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# Poultry manureshed management: Opportunities and challenges for a vertically integrated industry

Ray B. Bryant[1] | Dinku M. Endale[2] | Sheri A. Spiegal[3] | K. Colton Flynn[4] | Robert J. Meinen[5] | Michel A. Cavigelli[6] | Peter J. A. Kleinman[7]

[1] USDA-ARS Pasture Systems & Watershed Management Research Unit, University Park, PA 16802, USA

[2] USDA-ARS Southeast Watershed Research Lab., Tifton, GA 31793, USA

[3] USDA-ARS Jornada Experimental Range, Las Cruces, NM 88003, USA

[4] USDA-ARS Grassland Soil and Water Research Lab., Temple, TX 76502, USA

[5] Dep. of Animal Science, The Pennsylvania State Univ., University Park, PA 16802, USA

[6] USDA-ARS Sustainable Agricultural Systems Lab., Beltsville Agricultural Research Center, Beltsville, MD 20705, USA

[7] USDA-ARS Soil Management and Sugarbeet Research Unit, Fort Collins, CO 80526, USA

**Correspondence**
Ray B. Bryant, USDA-ARS Pasture Systems & Watershed Management Research Unit, University Park, PA 16802, USA.
Email: ray.bryant@usda.gov

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**Abstract**

Manureshed management seeks to address systemic imbalances in nutrient distributions at scales beyond the farmgate and potentially across county and state boundaries. The U.S. poultry industry, which includes broilers, layers, pullets, and turkeys, has many characteristics that are compatible with achieving a vision of manureshed management, including a history of engaging in local and regional programs to better distribute manure resources. Despite widespread vertical integration that supports large-scale strategic decision making and dry manures that favor off-farm transport, there are still many challenges to poultry manureshed management that require engaging stakeholders other than just the poultry industry. Analysis of county-level nutrient budgets highlights the industry's "mega-manureshed," extending from the Mid-Atlantic, across the southeast, and into northwest Arkansas, Oklahoma, and Texas. The analysis also identifies areas with legacy nutrient build-up that are still present today. Implementing manureshed management in the U.S. poultry industry requires comprehensive consideration of manure treatment technologies, alternative uses such as bioenergy production, market development for treated manure products, transport of manure nutrients from source to sink areas, and manure brokering programs that promote manure nutrient distribution. Fortunately, past and present evolution and innovation within the industry places it as a likely leader of the manureshed vision.

## 1 | INTRODUCTION

Livestock and poultry production has become increasingly specialized, vertically integrated, and concentrated. For poultry, this trend began in the 1950s. Today, poultry production is perhaps the most specialized animal production system in the United States, with a portion of feed grains grown at substantial distance from where the animals are raised (National Chicken Council, 2020a). A key outcome of this situation is the accumulation of nutrients, including nitrogen (N) and phosphorus (P), excreted in manure that often exceeds the nutrient requirements for local crop production. Without a mechanism to distribute manure nutrients more widely, this situation results in surpluses in local soils that receive

**Abbreviations:** IPNI, International Plant Nutrition Institute.

manure. The local and regional accumulation of manure nutrients is considered a key driver of the "wicked problem" of eutrophication of water bodies; that is, the biological enrichment of water bodies derived from nutrient pollution (Shortle & Horan, 2017) and occurrence of harmful algal blooms (Glibert, 2020). Spiegal et al. (2020) explored the concept of the "manureshed," which is the geographic area surrounding one or more livestock and poultry operations where excess manure nutrients can be recycled for agricultural production. Central to the concept of the manureshed are sources and sinks, which represent spatial extents where the N and P in livestock and poultry manure produced exceeds the nutrient needs of crops in the area (sources) or falls short of crop needs (sinks). The current study assesses the nutrient management challenges that confront the poultry industry (broilers, layers, pullets, and turkeys) in the context of manuresheds and in recognition that manure nutrients from poultry production sometimes coexist with manure nutrients from other concentrated livestock operations, most often swine, but also with dairy in the Puget Sound region of Washington state (Spiegal et al., 2020). Although manure N and P co-occur as sources and sinks and must be co-managed, we focus our analysis on P because the plant-available N/P ratio in poultry manure is low (<4) relative to crop needs (~10) (Heckman et al., 2003; Preusch et al., 2002), increasing the risk of soil P buildup and P enrichment of runoff when poultry litter is overapplied (Maguire et al., 2008).

The justification in our work for focusing on P from poultry is echoed in the work of Sabo et al. (2021) wherein, linking N and P inventories for the conterminous United States for the years 2002, 2007, and 2012 with a point source database, they developed a simplified metric that gives subbasin (Hydrologic Unit Codes-8, ≈1,800 km$^2$) level distribution of point and nonpoint source nutrient releases as an aid for the development of watershed restoration plans at the local, state, and national level. For example, they found that a small proportion of the landscape (<25% of subbasin area of the United States) contains 50% of anthropogenic and agricultural N and P surplus. For P, 17% of the subbasin area contains 50% of pollution sources associated agricultural surplus. These surpluses are often co-located, especially in areas of extensive livestock production. Sabo et al. (2021) point out that targeting only a small part of a watershed for restoration associated with a specific nutrient source might present a most effective way to achieve desired reduction in nutrient releases to the environment.

