizer.

Manure is a co-product of raising livestock and poultry and has various characteristics depending on facility type, species, diet, and a host of other factors. Once thought of as a waste product, it has become valuable as a fertilizer (Andersen 2017). There are three types of manure: lagoon liquid, slurry liquid, and semi-dry or dry. These types are differentiated by moisture content and collection method. For cattle and hogs raised in confinement, manure is either siphoned off to a lagoon (lagoon liquid) or kept in a pit (slurry liquid). Poultry and open-lot cattle produce semi-dry and dry manure, often referred to as solid manure (Lim et al. 2023). Data from the Crop Production Practices report of the United States Department of Agriculture's 2010 Agricultural Resource Management Survey shows that 30% of corn acres in surveyed states were fertilized with slurry liquid, 46% were fertilized with semi-dry or dry manure, and 24% were fertilized with lagoon liquid.[2]

Manure uses fall broadly into fertilizer and non-fertilizer uses. When used as fertilizer, application methods are different for each manure type with varying types of equipment employed. Common methods include surface application, with or without incorporation; subsurface application; spraying through irrigation systems; and side-dressing. Absorption, volatilization, and runoff differ for each method. Surface applications are the most common and require the least-specialized equipment. For all crops in the United States, the largest share of manure used as fertilizer, 78%, is applied to crops owned by the animal producer. Manure purchased for application to crops is next at 14%. Finally, 8% of manure is given away, and producers pay to dispose less than 1% of manure (Lim et al. 2023). Non-fertilizer uses of manure include energy production and fiber products (Lim et al. 2023). Application in the spring is preferred in the Midwest to maximize nutrient retention (TeBockhorst and Andersen 2022).

First-year nutrient availabilities for each animal type and manure category are provided in table 1 (Sawyer and Mallarino 2016). These values do not account for losses due to volatilization or application method. First-year availability is highest for swine manure, whether from a pit or lagoon. Both poultry and cattle manure provide substantially less nitrogen, while phosphorus and potassium availability are similar to swine manure.

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1 This report contains production costs for fertilizer, propane, and farm diesel in the state of Iowa. It can be accessed at https://mymarketnews.ams.usda.gov/viewReport/2863.

2 This report contains information on the agricultural uses of manure, manure sources, application methods, and a variety of related topics. It is a tailored report, accessible at https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

Table 1. First-year Nutrient Availability for Animal Type and Manure Category

Species	Type	Nitrogen	Phosphorus	Potassium
Pig	Liquid	90-100%	90-100%	90-100%
Cattle	Liquid or solid	30-50%	80-100%	90-100%
Poultry	Solid	50-60%	90-100%	90-100%

Source: Sawyer and Mallarino (2016).
Notes: This table presents first-year nutrient availability percentages for livestock and poultry manure types. It does not account for volatilization. “Liquid” refers to liquid from lagoons, not settled solids.

In addition to nutrient availability, swine manure is desirable as a fertilizer for its soil and environmental benefits. Xia et al. (2017) find, in a meta-analysis, that substituting manure for commercial fertilizer can increase yields and decrease nitrogen losses due to volatilization, leaching, and runoff. Simultaneously, they find that manure application can increase soil organic carbon in upland fields, creating a carbon sink. In a separate literature review, Yost et al. (2022) find that manure can increase soil organic carbon, micronutrients, and resistance to compaction. Both studies note, however, that benefits to soil health are conditional on the chemical properties of the applied manure and soil. An opposing line of research, summarized by Lim et al. (2022), report potential environmental challenges from manure application, including volatilization, overapplication, nutrient imbalance, and GHG emissions. Manure management practices have evolved to offset some methane emissions (United States Environmental Protection Agency 2022). To summarize, potential benefits and challenges of manure use as fertilizer depend on agronomic conditions, which in turn vary throughout the United States.

Animal and Crop Production in the United States

A complete analysis of the opportunities for swine manure requires examining livestock and crop production on a region-by-region basis. Ten swine production regions are adopted from Matlock et al. (2014) and shown in figure 1. In contrast with the USDA Economic Research Service’s Farm Resource Regions (Heimlich 2000), which are based on geographic specialization in commodity production, regions from Matlock et al. (2014) are designed to study water use in swine production.

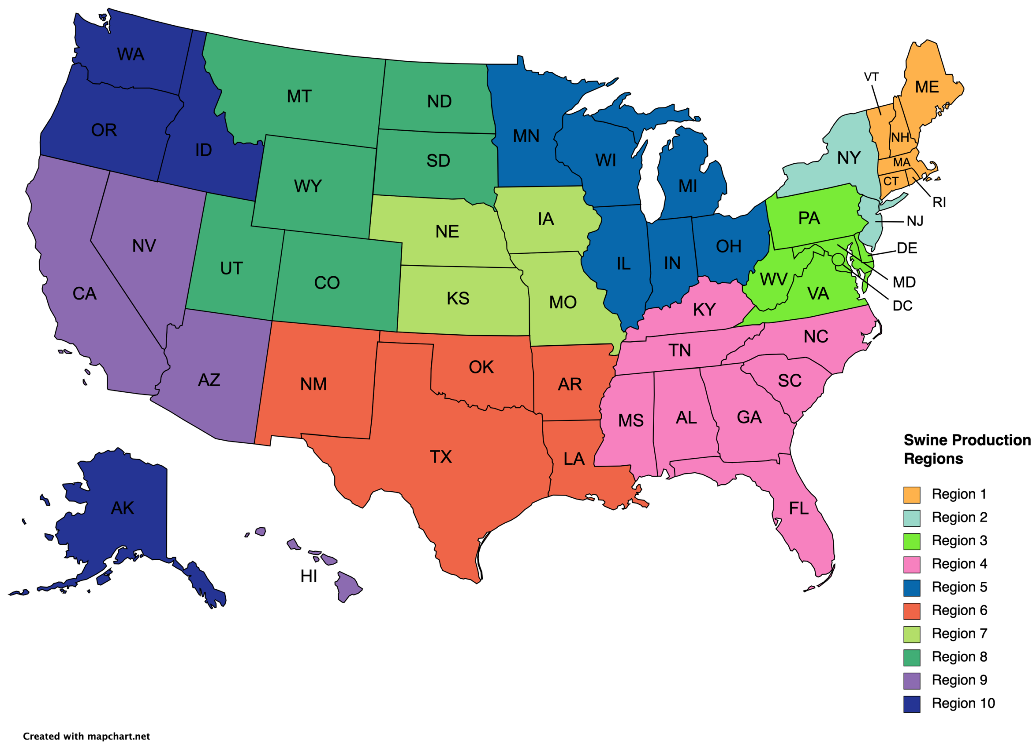

Figure 1. Swine production regions in the United States.
Source: Matlock et al. (2014).
Notes: Image generated with mapchart.com.

Manure's use as a fertilizer is contingent on the proximity of livestock to field crops. Atlas maps from the USDA 2017 Census of Agriculture correlate the locations of commercial crop and livestock production.[3] Figures 2, 3, and 4 display inventories of hogs and pigs, cattle and calves, and broilers. Note that hog and pig production is concentrated in the Corn Belt, but large inventories also exist in Pennsylvania, North Carolina, and the Texas-Oklahoma panhandle. Cattle are ubiquitous, and broilers are primarily produced in the southeast, with concentrated production in other states.

[3] Ag Atlas Maps from the 2022 Census of Agriculture were not available at the time of writing.