Identifying manure source and sink areas is an important first step in defining manuresheds (Spiegal et al., 2020). So, after providing an overview of the characteristics and distribution of the U.S. poultry industry and poultry manure characteristics, we focus briefly on methodologies used and then discuss poultry manuresheds identified east of the Mississippi across the Southeast and Mid-Atlantic regions where over 55% of the U.S. poultry production is located. The analysis also recognizes areas with legacy nutrient build-up that are still present today. We then highlight challenges for manureshed management that include legacy P, marketing, transport, and manure treatment and alternative use technologies.

**Core Ideas**

- Vertical integration of U.S. poultry production offers advantages for manure management.
- Intensive poultry production in southeastern U.S. states constitutes the largest manureshed.
- Poultry manure is valuable as a fertilizer, but surplus near production areas is a concern.
- Dry poultry manure lends itself to transport and redistribution from source to sink areas.
- Treatment can increase the value of poultry manure as a fertilizer and for other beneficial use.

## 2 | THE U.S. POULTRY INDUSTRY

The poultry industry, consisting of broiler, turkey, and egg production and processing sectors, makes significant contributions to the U.S. economy and those of individual states. According to a 2 Dec. 2020 joint press release by the U.S. Poultry & Egg Association, National Chicken Council, National Turkey Federation, and United Egg Producers, the industry provides 2.14 million direct and service-related jobs that pay \$121.1 billion in wages and generate \$576.6 billion and \$41.9 billion in economic activities and government revenues, respectively (National Chicken Council, 2020b). Moreover, the National Chicken Council (2020c) reports that ~95% of broiler chickens are raised on some 25,000 farms under a vertically integrated contract arrangement with ~30 federally inspected companies that process and market the products. Table 1 presents U.S. poultry production and economic value for 2012, 2017, and 2019 as given in USDA-NASS (2013, 2018, 2020). Mean annual increases of 1.3, 0.2, and 1.1% are projected in broiler and turkey meat and egg production, respectively, from 2022 through 2028 (USDA, 2020).

Data for U.S. broiler production from 2012 to 2017, when total production varied between 8.4 billion and 9.0 billion head, show that the southeastern states of Alabama, Arkansas, Georgia, Mississippi, and North Carolina account for 57% of the annual U.S. broiler chicken production. The convergence of several factors contributed to the transition from small-scale subsistence farming to a highly integrated and mechanized industry as highlighted by Weinberg (2003)

**TABLE 1** U.S. poultry production and value for 2012, 2017, and 2019

| Poultry | Number billion | Value billion $ | Live-weight billion kg |
|---|---|---|---|
| | **2012** | | |
| Broiler | 8.44 | 24.76 | 22.47 |
| Turkey | 0.25 | 5.44 | 3.42 |
| Chicken (nonbroiler) | 0.18 | 0.08 | 0.41 |
| Eggs laid | 92.89 | 7.82 | NA |
| | **2017** | | |
| Broiler | 8.91 | 30.23 | 25.21 |
| Turkey | 0.24 | 4.84 | 3.40 |
| Chicken (nonbroiler) | 0.21 | 0.09 | 0.48 |
| Eggs laid | 105.69 | 7.55 | NA |
| | **2019** | | |
| Broiler | 9.18 | 28.31 | 26.43 |
| Turkey | 0.23 | 4.30 | 3.37 |
| Chicken (nonbroiler) | 0.19 | 0.04 | 0.46 |
| Eggs laid | 113.25 | 7.70 | NA |

*Note*. Data are rounded to two decimal places. Data from USDA-NASS (2013, 2018, 2020). NA, not appliable.

using north Georgia as an example. Reconstruction after the civil war encouraged transition of subsistence farming to commercial cotton and corn production through tenancy and sharecropping arrangements. Through the 1920s the boll weevil devastated cotton crops, the stock market crashed, and commodity prices slumped. Agricultural policy thereafter favored larger farms, which curtailed tenancy and sharecropping. The marginal nature of farming incentivized the region's emergence as an important poultry production zone. Entrepreneurs expanded into poultry feed production and processing for growing urban markets, thus birthing the concept of vertical integration. During World War II the federal government became a large guaranteed market to feed its army at war, thus expanding poultry production into adjacent counties and states. Vertical integration offered opportunities to producers with little land holdings to earn income from poultry production. As complexities of the industry in terms of poultry and feed production, processing, and marketing within and outside the nation increased, healthy profit margins became critical, which necessitated expansion to the south and southwest where cheap labor was available.

Due to its generally dry nature, poultry manure is best suited for transport programs that are central to achieving nutrient balances within a manureshed. Pagliari, Wilson, & He (2019) point out that the terms "poultry manure" and "poultry litter" are used interchangeably in the literature, but they differ in important ways. Poultry manure typically consists of bird excreta (feces and urine), spilled feed and water, and shed feathers from breeder and egg-laying facilities. The manure storage and handling techniques determine whether it can be treated as a solid, slurry, or liquid manure. Poultry litter refers to the material removed from chicken broiler and turkey grow-out facilities that produce meat and consists of the mixture of bedding material (wood shavings, sawdust, and rice or peanut hulls), excreta, feathers, and spilled feed and water. These differences result in different poultry manure and poultry litter characteristics. In this paper, we use poultry manure to refer to both forms of poultry by-products to simplify the narrative and presentations in tables and figures, but we highlight any similarities and/or differences where applicable.

## 3 | PRODUCTION FACTORS INFLUENCING MANURE CHARACTERISTICS

A recent book on animal manure edited by Waldrip et al. (2019) provides several chapters that comprehensively present the myriad aspects of poultry production and corresponding manure quantity and quality (Ashworth et al., 2019; Janni & Cortus, 2019; Pagliari, Wilson, & He, 2019; Pagliari, Wilson, Waldrip, et al., 2019; Zhang et al., 2019). Similarly, the Foreign Animal Disease Preparedness & Response Plan Poultry Industrial Manual (FAD PReP, 2013) provides extensive production details. The following summary is gleaned from these and other cited sources.

In poultry production, housing, flock management, and manure collection, handling and storage management often vary depending on the type of poultry being raised, stage of production, targeted market, and environmental factors. Poultry houses are constructed according to environmental standards that ensure that the houses do not act as point sources for nutrient loss that affects water quality. For example, Delaware's Poultry Construction Guide (dechickenchecklist.com) lists at least five state and federal agencies that administer permits. Permits required through the various rules and regulations often need to be coordinated with financing requirements.

Layers, raised for egg production, are hatched at commercial hatcheries owned and operated by genetic companies. One-day-old chicks are purchased by farms where they spend the first ~18 wk of life as pullets. At that point they are moved to a laying house where hens lay eggs from ~20 to 80 or 85 wk of age. They are then sold or molted (shed feathers) before beginning another cycle of egg laying. A set of laying hens is kept for one to three laying cycles before a new set of pullets is brought in. Layers are housed in single or stacked cages, 5–10 to a cage. Manure falls from the cages and collects on the floor below or onto belts that deliver it outside to a storage area. Manure collecting on the floor may be removed only once per year as a solid material and either directly applied to fields or stored for later use, either as manure or composted manure. Some layer facilities equipped with a flushing system move the manure as a liquid into lagoons or concrete/steel structures. Consumer willingness to pay higher premiums for products from facilities with better animal welfare drive production innovations such as cage-free egg production where more floor space and tiered structures allow more natural behavior of birds, like perching and dust bathing. Contemporary cage-free barns have specialized floors to minimize the need for bedding or manure belts to move manure outside of the barn.

Broiler chicken production is a three-step process. First, specialized poultry genetics companies use the latest genetics technology to breed birds with improved traits such as growth rate, feed efficiency, and quantity and quality of meat. The FAD PReP (2013) Poultry Industry Manual suggests that only a few companies dominate this sector. Second, commercial breeding companies raise the selected pedigree birds (parent breeders) in specially built breeder houses to produce eggs for company-owned hatcheries. Third, day-old chicks from hatcheries are sent to commercial broiler farms that are owned or contracted to the same company to be raised as broilers. It takes the day-old chicks 6–7 wk to attain the marketable weight of 3.17–5.44 kg (7–12 lbs). In this vertically integrated system, broiler companies provide the chicks and all associated food and medication to independent growers and transport chicks to, and fully-grown birds from, the farm.

Housing to raise broiler chickens consists of environmentally controlled barns sized for optimal stocking density, which varies by location, for best broiler health and performance. The larger-sized barns (~3,250 $m^2$ [35,000 $ft^2$]) can each house up to 50,000 birds. The floor of such barns (concrete or soil) is covered with organic material to a depth sufficient to serve as bedding that insulates the floor in cold weather, cushions birds while walking or laying down, and absorbs moisture from bird droppings. Common and preferred bedding materials include pine shavings and rice hulls, but peanut hulls, sawdust, chopped straw, pine bark, hardwood shavings, and even sand are used as alternatives. Cost considerations and constraints in availability of suitable bedding materials may force broiler growers to use the same bedding to raise up to six broiler flocks before completely replacing the bedding. Generally, most growers clean out broiler houses of manure once a year and, depending on state regulations, place the manure in roofed stacking sheds with a concrete floor and full or partial walls, or stack manure in the open (either on pads or in the field) for short periods of time prior to land application.

Vertically integrated companies control the different stages of commercial turkey production in the same way as in the broiler industry. However, there are differences in how breeding stock are raised and managed and how production on grow-out farms is managed. Turkey genetics companies select turkeys for better performance traits and breeding farms produce fertile eggs that are taken to hatcheries. There, the eggs are incubated for ~3.5 wk and then moved to a hatcher, where they hatch after almost 4 wk. Poults receive various health-related servicing before they are taken to specially designed brooding houses for a period of 5–6 wk. They are then transferred to hen or tom grow-out farms until they reach the desired market weight of about 9.1 kg (20 lb) for hens and close to 22.7 kg (50 lb) for toms. They are then taken to processing plants and packaged for the market. The housing arrangement, growth, and manure management in turkey grow-out farms is similar to that for broilers.

## 4 | POULTRY MANURE CHARACTERISTICS

Table 2 shows a summary of estimated means of manure production rates and quality, as excreted, for broilers, layers, and turkeys. Note that the values for layers and turkeys are given as percentage deviations from those of broilers. The table shows that both manure production rates and nutrient content vary considerably by sector. For example, manure production rates (tonnes per animal unit per year) for layers and turkeys are ~30 and 60% lower, respectively, than for broiler chickens. In contrast, N on a wet weight basis is ~70 and 50% greater, respectively, and P is ~85 and 50% greater, respectively. Other nutrients also vary by sector.