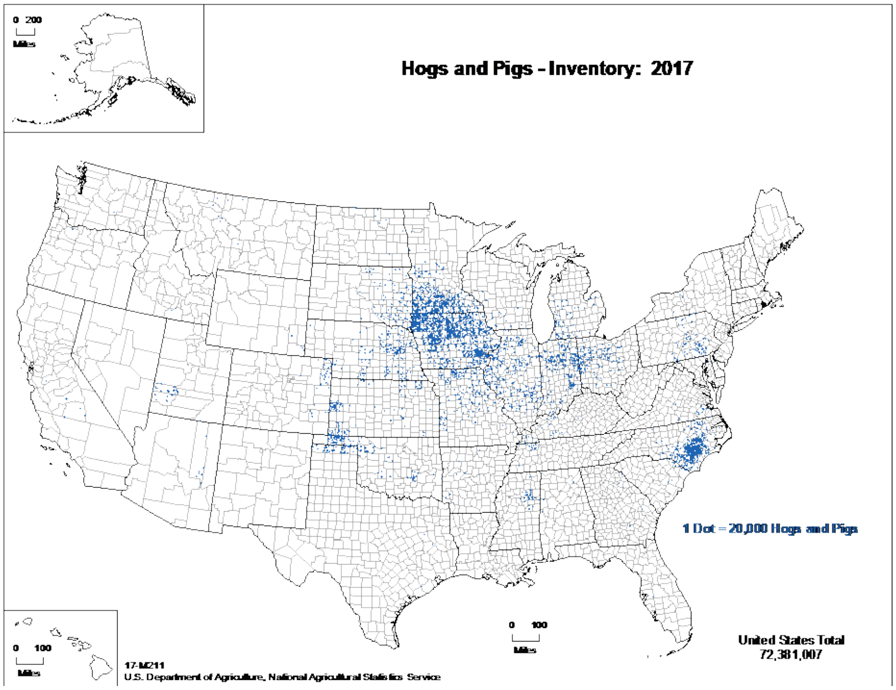

Figure 2. Hog and pig inventory, 2017.
Source: US Department of Agriculture, National Agricultural Statistics Service. 2017 Census of Agriculture.
Notes: Each dot represents 20,000 hogs and pigs. Inventory taken as of December 31, 2017.

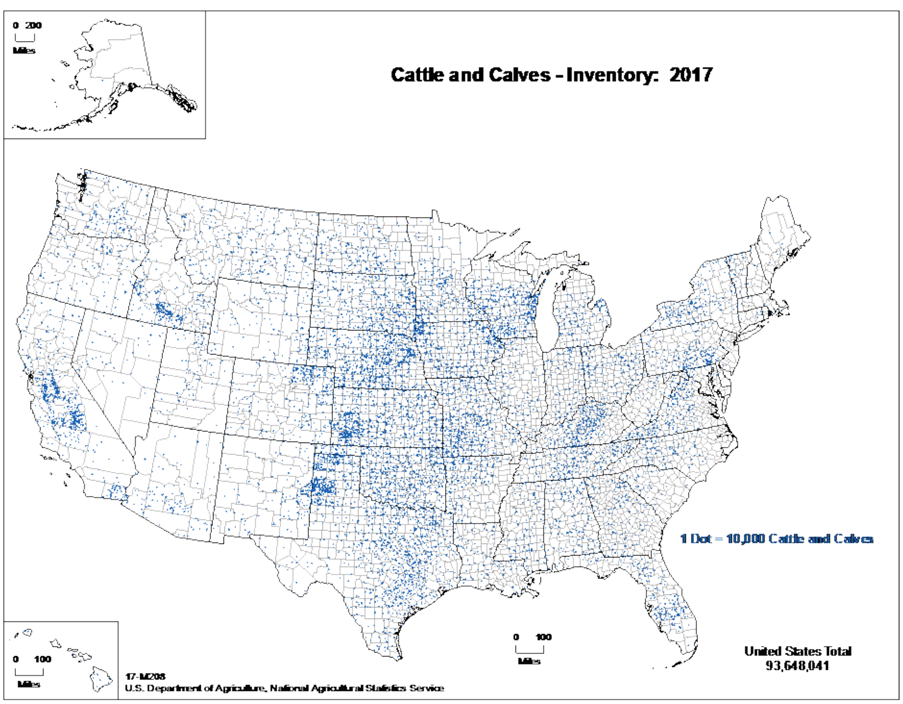

Figure 3. Cattle and calf inventory, 2017.
Source: US Department of Agriculture, National Agricultural Statistics Service. 2017 Census of Agriculture.
Notes: Each dot represents 10,000 cattle and calves. Inventory taken as of December 31, 2017.

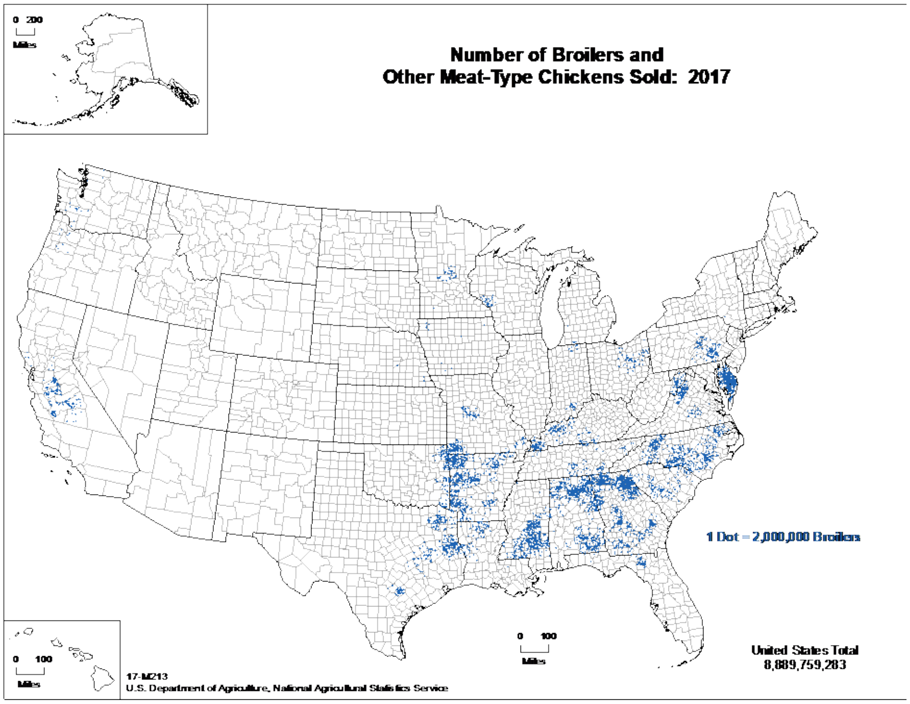

Figure 4. Broilers sold, 2017.
Source: US Department of Agriculture, National Agricultural Statistics Service. 2017 Census of Agriculture.
Notes: Each dot represents 2,000,000 broilers. Sales for entire year ending December 31, 2017.

Figures 5, 6, 7, and 8 present the location of corn, soybeans, wheat, and cotton, which are the most common crops fertilized with manure. MacDonald et al. (2009) note that the primary drivers of manure use as fertilizer are crops' agronomic needs and transportation costs. Since transportation costs are relatively high, manure is typically applied close to where livestock are produced. For instance, corn is heavily concentrated in the Corn Belt and has the largest overlap with swine production. Soybeans are similarly located with many acres harvested along the lower Mississippi River plain. Wheat is primarily located in the Plains and overlaps with beef cattle production. Cotton is dispersed among southern states and overlaps with broilers and some swine production.