Based on production factors described above and management practices determined at the farm scale, the amount and quality characteristics of manure from different poultry production operations is highly variable. Indeed, Ashworth et al. (2019) emphasize that values for the quantity and quality of manures, as excreted, are, at best, estimates useful for planning purposes since actual values can vary by up to 30% because of differences among operations within the same sector. Accurate assessment of the nutrient content of manure produced at individual poultry operations is a critical aspect of any nutrient management program, including the manureshed approach.

## 5 | POULTRY MANURE AS A FERTILIZER

Poultry manure can be a valuable source of fertilizer because it can contain all essential and some beneficial plant macro- and micro-nutrients, depending on types of feed, supplement, and enzyme additions used at a given poultry production facility (Tewolde et al., 2005). Poultry manure has been used as a fertilizer most extensively on forage and pasture crops grown near poultry houses, although it is also an effective fertilizer for row crops and forest trees (Endale et al., 2008; Lin et al., 2016; Mitchell & Tu, 2005; Tewolde et al., 2008). In recent years, interest in using poultry manure as a

**TABLE 2** Amount and composition of as-excreted manure from broilers, layers and turkeys modified from Kellogg, Moffitt and Gollehon (2014) and Ashworth et al. (2019)

| | | | Percent deviation from Broiler chicken | | | |
|---|---|---|---|---|---|---|
| | Broiler chicken | | Layer chicken | | Turkey | |
| **Characteristic** | **Wet wt.** | **Dry wt.** | **Wet wt.** | **Dry wt.** | **Wet wt.** | **Dry wt.** |
| Manure production | | | | | | |
| t/animal unit $yr^{-1}$ | 14.49 | 3.76 | −28.68 | −31.3 | −57.23 | −57.1 |
| N, kg $Mg^{-1}$ | 10.94 | – | 69.0 | – | 49.4 | – |
| P, kg $Mg^{-1}$ | 3.16 | – | 85.3 | – | 50.2 | – |
| Manure quality | | | | | | |
| Moisture, % | 74 | | 1.4 | | 1.4 | |
| Total solids, % | 26 | | −3.8 | | −3.8 | |
| Oxygen demand, mg $kg^{-1}$ | 197,000 | | −10.7 | | 19.8 | |
| Density, kg $m^{-3}$ | 1,025.2 | | −3.1 | | −1.6 | |
| | kg $Mg^{-1}$ | % dry basis | kg $Mg^{-1}$ | % dry basis | kg $Mg^{-1}$ | % dry basis |
| Total Kjeldahl N | 13.00 | 5.00 | 3.8 | 8.0 | 7.7 | 12.0 |
| Total ammoniacal N | 3.35 | 1.29 | −1.5 | 2.3 | 20.9 | 25.6 |
| Organic N | 9.65 | 3.71 | 5.7 | 10.0 | 3.1 | 7.3 |
| C | – | 40.60 | – | 3.9 | – | 3.9 |
| C/N ratio | – | 8.12 | – | −3.9 | – | −7.1 |
| Total P as $P_2O_5$ | 8.00 | 3.08 | 31.3 | 36.4 | 50.0 | 55.8 |
| Total K as $K_2O$ | 6.00 | 2.31 | 0.0 | 3.9 | 0.0 | 3.9 |
| Ca | 5.00 | 1.92 | 310.0 | 327.1 | 170.0 | 181.3 |
| Mg | 1.75 | 0.67 | 22.9 | 28.4 | −11.4 | −7.5 |
| S | 1.00 | 0.38 | 115.0 | 126.3 | 65.0 | 73.7 |
| Na | 1.75 | 0.67 | 2.9 | 7.5 | −20.0 | −16.4 |
| $Cl^-$ | 9.00 | 3.46 | 11.1 | 15.6 | 0.0 | 4.0 |
| Fe | 0.95 | 0.37 | 5.3 | 8.1 | 68.4 | 73.0 |
| | | mg $kg^{-1}$ dry basis | | mg $kg^{-1}$ dry basis | | mg $kg^{-1}$ dry basis |
| Zn | 0.04 | 162 | 75.0 | 72.8 | 675.0 | 665.4 |
| Cu | 0.01 | 38 | 0.0 | 5.3 | 50.0 | 57.9 |
| Mn | 0.10 | 385 | −20.0 | −16.9 | −50.0 | −48.1 |
| B | 0.03 | 115 | −16.7 | −13.0 | −99.8 | −73.9 |

low-cost alternative to inorganic chemical fertilizer sources has increased among row crop producers because of increasing prices for inorganic fertilizers, local availability, and the potential for improving crop production through increased soil organic matter and improved soil properties (Adeli et al., 2008; Nyakatawa et al., 2000).

Despite these potential advantages, traditional barriers to widespread poultry manure use include (a) limited availability at the appropriate time, (b) risks perceived by farmers due to variability in nutrient contents, (c) lack of expertise on how and where to use it, and (d) lack of information on how it performs under different tillage and crop management systems. In addition, applying poultry manure involves specialized equipment and possibly storage space. In contrast, commercial fertilizers are often applied by contractors. Although dry poultry manure is nutrient dense, long-distance transportation nonetheless remains costly, which has led to its repeated application to agricultural lands within short distances of poultry-producing facilities. Such practices can lead to overapplication and negative environmental impacts on air, soil, and water quality. Increases in concentrations of P, K, Ca, Mg, Cu, and Zn have been found for soils receiving poultry manure for an extended period of time (Kingery et al., 1994; Mitchell & Tu, 2006).