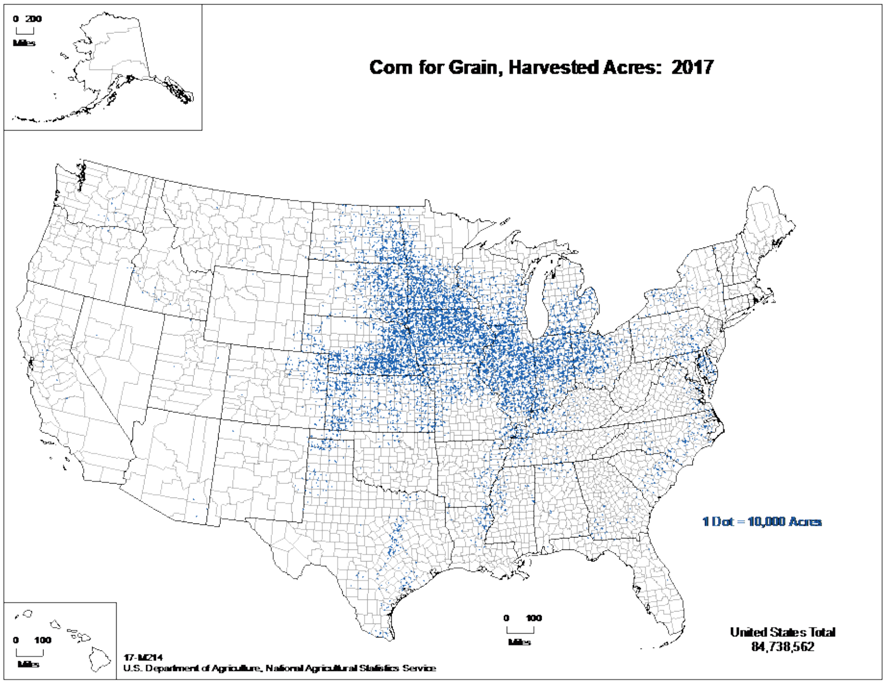

Figure 5. Corn acres harvested, 2017.
Source: US Department of Agriculture, National Agricultural Statistics Service. 2017 Census of Agriculture.
Notes: Each dot represents 10,000 acres. Harvested acres for entire year ending December 31, 2017.

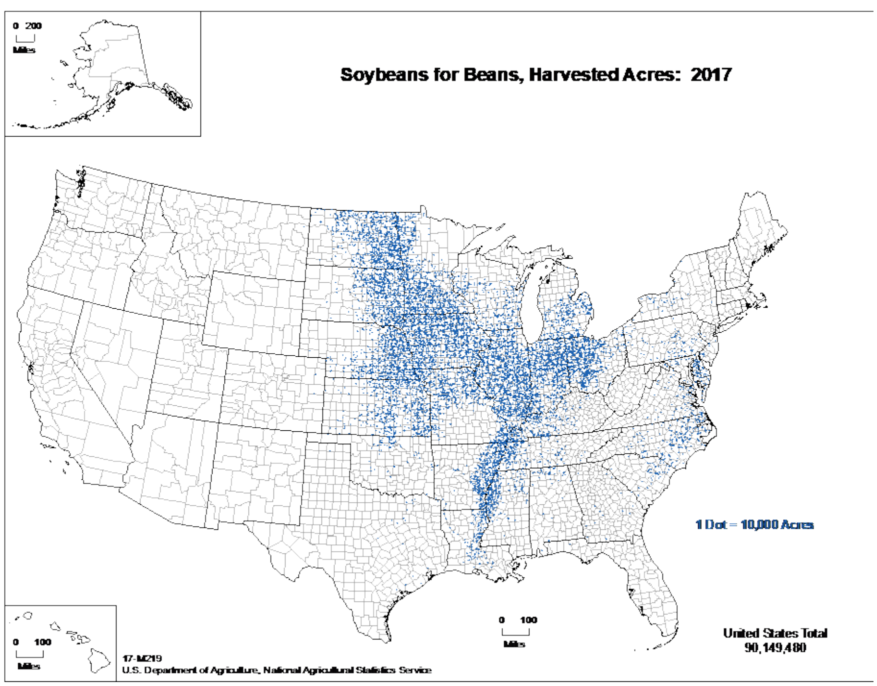

Figure 6. Soybean acres harvested, 2017.
Source: US Department of Agriculture, National Agricultural Statistics Service. 2017 Census of Agriculture.
Notes: Each dot represents 10,000 acres. Harvested acres for entire year ending December 31, 2017.

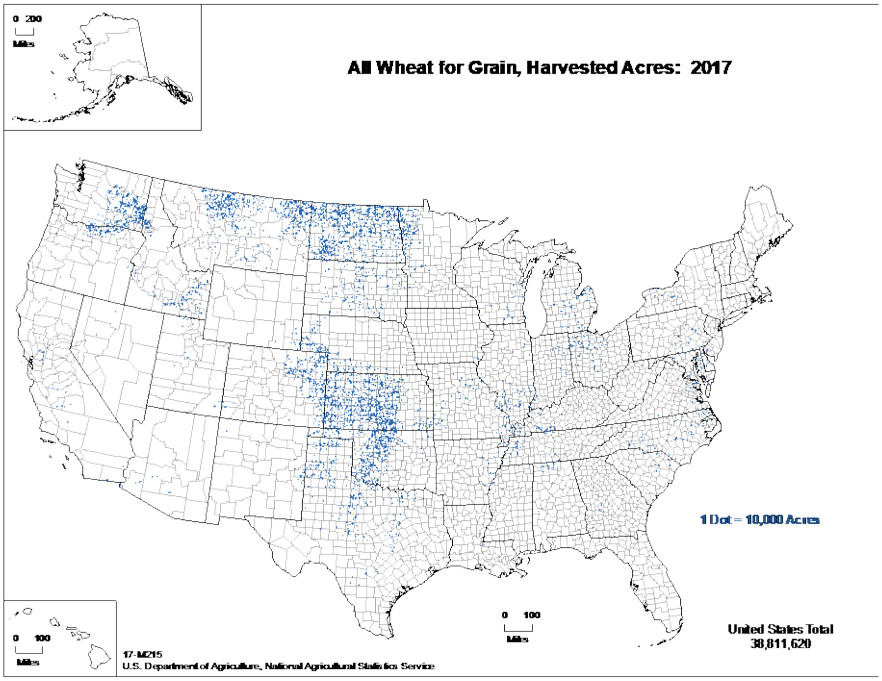

Figure 7. Wheat acres harvested, 2017.
Source: US Department of Agriculture, National Agricultural Statistics Service. 2017 Census of Agriculture.
Notes: Each dot represents 10,000 acres. Harvested acres for entire year ending December 31, 2017.

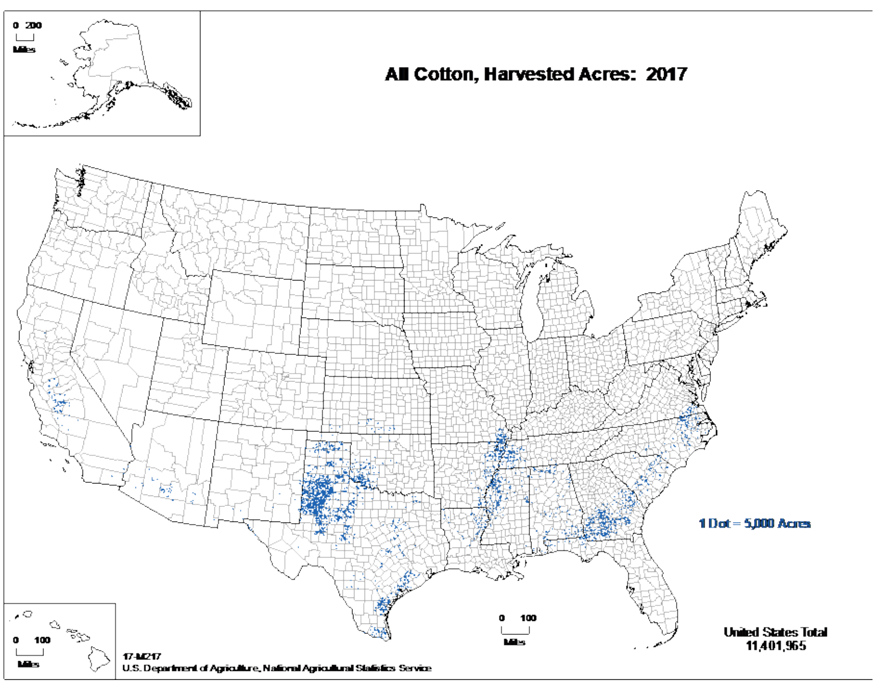

Figure 8. Cotton acres harvested, 2017.
Source: US Department of Agriculture, National Agricultural Statistics Service. 2017 Census of Agriculture.
Notes: Each dot represents 10,000 acres. Harvested acres for entire year ending December 31, 2017.

Nutrient needs and the relative availability of nutrients from manure tie livestock and crop production together. Spiegal et al. (2020) classify counties into manure sources and sinks using these five steps:

1. A county is a phosphorus (nitrogen) source if its phosphorus (nitrogen) availability from manure is greater than the net removal by crops.
2. A county is excluded if it is not a source and has less than 500 hectares of cropland.
3. A county is a phosphorus (nitrogen) sink due to deficit if the phosphorus (nitrogen) available from manure and applied through fertilizer is less than the net removal by crops.
4. A county is a phosphorus (nitrogen) sink due to fertilizer surplus if the fertilizer applied is greater than the net removal by crops.
5. A county is a phosphorus (nitrogen) candidate for within-county manure transfer if it is none of the prior classifications.

Figure 9 maps county classifications for phosphorus and nitrogen. Manure phosphorus sources overlap with poultry production. Much of the Corn Belt is a manure nitrogen sink and has phosphorus and nitrogen fertilizer surpluses. Note that many counties in Iowa and Minnesota are candidates for within-county transfer of manure for phosphorus but not nitrogen. This is because Spiegal et al. (2020) assume 50% nitrogen availability for county classification thresholds. Given large swine production in Iowa and Minnesota and 90%–100% nitrogen availability from swine manure, many of those counties are likely also candidates for within-country transfer of manure for nitrogen. This is also present to a lesser extent in Pennsylvania and North Carolina.

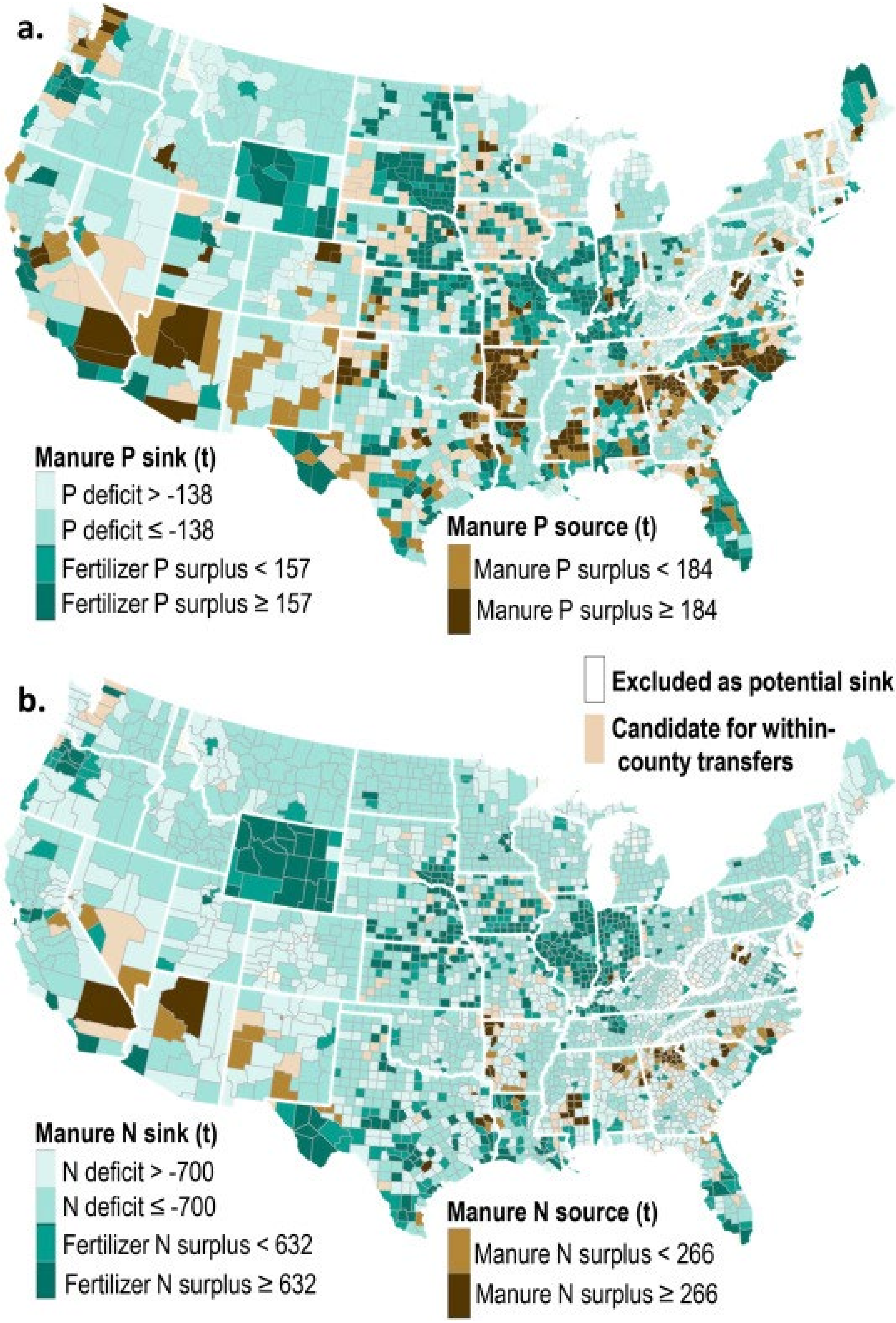

Figure 9. County-level manure nutrient sinks and sources.
Source: Spiegal et al. (2020).
Notes: Nitrogen availability assumed to be 50%. Counties classified using nutrient availability relative to need.

Business Cases for Swine Manure

Given the geographic characteristics of livestock and crop production and relative manure availability, three business cases for swine manure are investigated which include cost savings from use as fertilizer, sale as manure or manure products, and reduced GHG emissions. Granular data at the farm or county level could address case by case differences and nuances in the uses of swine manure. This data, however, is not readily available. Instead, opportunities within and across regions are broadly assessed based on a set of statistics derived from publicly available data from the 2022 Census of Agriculture.

Cost savings from using manure as fertilizer is best accomplished with high commercial fertilizer prices and/or diversified production of swine and crops. Data on the number and size of farms with diversified production are not readily available. Publicly available data on hog operations using their own manure as fertilizer was last published in 2015 by the USDA in the Crop Production Practices reports that relied on 2013 Agricultural Resource Management Survey data.[4] Even in that report, only certain states are available. Alternatively, the nitrogen and phosphorus expenses offset by using swine manure as fertilizer could be calculated as a manure credit (Schulz 2023). However, nitrogen and phosphorus prices in the USDA Agricultural Prices report are at a national level, which does not comport with the selected regions. The USDA Agricultural Marketing Service publishes six bi-weekly state or regional Production Cost reports that include fertilizer prices. These reports do not cover all states, however, so they are, again, insufficient for the regions in Matlock et al. (2014). Proxies for potential cost savings from same-operation manure use as fertilizer include average fertilizer expense per acre and per operation, crop acres per operation, and pig inventory per operation. Fertilizer expense is a (partly) displaceable cost in diversified operations. Crop acres and pig inventory correlate manure needs with manure availability, again with diversified operations in mind.

Swine manure's sale value depends on the demand for fertilizer and supply of swine and other manure types. Often, swine manure's value is assessed by its nutrient components (Leibold and Olsen 2022). The USDA Economic Research Service publishes swine manure values in its Commodity Costs and Returns estimates.[5] However, public data on manure prices and volumes are not available. The number of acres fertilized and the share of those acres fertilized with manure or approved organic fertilizers proxy for fertilizer demand. The total inventory of pigs, cattle, and poultry, which indicate manure availability, proxy for fertilizer supply. In regions with a relative oversupply (undersupply) of manure, its sale value should be lower (higher). If other manure types are readily available, then opportunities for swine manure may be limited. Roka and Hoag (1996) find that manure has a negative value in most situations. Conversion to energy source or fiber products requires specialized equipment and is only profitable at a commercial scale (Lim et al. 2023). Organic fertilizer products often command a premium, which could offset manure transportation costs.