## 6 | MANURESHEDS

Spiegal et al. (2020) used data from the U.S. Census of Agriculture (USDA-NASS, 2013) and coefficients determined by

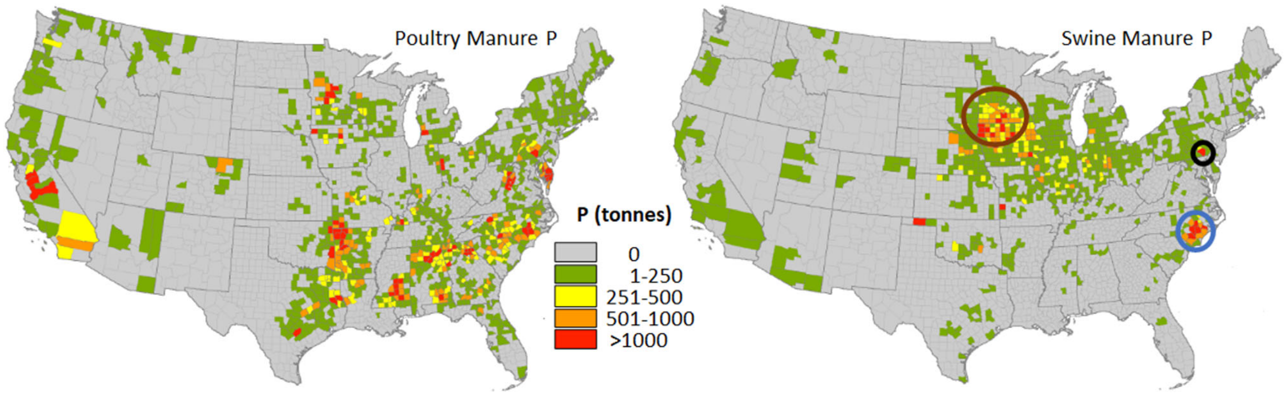


FIGURE 1 Tonnes of poultry and swine manure P produced by county in 48 conterminous states in 2012. Circled areas have concentrated production of both poultry and swine. Manure P totals were derived from a combination of U.S. Census of Agriculture (USDA-NASS, 2013) data and coefficients determined by Kellogg et al. (2014). For an in-depth explanation of these calculations, see Spiegal et al. (2020)

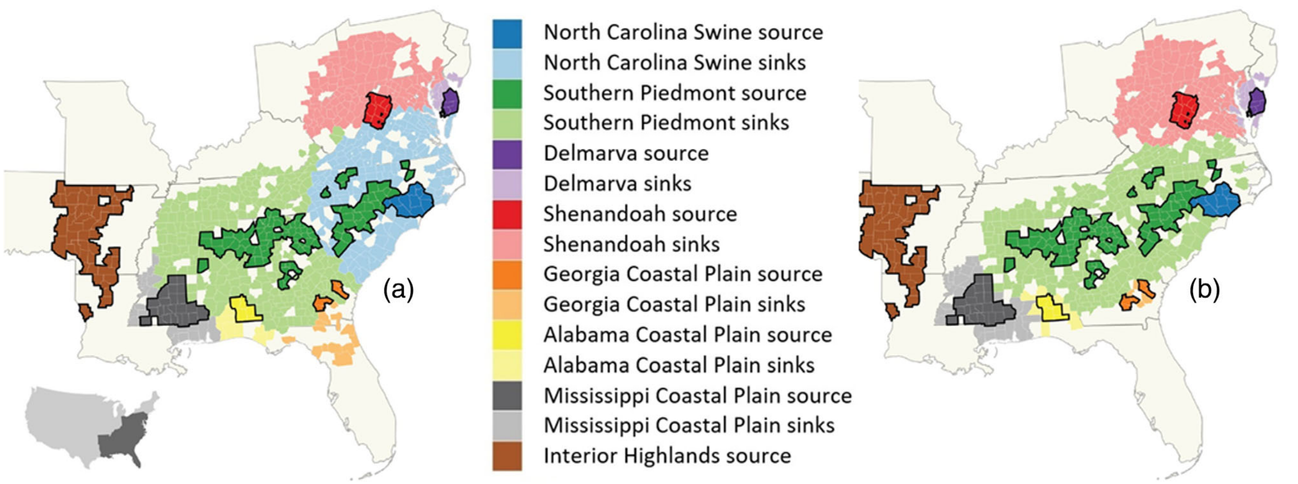


FIGURE 2 Mega-manureshed. Sources and sinks for P across the southeast (a) including and (b) excluding swine manure P. Counties shown in white are neither sources nor sinks, with many considered candidates for within-county transfers of manure and fertilizer because P inputs are roughly in balance with crop uptake. Data for the calculations of sources and sinks were obtained from the International Plant Nutrition Institute's (IPNI) Nutrient Use Geographic Information System (IPNI, 2012). Methods modified from Spiegal et al. (2020) were used to calculate the source and sink values, serving as the basis for the potential redistribution exercise depicted

Kellogg et al. (2014) to identify the magnitudes of manure P produced by the poultry and swine industries, respectively, in each of the 3,109 U.S. counties of the 48 conterminous U.S. states in 2012. Mapping these values shows that the poultry industry is widely distributed across the United States, but highest concentrations are found from the Mid-Atlantic (Delmarva peninsula, southeastern Pennsylvania, and northern Virginia), across the southeast, into Arkansas and Texas, and in pockets such as central California and across the border of Iowa and Minnesota (Figure 1). In contrast, manure P from swine production is largely concentrated in the Midwest. However, there are some notable areas where both poultry and swine production are concentrated, which complicates manureshed nutrient management. In the Midwest, turkey production overlaps swine production (circled in brown; Figure 1). In North Carolina, turkey and broiler production overlap swine production (circled in blue). And, in southeastern Pennsylvania, production of pullets, layers, and broilers coexists with concentrated swine production (circled in black). Because poultry manure is generally dry and swine manure is usually liquid, manure source type does affect opportunities and challenges for nutrient management, which is discussed below.