Estimates from USDA's Economic Research Service are used for manure-to-fertilizer conversion factors (MacDonald et al. 2009). These figures assume no nitrogen volatilization and are based on the nitrogen requirements of corn. A hog operation that finishes 6,000 hogs per year can fertilize 480 acres. These figures do not correspond perfectly to inventories, however. To link the hog inventory (not annual) with manure production, 2.4 turns per year are assumed. This means that a hog operation that finishes 6,000 hogs per year actually has 6,000/2.4=2,500 animal spaces, which is typical for a finishing barn. So, if a hog operation is at full capacity and has an inventory of 2,500, then it can fertilize 480 acres (0.192 acres per hog). For operations with differing soil needs or crop

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[4] Information on these surveys and the data that are collected can be found at https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

[5] These reports can be found at: https://www.ers.usda.gov/data-products/commodity-costs-and-returns/. For hog reports, manure values are labeled "Other income."

rotations, these figures change. For instance, a corn-corn rotation in Iowa requires fewer than half of the acres that a corn-soybean rotation requires (Freese 2018).

Finally, potential value from reduced GHG emissions is considered through payments for carbon sequestration and associated costs for an average hog operation. Other manure management practices such as composting and increasing spread frequency are hampered by high moisture content and labor intensity, respectively, in addition to not having a clear economic benefit. For carbon offsets, prices are complicated, often opaque, and not publicly available.[6] So, value from reduced GHG emissions is evaluated using features of an operation that could make carbon sequestration profitable at varying levels of carbon prices. The University of Nebraska – Lincoln provides an example for a covered lagoon on a hog operation (Powers et al. 2009). Their baseline calculation is used to find the annual price per ton for sequestered carbon dioxide that would pay off the lagoon cover in ten years. This calculation assumes a wean-to-finish operation with only one turn of pigs per year, 72 square feet of lagoon per pig, and a cover cost of $4 per square foot. At these values, a hog operation would need $73 per metric ton of carbon sequestration per year to pay off a lagoon cover in ten years without cost savings or income from generating electricity. This estimate is unrealistically high but provides a ceiling for carbon prices that would make a covered lagoon profitable. On the low end, Key and Sneeringer (2011) find that it is profitable for a majority of hog operations with at least 2,000 head to adopt methane digesters with a carbon price of $26 per ton. At this price, hog operations begin to adopt with at least 500 head. Key and Sneeringer also find that without carbon offsets no hog operations profit from a methane digester. More recently, Dumortier et al. (2024) evaluate rates of return for anaerobic digesters in swine production across regions, production practices, and a variety of operation-specific factors.[7] They find that broad adoption of anaerobic digesters depends on the long-term certainty of carbon payments.

To make anaerobic digestion profitable, farms can incorporate co-digestion.[8] These benefits are difficult to assess due to the limited literature on the topic and variability in co-digesters' inputs and outputs (Dennehy et al. 2018). Sales of co-products or tipping fees may still be necessary for digesters to be economically feasible (Bishop and Shumway 2009; Usack et al. 2017). Transportation costs and the availability of food waste are constraints on the operational and economic feasibility of co-digestion (Dennehy et al. 2017). For hog operations located in more densely populated areas, food waste may be more accessible, while more remote operations may be limited to agricultural by-products such as corn stover, alfalfa silage, grass, or wheat (Hamilton 2016; Søndergaard et al. 2015). MacDonald et al. (2009) note that hog operations in the Midwest are more likely to have pits, while operations in the Southeast are more likely to have lagoons. Lagoons have a higher methane emissions and, thus, can offset more carbon than pits. This highlights the need for a regional analysis because differences in farm characteristics can account for different levels of profitability and adoption of manure management practices.

To further motivate the need for a regional analysis, consider the economic values used to evaluate opportunities in each region. Fertilizer prices in the USDA Agricultural Marketing Service's Production Cost reports vary by region, which implies different potential cost savings from using manure as fertilizer. Large, commercial operations generally preside in the Corn Belt and are co-located with crop production. However, there is still considerable swine production in other regions, shown in figure 2, where operation sizes tend to be smaller on average. Feasibility of methane

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[6] See Wongpiyabovorn et al. (2022) for a policy-oriented analysis of voluntary carbon markets.
[7] An accompanying tool for this paper allows users to calculate returns from installing an anaerobic digester based on operation characteristics and carbon prices. It is available at https://www.card.iastate.edu/tools/ad-carbon-markets/.
[8] Co-digestion is the incorporation of manure and other substances in anaerobic digestion. The United States Environmental Protection Agency provides an overview at https://www.epa.gov/agstar/how-does-anaerobic-digestion-work.

digesters depend on farm characteristics and electricity prices, which also vary with regional production practices (MacDonald et al. 2009). In addition to USDA environmental programs such as the Environmental Quality Incentives Program (EQIP) and Conservation Stewardship Program (CSP),[9] there are even state-level carbon offset and water quality programs that must be considered.[10] Because of these varying factors, opportunities for swine manure must be considered on a regional basis.

Region 1

Region 1 is comprised of Connecticut, Maine, New Hampshire, Vermont, Massachusetts, and Rhode Island. There is very little swine production in this region. Hog operations have 13 head on average, which translates to less than 3 hog manure acres. Fertilizer expenditures are low per operation ($9,850) but relatively high per acre ($224). Farms that grow crops average 72 acres of crop land. Comparing the crop acre average with the average hog manure acres, diversified operations have minimal cost savings from swine manure use as fertilizer.

Region 1 has 472,811 fertilized acres, with 48% fertilized with manure and 4% using approved organic fertilizers. There are 19,102 hogs, 353,453 cattle, 315,186 broilers, and 40,823 turkeys, and 3,668 available hog manure acres. With few available hog manure acres, markets would have few buyers and sellers.

On GHG emissions reduction, the size of the average hog operation would not support the equipment necessary for anaerobic digestion. This does not mean digestion cannot be implemented—alternative financing and revenue streams can make co-digestion profitable. One example, a dairy farm in Massachusetts, operates a co-digester for a renewable energy investor (Wilcox 2023). With the small scale of farms, however, intensive manure management may be more practical, particularly increasing the frequency that manure is spread during warmer months. This is almost certainly not cost effective, however, without public subsidies or carbon offsets.

Small hog and crop operations and limited manure availability will make marketing swine manure difficult in this region. In addition, operations do not have sufficient scale for carbon sequestration payments to be viable. In this region, the best use of swine manure is fertilizer for cost savings or sale to organic crop growers. The relatively high share of organic acres suggests that this may already be a common practice.

Region 2

Region 2 is comprised of New York and New Jersey. Most swine production in this region is in western New York. Farms that use fertilizer average $25,143 in fertilizer expenditure and $191 per acre. Hog operations have 30 head on average. This translates to less than 6 hog manure acres. Farms have 171 acres of cropland on average. Region 2 has a similar situation to region 1 where operation sizes and manure production are mismatched, and cost savings from manure use as fertilizer are minimal. Region 2 has 2,340,305 acres fertilized, with 36% using manure and 3% approved organic fertilizers. There are 50,165 hogs, 1,406,137 cattle, 512,351 broilers, and 29,543 turkeys, and 9,632 hog manure acres. The ratio of hog manure acres to total acres fertilized is similar in regions 1 and 2. However, in

[9] The USDA Natural Resources Conservation Service administers these programs, and available practices vary by state. EQIP offers technical and financial assistance for natural resource concerns, including water and air quality (https://www.nrcs.usda.gov/programs-initiatives/eqip-environmental-quality-incentives). CSP offers technical and financial assistance and is targeted toward maintaining existing levels of conservation (https://www.nrcs.usda.gov/programs-initiatives/csp-conservation-stewardship-program).