To further explore the concept of the manureshed, sources and sinks for P from the Mid-Atlantic across the Southeast were determined (Figure 2). Here, we used estimates from the International Plant Nutrition Institute's (IPNI) Nutrient Use Geographic Information System (IPNI, 2012) to

**TABLE 3** Summary of poultry and swine manure P source areas in the southeast, amount of P surplus, number of source counties, required number of sink counties to accept surplus P, and maximum transport distance required to assimilate surplus manure P from source areas to surrounding sink counties

| Manureshed | P surplus | Source counties | Sink counties a[a] | Maximum distance | Sink counties b[b] | Maximum distance |
|---|---|---|---|---|---|---|
| | Mg | ———— | *n* ———— | km | *n* | km |
| North Carolina swine | 21,407 | 11 | 156 | 317 | swine excluded | – |
| Southern Piedmont | 34,264 | 93 | 235 | 187 | 241 | 105 |
| Delmarva | 1,808 | 4 | 7 | 51 | 11 | 52 |
| Shenandoah | 11,254 | 8 | 116 | 252 | 139 | 235 |
| Georgia Coastal Plain | 675 | 6 | 13 | 225 | 4 | 15 |
| Alabama Coastal Plain | 717 | 5 | 8 | 81 | 8 | 38 |
| Mississippi Coastal Plain | 8,709 | 23 | 19 | 87 | 28 | 85 |

[a]For Sink counties a, the source-sink manureshed delineation starts with the North Carolina swine manureshed, then continues in order of listed manuresheds.
[b]For Sink counties b, the source-sink manureshed delineation starts with the Southern Piedmont manureshed, then continues in order of listed manuresheds .

identify manure-based P produced (tonnes per county aggregated among all livestock types), crop nutrient needs (tonnes per county based on the total need of 21 common crops/forages), and fertilizer applied to farmland (tonnes per county). A classification approach was then used to determine whether each county was a source or a sink (see Spiegal et al. [2020] for details). Source counties where poultry or swine dominated the manure production were selected and grouped into clusters for use in further analysis (dominance was based on methods described for Figure 1).

The next step was a stepwise spatial analysis (Figure 2) to identify the nearest sink counties available for redistribution of manure-based P from each source county cluster. This was accomplished by allocating the surplus manure P in each source cluster to the nearest sink counties until the source was balanced. When a county representing a sink was used, the spatial allocation of source values moves on to the next nearest sink county. The result was a "mega-manureshed," the largest contiguous area of source and sink counties in the United States (Figure 2). The mega-manureshed extends from the Mid-Atlantic, across the southeast, and into northwest Arkansas, Oklahoma, and Texas, because sinks for the Interior Highlands source area adjoin sinks for the Mississippi Coastal Plain source area in the Mississippi delta. However, for our analysis, we used the Mississippi River as the western boundary of our study area. Opportunities and constraints for manureshed management originating from the Interior Highlands was explored in detail by Spiegal et al. (2020).

When swine manure P is included in the manureshed (Figure 2a), 156 counties that can serve as sinks are required for redistributing surplus P from the North Carolina swine source, and the maximum hauling distance (measured from source cluster edge to sink county centroid) is 317 km (Table 3). Liquid swine manure has the lowest nutrient density of all forms of manure and is therefore the costliest to transport. If all liquid swine manure could be treated to remove P and eliminate the need to transport and land apply it to sink areas, the resulting manureshed for poultry manure P would shrink (Figure 2b). The maximum hauling distance for the Southern Piedmont source area decreases from 187 to 105 km (Table 3). The maximum hauling distance for all other source areas either decreases or remains the same. This analysis demonstrates that, under the manureshed concept, nutrient management issues faced by one industry do not exist in a vacuum. Rather, issues and challenges must be addressed at the level of agricultural production systems as a whole, including both animal and crop production.

The nation-wide analysis by Spiegal et al. (2020) identified some counties where commercial P fertilizers are applied, sometimes resulting in P surpluses, despite manure nutrients—which could have been used to offset fertilizer costs—being readily available. As highlighted in Cordell and White (2014), sources of inorganic P fertilizer are finite, motivating the need to recycle manure P more efficiently. These "sinks due to fertilizer surplus" were included in the manureshed analysis (Figure 2). In this way, manureshed analysis can be used to identify such apparent missed opportunities for recycling nutrients. Future industry expansion that includes locating new production in sink areas, while simultaneously considering other livestock production industries, can benefit agricultural industries and the environment. Redistribution of manure nutrients from source to sink areas is but one solution to achieving nutrient balance within a manureshed; manureshed nutrient management also includes other strategies for promoting the recycling of nutrients, including manure treatment.

## 7 | MANURE TREATMENT

Even though most poultry manure is relatively dry, bulkiness and water content remain major drawbacks to transportation of raw forms of poultry manure. Thus, fulfilling the distribution potential of manure nutrients outlined in the manureshed analysis described above might require that poultry manure be treated to allow for more economic redistribution. Compared with raw manure, treated manure often has lower transportation cost due to reduced bulkiness and water content while also having increased economic value and market potential.

Hao and He (2019) address pelletizing of animal manure and highlight improvements that could potentially increase use as a fertilizer. Pelletizing can reduce manure volume and weight by 20–50% while producing a product that is more uniform and easier to handle than unpelletized manure. Pelletizing reduces storage, transportation, and application costs. Pelletized manure can be used off-farm in horticultural production and on sport fields and parks, where unpelletized manure is not an attractive option due to odor issues or challenges surrounding storage and application. Inorganic fertilizers can be added during the pelletizing process, leading to the development of formulations for specific purposes, especially as slow-release fertilizers. Although the benefits of pelletizing are attractive, success is not guaranteed. An early pelletizing plant that could produce 72,575 Mg (80,000 tons) s of fertilizer pellets per year—Agri-Recycle (Georgetown, DE), a Perdue subsidiary—was never profitable and no longer pelletizes poultry manure. Profit margins and demand for pelletized litter can depend on fertilizer price, commodity prices, and cost of pellet production. Currently there are about a dozen pelletizing plants operating across the country. Most process layer manure, but some process broiler litter. In Pennsylvania, construction will soon begin on a pelletizing plant that will process 726 Mg (800 tons) of manure per day for 225 d $yr^{-1}$. The system will move the pelletized product to New Jersey for sale to home gardeners and vegetable farmers, removing 4,980 and 4,736 Mg of N and P, respectively, from manureshed source counties in the state. The new facility will process only layer manure that is dried on modern in-house belts, reducing manure moisture to increase process efficiencies. The product can satisfy nutrient requirements under organic vegetable production guidelines and replace commercial fertilizer use in sink areas. Hao and He (2019) note that pelleting is a promising option for managing animal manures but emphasize that more research is needed on all aspects of this technology.

During composting, when done properly, components of poultry manure (feces, urine, wasted food, bedding) are decomposed, producing a material that has a finer, more uniform texture a that is well-suited for pelletizing. Benefits of composting include volume and odor reduction compared with raw manure and destruction of harmful pathogens and weed seeds (Modderman, 2019). Compost from poultry manure produced by non-organic operations can satisfy organic certification and manure application timing requirements for organic vegetable production because the process kills pathogens and breaks down any antibiotics that may have been used in production.

Vanotti et al. (2019) present a good summary of several nontraditional approaches to manure treatment including on- or off-site removal and recovery of nutrients from manure. They describe a variety of biological, physical, or chemical removal and recovery processes and agronomic use of the resulting products. Of particular note are two patented processes for efficient P recovery from liquid manures as magnesium ammonium phosphate crystals (struvite) and as calcium phosphate. We do not address these here but refer readers to this reference.

Although animal manure is primarily used as fertilizer, it also has other beneficial uses. Several articles in Waldrip et al. (2019) address this topic. For example, Guo et al. (2019) describe the potential of animal manure, with its high organic carbon and mineral nutrient content, as feedstock for bioenergy and biochar production. They address combustion, pyrolysis, gasification, and hydrothermal liquefaction as thermochemical techniques feasible for converting animal manure into valuable bioenergy and/or biochar products. Combustion is an efficient method for producing bioenergy from manure. Pyrolysis can produce biochar and bio-oil, gasification can produce syngas and biochar, and hydrothermal liquefaction can produce biocrude oil and hydrochar. Guo et al. (2019) stress that, although they are technically feasible, these methods need to be improved for economic viability. Studies are also needed to ascertain effectiveness and safe use of products and residuals.

## 8 | LEGACY P

Repeated overapplication of P to crops in excess of crop removal results in an accumulation of soil P, referred to as "legacy P" (Kleinman et al., 2011; Lou et al., 2018). There is broad consensus that loss of dissolved P from legacy P soils is one of the greatest challenges to improving water quality by reducing P loads (Jarvie et al 2013; Kleinman et al, 2019; Sharpley et al., 2013). "Phytomining" (i.e., creating a negative P balance by harvesting crops without P inputs) has been proposed as a strategy for mitigating legacy P (Svanback et al., 2015). In the manureshed analysis, manure P from source areas is allocated to sink areas to meet, but not exceed, crop needs. The challenge presented by legacy P, and not addressed in our analysis, is that if soils in sink areas contain legacy P, any additional P input compromises the phytomining strategy.

Sabo, Clark, et al. (2021) estimated legacy P accumulation from 1945 to 2001 across the conterminous United States as the sum of the annual time series of the difference between total annual inputs and nonhydrological annual outputs (i.e., crop removal). Figure 3 shows the distribution of legacy P in the mega-manureshed developed from