[10] Some examples of state-level programs include the California Air Resources Board's Direct Environmental Benefits in the State, which establishes a cap-and-trade program and the Department of Ecology for the State of Washington's Climate Commitment Act, which establishes a cap-and-invest program.

region 2, there are more likely to be scale benefits due to the size of operations and larger number of animals.

As with region 1, farms are too small for carbon sequestration to offset equipment costs without public subsidies or other external funding. Hog operations that are intensively managed could again spread manure more frequently to reduce GHG emissions, but this is unlikely to be cost effective. Swine and crop operations are small in region 2, like region 1. Carbon payments are unlikely to be profitable. This region has a similarly high share of organic production, and the most valuable use of swine manure is likely same-operation fertilizer application or sale to organic growers.

Region 3

Region 3 is comprised of Delaware, Maryland, Pennsylvania, West Virginia, and Virginia. Pennsylvania and Virginia have substantial swine production. On average, hog operations have 315 head, which equates to 60 hog manure acres. Pennsylvania is an outlier for hog operation size where operations have 532 head on average (102 hog manure acres). Farms that use fertilizer spend $18,859 on average and $194 per acre. Farms that grow crops have an average of 139 acres of cropland. In contrast with regions 1 and 2, diversified hog operations in region 3 can have considerable savings from applying manure as fertilizer.

States in region 3 fertilize 5,706,405 acres, 30% with manure and 2% approved organic fertilizers. There are 1,653,221 hogs, 3,139,237 cattle, 217,309,712 broilers, and 9,641,633 turkeys, and 317,418 hog manure acres. For perspective, over 5% of fertilized acres can, in theory, be covered by hog manure in region 3 compared to less than 1% in regions 1 and 2. Hog manure is a viable product for local sale in region 3. Maryland farms can use the Manure Transport Program to offset manure transportation costs.[11] This program is intended to transfer manure to farms that need phosphorus.

Larger hog operations, particularly in Pennsylvania,[12] are likely to have sufficient size to profit from carbon sequestration. Operations that are on the margin would likely benefit from co-digestion. Both Maryland and Virginia offer cost-share programs to incentivize conservation practices, including nutrient management plans.[13,14]

Commercial hog operations in this region are likely to incur cost savings by also producing crops. This is limited by relatively low fertilizer expenses. Additionally, the high volume of poultry production will limit swine manure's sale value. Carbon payments are likely profitable for larger operations. There is still a relatively high share of organic acres, which could boost the value of swine manure. Hog operations have more choices that can be tailored to geography, local market conditions, and operational structure than in regions 1 and 2.

Region 4

Region 4 covers Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee. Of these states, North Carolina dominates swine production. On average, hog operations have 944 head (181 hog manure acres), but this is much larger in North Carolina, which

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[11] Details on this program can be accessed through: https://mda.maryland.gov/resource_conservation/Pages/manure_management.aspx.

[12] The United States Environmental Protection Agency cites Remley Farms in Pennsylvania as an example of a hog operation that implements co-digestion: https://www.epa.gov/agstar/anaerobic-digestion-swine-farms.

[13] Maryland's cost-share program is the Maryland Agricultural Water Quality Cost-Share Program (MACS). Details, including cost-share rates for waste storage, can be found on the Department of Agriculture website here: https://mda.maryland.gov/resource_conservation/Pages/macs.aspx.

[14] Virginia's cost-share program is offered in tandem with its soil and water conservation districts. Eligibility, rates, and other information can be accessed through the Department of Conservation and Recreation website here: https://www.dcr.virginia.gov/soil-and-water/vacs-program-overview.

has 3,287 head on average (631 hog manure acres). Farms that use fertilizer spend, on average, $23,959 per year at $189 per acre, and farms with crops have 218 acres on average. Hog operations in North Carolina have excess manure they must dispose of or sell.

There are 21,513,307 fertilized acres in region 4. Of these, 13% are fertilized with manure and 2% with approved organic fertilizers. This region is the third largest in hog production with 9,315,235 head. There are 9,157,761 cattle, 917,018,130 broilers, and 23,024,804 turkeys. Hog manure acres are substantial as well, with 1,788,525 available. Over 8% of fertilized acres in this region can be fertilized with hog manure alone. With large cattle and poultry inventories, there is a manure excess, especially in North Carolina, as shown in figure 9. This can adversely affect the sale value of swine manure if it must be transported a long distance, turning into a disposal expense.

Larger farms in this region will have economic benefits from methane digesters. Depending on access to food waste, co-digestion could supplement these benefits. Hog operations in North Carolina, in particular, are run at a commercial scale and can viably purchase equipment for carbon sequestration. Because of the scale of hog operations in this region, producers have a variety of options for manure management. Excess swine manure in North Carolina has prompted innovation in the private sector. One example is sludge dryers to manage phosphorus deposits (Howard 2022). In North Carolina, the state has an opportunity to be a market-maker by offering manure transportation subsidies, similar to Maryland. This would incentivize hog operations to transport excess manure and prevent overapplication, which is a possible outcome when commercial fertilizer is cheap, transportation is expensive, etc.

Hog operations in North Carolina and Mississippi are of sufficient scale to benefit from carbon sequestration and same-operation fertilizer use. In North Carolina, specifically, hogs are co-located with corn production, giving diversified operations a similar advantage to operations in the Corn Belt. This region has large broiler production, so swine manure's sale value and marketing opportunities will be secondary to broiler manure, which is semi-dry or dry and often sold commercially. Regardless, there are likely marketing opportunities for swine manure as fertilizer, especially in North Carolina where operations likely produce a surplus of manure relative to available manure acres. This is confirmed by figure 9, which shows that North Carolina is a large manure source. In fact, large, concentrated production in North Carolina may hurt the sale value of swine manure given its relative availability. This could be addressed with recent, county-level data, similar to Spiegal et al. (2020).

Region 5

Region 5 contains Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin. Each state has commercial swine production. Average hog operations have 1,615 head (310 hog manure acres), and operations in Illinois and Minnesota average 3,101 and 3,031 head, respectively. These are large commercial operations and often incorporate crop production. Fertilizer expenses are $50,000 per operation and $172 per acre, and farms with crops have 343 acres on average. As with region 4, there is parity between average hog manure acres and average crop acres.

In total, 59,945,409 acres are fertilized in this region, with 10% using manure and 1% approved organic fertilizers. Region 5 produces the second most swine in the nation. There are 22,800,215 hogs, 9,513,658 cattle, 47,004,648 broilers, and 31,823,918 turkeys. Again, hog manure acre availability is high, at 4,377,641 acres. This could account for over 7% of all fertilized acres in the region. In contrast with region 4, swine production, and thus manure, is more dispersed among these states. Looking to figure 9, there are fewer manure surpluses, so swine manure should be marketable.

Given the average hog operation has 1,615 head, most operations in this region can benefit from carbon offset payments and anaerobic digesters. Depending on the distance to food waste and its availability, co-digestion may increase the value of anaerobic digestion. Operations in sparsely population areas may see less benefit. Public programs for carbon offsets and manure management are surprisingly lacking in this region. One public environmental initiative worth noting is Wisconsin's Manure Management Advisory System, which can help farmers assess runoff and nutrient needs.[15] By reducing runoff, farmers applying manure as fertilizer can reduce emissions and cut costs while preserving water quality. Similar to North Carolina, there are manure surpluses in this region, and overapplication—leading to excess runoff and sub-optimal returns—can occur under certain circumstances. Again, states have an opportunity to be market-makers and incentivize manure transfers from surplus areas to sink areas.

A large share of hog operations in this region benefit from same-operation fertilizer use and are of sufficient size to profit from carbon sequestration. Manure's sale value and marketability are likely to be profit sources as well, given the high level of corn production in these states. Unlike North Carolina, there is less competition from poultry manure and sufficiently high crop production to increase the sale value of manure. Transportation costs are likely to be the constraint on swine manure's marketability since both swine and crop production are dispersed throughout the region.

Region 6

Region 6 covers Arkansas, Louisiana, New Mexico, Oklahoma, and Texas. Most hog production in this region takes place in Oklahoma and the Texas panhandle. Hog operations have, on average, 345 head (66 hog manure acres). In Oklahoma, hog operations average 972 head (187 hog manure acres). Farms with fertilizer expenditures spend $22,504 on average at $102 per acre. Farms with cropland average 506 acres. Average hog operations have a substantial manure deficit relative to average crop acres. For larger operations in Oklahoma and the Texas panhandle, this manure-to-acres mismatch is smaller.

There are 28,671,137 fertilized acres in this region. Of these, 10% are fertilized with manure, and 1% are fertilized with approved organic fertilizers. Cattle and poultry dominate this region. There are 20,705,519 cattle, 420,127,853 broilers, and 12,152,892 turkeys, but only 3,498,946 hogs and 671,798 hog manure acres. Available hog manure acres, which is designed for application as fertilizer to corn, can cover 2% of fertilized acres. This is imprecise, however, because soybeans, wheat, and cotton have a large share of output near swine production, shown in figures 4–7. In contrast with the regions 5 and 7 where swine manure is applied to corn, fertilizer requirements may be lower for crops grown in region 6. However, looking to figure 2, the concentration of hogs is likely to depress the value of their manure because of high transportation costs.

Commercial hog operations in Oklahoma are large enough for carbon sequestration payments from anaerobic digesters to be feasible. Benefits from co-digestion are likely constrained due to insufficient food waste. In other states, profitability will be limited and likely depend on public subsidies. Texas's Water Quality Management Plan includes a cost-sharing program that incentivizes swine producers to build facilities and adopt environmentally friendly practices.[16]

Similar to region 4, hog production is geographically concentrated in the Oklahoma and Texas Panhandles. Diversified operations are large enough for appreciable cost savings from fertilizer use and profit from carbon sequestration. Crop acres are also concentrated in this region, so manure sales are viable. Cattle inventories are high in this area as well, so swine manure will face competition from cattle manure from feedlots. In the remainder of the region, however, operations are small and do not overlap heavily with crop production, so cost savings from same-operation fertilizer use and payments for carbon sequestration will be minimal. The share of organic acres is also relatively small, so there is not likely a premium for manure use as fertilizer.

[15] Information on this program is available at http://www.manureadvisorysystem.wi.gov.
[16] Details, including a list of approved practices, can be accessed at https://www.tsswcb.texas.gov/programs/water-quality-management-plan.

Region 7
Region 7 consists of Iowa, Kansas, Missouri, and Nebraska. Hog operations are among the largest at 3,490 head on average or 670 hog manure acres. At the upper end, Iowa operations average 4,532 hogs, and at the lower end, Missouri operations average 1,466 hogs. Farms with fertilizer expenses spend $51,548 on average at $131 per acre, and farms with cropland have 555 acres on average. Hog operations that also grow crops can offset a large share of their fertilizer expense.

There are 61,267,432 fertilized acres in this region, with 7% fertilized with manure and 1% with approved organic fertilizers. Each state has commercial swine production, but Iowa dominates. There are 32,613,288 hogs, 20,039,270 cattle, 75,461,520 broilers, and 12,608,454 turkeys. A majority of hogs (23,808,603) are in Iowa, and a majority of broilers (56,614,738) and turkeys (7,168,069) are in Missouri. Hog manure acres are plentiful at 6,261,751 acres, which could account for 10% of all fertilized acres. Looking to figure 9, many counties in this region, especially in Iowa, are manure surpluses, so the sale value of manure may be low if it must be transported. Manure should be marketable in this region, given that swine and corn production are ubiquitous.

Carbon sequestration payments from anaerobic digesters are viable for nearly all hog operations in this region. As with region 5, benefits from co-digestion are available for operations located near food waste. Surprisingly, despite producing the most hogs of any region in the United States, there are few public programs for carbon offsets or manure management. Iowa's Department of Agriculture and Land Stewardship maintains the Resource Enhancement and Protection program, which provides funds to producers for manure management systems.[17] Missouri offers indirect finance programs to guarantee loans to independent livestock producers and reduce interest rates for building animal waste treatment.[18] Missouri has a much higher population density than other states in this region, so environmental issues may be a larger concern for the general public. States in this region, especially Iowa, have the opportunity to create markets for swine manure by incentivizing transportation of surplus manure to areas with manure deficiencies.

As with region 5, many operations are diversified and generate considerable cost savings from using swine manure as fertilizer. Iowa, in particular, is largely a manure source, shown in figure 9. The availability of hog manure acres and demand for fertilizer increase the sale value of manure and its marketability. Cattle and poultry inventories suggest that swine manure substitutes are readily available. Most hog operations are large enough for carbon sequestration to be profitable.

Region 8
Region 8 spans Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming. Average hog operations have 1,127 head (216 hog manure acres), but South Dakota is an outlier with 3,721 head on average. Fertilizer expenditures average $66,144 for farms that buy fertilizer, and these farms spend an average of $98 per acre. Cropland averages 1,129 acres per operation, but Utah is the outlier at 199 acres. A hog operation that also grows crops in South Dakota will be much more similar to Iowa, Minnesota, or Nebraska than an operation in Utah or Colorado simply based on crop decisions. Low fertilizer expenses limit potential cost savings. This, too, is related to crop decisions since only North and South Dakota have appreciable corn production.

There are 38,941,572 fertilized acres with 4% fertilized with manure and 1% approved organic fertilizers. Most of the fertilized acres are in North and South Dakota. Livestock inventories are relatively low. There are 3,553,254 hogs, 11,928,447 cattle, 306,234 broilers, and 5,531,887 turkeys. Over half of the hogs are in South Dakota, though eastern Colorado and Utah have sizeable

[17] This program is administered by soil and water conservation districts in the state of Iowa. An overview is provided at: https://iowaagriculture.gov/field-services-bureau/water-quality-protection-projects-and-practices.
[18] For more information on financial assistance programs available to swine producers in the state of Missouri, see the Production Agriculture section at: https://agriculture.mo.gov/abd/financial/.

inventories. Hogs in Utah are located almost exclusively around the city of Milford. Hog manure acres are similarly concentrated, and there are 682,225 available for the region. This could cover, in theory, less than 2% of total fertilized acres. Since crop production varies so much throughout this region, this is imprecise. Most hog manure acres are located in South Dakota, where agronomic and market conditions are similar to Iowa. There is unlikely to be a market for swine manure in this region given the concentration of animals and large distances for transportation.

Commercial hog operations in South Dakota are likely to benefit from carbon payments. Like region 6, there is likely not enough food waste for operations to benefit from co-digestion. Depending on public subsidies, adopting methane digesters in other states may be profitable. North Dakota's Livestock Pollution Prevention Program offers cost-sharing for manure containment systems.[19] This program offers separate cost-sharing for full and partial containment systems. In general, only large operations are likely to see a positive return on anaerobic digesters.

Producers in South Dakota face similar conditions and opportunities to producers in region 7, especially Iowa and Nebraska. Utah and Colorado have clusters of regional swine production. In Colorado, swine production overlaps with crops. In the remainder of the region, there is limited swine and crop production. Cost savings from fertilizer use can be realized in Colorado and South Dakota. The relatively low number of fertilized acres and lack of organic acres will hinder swine manure's marketability.