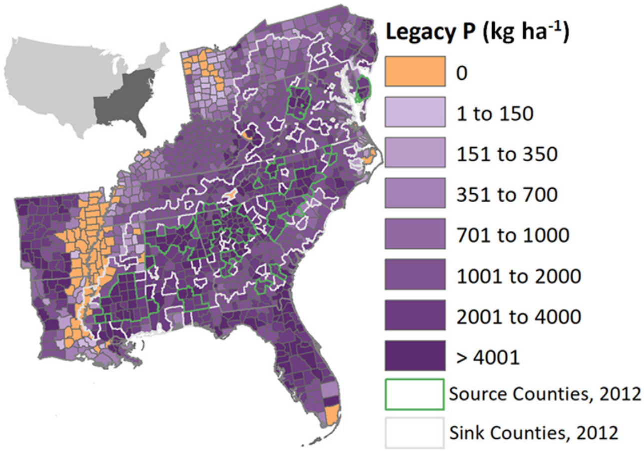


**FIGURE 3** Legacy P by county in the mega-manureshed region. Poultry source areas outlined in green; sink areas outlined in white (Figure 2; Sabo et al., 2021)

county-based data compiled by Sabo, Clark, et al. (2021) normalized by crop and forage areas per county. The Southern Piedmont source area had the highest legacy P, with a mean content of 6,333 kg ha$^{-1}$. Mean legacy P content in sink areas ranged from 1,260 kg ha$^{-1}$ in the Delmarva to 3,294 kg ha$^{-1}$ in the Alabama Coastal Plain.

Phosphorus indices are designed to identify soils with high legacy P levels that pose environmental risks to water quality and restrict additional P inputs. The manureshed analysis balances P input with crop removal, but if some soils are eliminated as candidates for P input due to high levels of legacy P, the geographical size of the required sink area might be greatly expanded. Because of uncertainties in the accurate inventorying of all inputs and outputs of the legacy P dynamics at the county scale that our study is focused on, we chose not to include legacy P in the source-sink–based manureshed analysis. Instead, we show legacy P as a separate entity (Figure 3) to stress that it must be considered in any practical transfer of animal manure nutrients from surplus to deficit areas.

## 9 | EXPERIENCE AND POTENTIAL FOR MANURESHED MANAGEMENT IN THE U.S. POULTRY INDUSTRY

The U.S. poultry industry, more than livestock industries, has participated in government-driven and informal efforts to redistribute poultry manure away from its source. Well-documented cases of regional manure management include the Perdue AgriRecycle plant of the Delmarva Peninsula (Dance, 2017), the FibroMinn manure-to-energy plant associated with Minnesota's turkey industry (Dunbar, 2017), and the Eucha-Spavinaw/Illinois River broiler litter transport program resulting from a litigated settlement between Arkansas and Oklahoma (Kleinman et al., 2015). Driven by regulation, government intervention has been required to implement and sustain these efforts, all of which have experienced challenges. In addition, there is considerable entrepreneurial experience with poultry litter transport from barn source to cropland destination. Poultry manure brokering programs and transport businesses for poultry manure are documented across the country, resulting in manure transfer within and across state lines (Mettler, 2008). Perils to commercial transport stem from narrow margins, unstructured markets, and changing markets (Kleinman et al., 2012; Ribaudo et al., 2003).

In addition to needing coordination between government and industry to frame the drivers and desired outcomes of manureshed management, systematic innovation and implementation of technologies, on and off the farm, is imperative for manureshed-scale nutrient management to succeed. For the U.S. poultry industry, innovation includes technologies and management strategies that concentrate nutrients, eliminate harmful pathogens, and produce a material with a consistent quality. Diverse innovations include using litter amendments to improve the stoichiometry and availability of nutrients in manure, particularly N/P (e.g., alum, Poultry Litter Treatment); processing manure to drive off moisture and kill pathogens (e.g., in-house dryers and composting, litter roasting, litter incineration); transporting and storing manure to ensure it is available on-demand by crop farmers, mushroom growers, and other end users (e.g., litter baling and wrapping); pelletizing; and cost-efficient delivery of manure nutrients to crops (e.g., subsurface application of manure).

Even with widespread vertical integration, the generally transportable and beneficial nature of dry manures as a soil amendment and fertilizer substitute, and considerable experience with facets of regional manure management, the U.S. poultry industry faces challenges, small and large, in achieving widespread implementation of manureshed nutrient balances as depicted in Figure 2. The vertical integration that is characteristic of meat and egg production components of the industry lends itself well to the infrastructure requirements and collective decision making needed to achieve manureshed management. As manure treatment innovations evolve, the U.S. poultry industry is poised to take advantage of insights gained from the manureshed approach to target manure nutrient redistribution efforts. Managing this redistribution will require the concerted and cooperative efforts of the poultry industry; farmers; government officials; manure brokers, haulers, and applicators; and others.

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## AUTHOR CONTRIBUTIONS

Ray B. Bryant, Supervision, Visualization, Writing-original draft, Writing-review & editing. Dinku M. Endale, Conceptualization, Investigation, Visualization, Writing-original draft, Writing-review & editing. Sheri A. Spiegal, Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Software, Writing-review & editing. K. Colton Flynn, Data curation, Formal analysis, Methodology, Software, Writing-review & editing. Robert J. Meinen, Investigation, Validation, Writing-review & editing. Michel A. Cavigelli, Investigation, Validation, Writing-review & editing. Peter J. A. Kleinman, Conceptualization, Investigation, Project administration, Supervision, Writing-original draft, Writing-review & editing.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## ORCID

*Ray B. Bryant* https://orcid.org/0000-0002-7464-4138
*Dinku M. Endale* https://orcid.org/0000-0001-5106-8468
*Sheri A. Spiegal* https://orcid.org/0000-0002-5489-9512
*Robert J. Meinen* https://orcid.org/0000-0002-3309-3528
*Michel A. Cavigelli* https://orcid.org/0000-0003-1483-018X
*Peter J. A. Kleinman* https://orcid.org/0000-0002-5093-3736

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