Region 9

Region 9 includes Arizona, California, Hawaii, and Nevada. Only California has substantial (reported) hog production. Operations in California average 60 hogs (12 hog manure acres). Fertilizer expenses are high, however, averaging $79,479 for operations that use fertilizer at a per-acre rate of $398. In Arizona, this figure is $100,254 per operation. Crop operations are relatively smaller, averaging only 240 acres. High fertilizer expenses create an opportunity for cost savings from same-operation manure use as fertilizer. Hog operations are so small, however, that this is not at a commercial scale. Application to high-value crops on small operations is the most likely use for swine manure in this region.

There are 8,143,005 acres receiving fertilizer in this region. Of these, 11% receive manure, and 5% receive approved organic fertilizers. California dominates the fertilizer use and livestock inventories in the region. There are 88,524 hogs, 6,807,039 cattle, 50,798,553 broilers, and 2,190,259 turkeys. There are 16,997 available hog manure acres, which is less than 1% of fertilized acres. Swine manure will not be marketable outside of niche production.

Given the small size of hog operations, carbon sequestration is unlikely to be profitable unless large subsidies are available. Larger operations in California may benefit from co-digestion. Similar to regions 1 and 2, intensive management of small operations may make frequent manure spread more likely, especially since this region's climate is more temperate and can receive manure in the winter. California offers incentives for a variety of environmental practices through its Department of Food and Agriculture.[20] Their Alternative Manure Management Program offers livestock producers financial assistance for manure management practices other than anaerobic digesters. California also allows swine producers with anaerobic digesters to participate in its Compliance Offset Program.[21]

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[19] Details on this program can be accessed through the North Dakota Department of Agriculture website here: https://www.ndda.nd.gov/divisions/grain-livestock-licensing/livestock-pollution-prevention-program.

[20] Multiple programs may offer benefits to swine producers. It is worth noting that financial assistance for methane digesters appears to be restricted to dairies at present. More details on these programs can be found here: https://www.cdfa.ca.gov/oefi/.

[21] Details on how swine producers can participate can be found in the Compliance Offset Protocols listed at: https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program.

Operations in this region are small and unlikely to profit from carbon payments without large subsidies. Swine manure's value from cost savings or sale is limited, but the high share of organic acres, production of high value crops, and high fertilizer costs make swine manure an attractive product for niche crop production. Transportation is the constraint here, so any swine manure use must be closely located to its source.

Region 10

Region 10 is comprised of Alaska, Idaho, Oregon, and Washington. Hog operations are small in this region, averaging only 19 head, which translates to fewer than 4 hog manure acres. Average fertilizer expenditure is $51,887 per operation and $212 per acre, and farms that grow crops average 392 acres. The large mismatch between average crop acres and available manure indicate that cost savings will be limited, despite relatively high fertilizer expenditures.

In total, 9,704,014 acres are fertilized in this region, of which 7% receive manure and 2% approved organic fertilizers. Hog inventories are limited, with 50,281 head in the region. There are 4,858,384 cattle, 8,769,103 broilers, and 17,111 turkeys. Hog manure acres are limited, with 9,654 available. Of the crops considered, wheat is the most common in this region, and swine manure provides phosphorus. The small share of hog manure acres—less than 1% of all fertilized acres—indicates that swine manure is unlikely to be marketable.

Due to small operation sizes, swine manure is unlikely to provide any economic benefit through carbon payments without drastic public subsidies. As with other regions that have small hog operations, frequent manure spreading may be feasible for reducing GHG emissions, but this is not likely to be cost effective. Washington's Department of Ecology manages carbon offsets as part of its Climate Commitment Act.[22] These allow livestock producers to receive carbon offsets for methane digesters.

Hog operations in this region are small, and crop acres are limited. The share of organic acres is low. Few good options exist for swine manure in this region due to the size of operations and regional agricultural production. Likely, the best use of swine manure will be cost savings from same-operation fertilizer use, but even this is severely limited.

Conclusions

When commercial fertilizer prices spike, farmers look for cheaper substitutes, including manure. While it was once considered a waste product, manure is now understood to be a commodity that can provide agronomic benefits and be used for electricity generation and a variety of fiber products. Nutrient availabilities vary by manure types and application methods. Recent research has shown the need for proper handling and application to minimize environmental harms and maximize soil and yield benefits. For swine manure, agronomic and environmental benefits depend on production practices and the crops to which the manure is applied.

In the United States, most swine production takes place in the Corn Belt, with substantial production in North Carolina. Swine production largely coincides with corn production, which is the most swine-manure-fertilized crop. Business cases for swine manure depend on the structure of swine production and various agricultural characteristics. We evaluate these as cost-saving measures or profit opportunities. Same-farm application of swine manure to crops can result in cost savings versus using commercial fertilizer. Swine manure can also be sold, but its value is capped by transportation costs. Hog operations can implement anaerobic digesters to generate electricity and sell carbon offsets. To evaluate these opportunities, we use simple statistics from the 2022 Census of Agriculture.

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[22] Information on this program can be found at: https://ecology.wa.gov/air-climate/climate-commitment-act/cap-and-invest/offsets.

Across the regions considered in this study, the best use of swine manure for most operations is application as fertilizer to that operation's crops. Other than commercial production in regions 4, 5, 7, and 8, hog operations in most regions tend to be small in absolute terms and relative to the average size of crop operations. In areas with manure surpluses, shown in figure 9, swine manure should be marketable. These are primarily in regions 4, 5, 7, and 8, where production is at a commercial scale. Swine manure may be marketable for local production of high value or organic crops. Anaerobic digesters are cost effective only at commercial scale or with subsidies. Farms on the margin may benefit from co-digestion. Hog operations in regions 4, 5, 7, and 8 can likely take advantage of carbon offsets, but cost feasibility must be considered on a state-by-state basis because many states offer cost-share programs. At present, these opportunities for swine manure are difficult to precisely assess at a regional level due, in large part, to a lack of data.

Granular data on the size and scope of diversified operations and manure sales are not readily available. With these, the potential cost savings and sale values for representative farms in each region could be calculated more precisely. Carbon prices are highly varied and not publicly available, which makes determining the profitability of carbon sequestration difficult. Updated manure data in the Farm Financial and Crop Production Practices report from the US Department of Agriculture's Agricultural Resource Management Survey would be useful in assessing opportunities and uses for swine manure on a state-by-state basis.[23] The most recent data is from 2015, but integrators have continued to grow in recent years, changing the structure of the swine industry (Lim et al. 2023). Another hurdle in assessing regional opportunities for swine manure from an environmental perspective is simply gathering relevant information on programs and financial assistance. A great resource for the dairy industry—and helpful in tracking down state-level programs in this analysis—are Nutrient Management Fact Sheets provided by the National Dairy FARM Program.[24] These fact sheets list relevant requirements for nutrient management plans and available technical and financial assistance for each state. This makes it easier for producers to assess opportunities that are available to them at a local level and is a model that the swine industry should consider emulating.

At present, there seem to be few marketing opportunities for swine manure, though areas with high commercial swine production or a swine manure surplus tend to overlap with high crop production. When fertilizer prices are high (e.g., 2020 to 2022), the value of manure should also increase since it is a fertilizer substitute. The key is having markets for swine manure so that it can be allocated to its most efficient use according to prices set by the market. During periods of low fertilizer prices, swine manure can generate cost savings and some profit from carbon sequestration for larger operations. Organic crops command a premium that may be passed through to swine manure prices in areas with small operations and low commercial production. States have an opportunity to be market-makers by incentivizing the transportation of swine manure from areas with surpluses to areas with nutrients needs. A current example of this is Maryland's Manure Transport Program, which subsidizes transportation costs. From a policy perspective, this can offset negative externalities without an excessive regulatory burden. By setting up manure markets, states can balance crops' nutrient needs with water quality and emissions initiatives.

[23] For more detail on this USDA product see https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

[24] These fact sheets can be found by searching "NMP Fact Sheet" on the National Dairy FARM Program website https://nationaldairyfarm.com/?s=nmp+fact+sheet.

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