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Manuresheds: Advancing nutrient recycling in US agriculture

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ABSTRACT

Nutrient recycling is fundamental to sustainable agricultural systems, but few mechanisms exist to ensure that surplus manure nutrients from animal feeding operations are transported for use on nutrient-deficient croplands. As a result, manure nutrients concentrate in locations where they can threaten environmental health and devalue manure as a fertilizer resource. This study advances the concept of the "manureshed" – the lands surrounding animal feeding operations onto which manure nutrients can be redistributed to meet environmental, production, and economic goals. Manuresheds can be managed at multiple scales, for example, on farms with both animals and crops, among animal farms and crop farms within a county, or even among animal farms and crop farms in distant counties. With a focus on redistribution among counties, we classified the 3109 counties of the contiguous United States by their capacity to either supply manure phosphorus (P) and nitrogen (N) from confined livestock production ("sources") or to assimilate and remove excess P and N via crops ("sinks"). Manure nutrient source counties were identified in 40 of the 48 states, with a substantial concentration in the southern US. Source counties for manure P greatly outnumbered source counties for manure N (390 vs. 100), and 99 of the 100 manure N source counties were also source counties for manure P. Conversely, sink counties for manure N outnumbered sink counties for manure P (2766 vs. 2317). We used the P balances of the source and sink counties to delineate four manuresheds dominated by various combinations of confined hog, poultry, dairy, and beef industries. The four manuresheds differed in the transport distances needed to assimilate excess manure P from their respective source areas (from 147 ± 51 km for a beef dominated manureshed to 368 ± 140 km for a poultry dominated manureshed), highlighting the need for systems-level strategies to promote manure nutrient recycling that operate across local, county, regional, and national scales.

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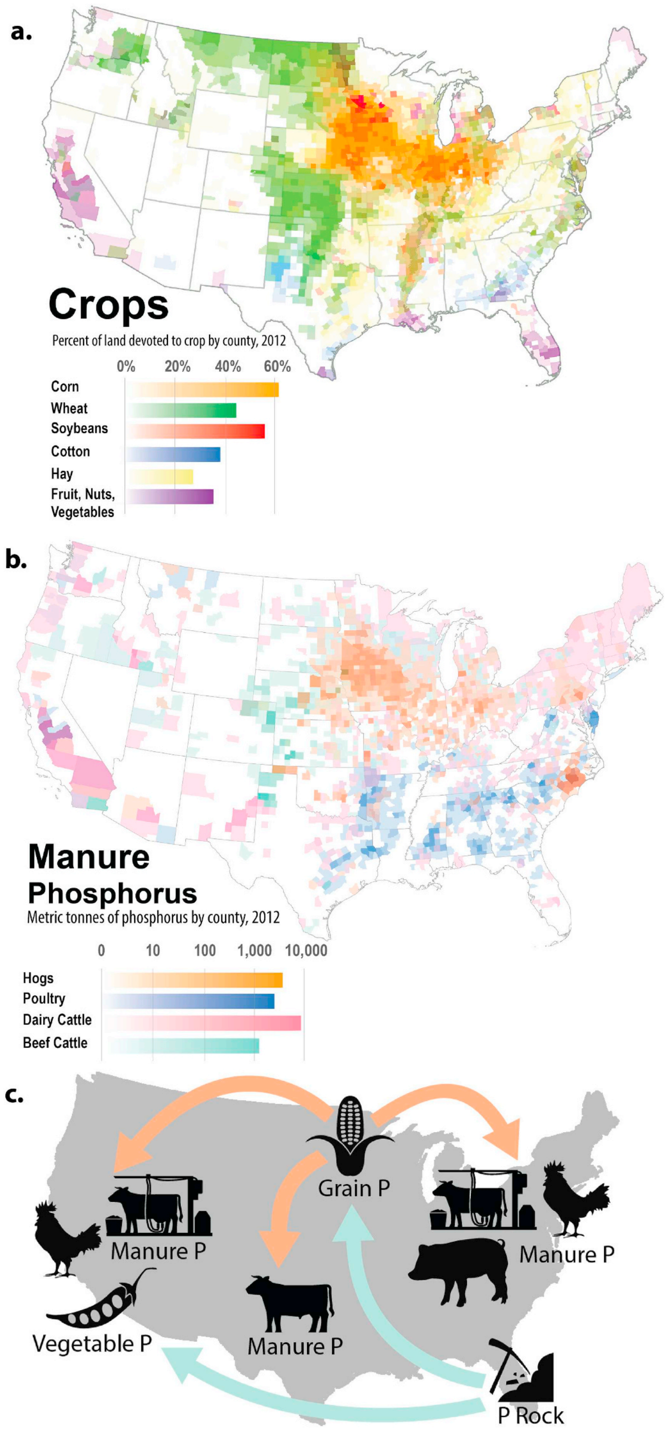


Fig. 1. a) Distribution of major commodity crop types, as a percentage of county area in 2012 (USDA-NASS, 2014). b) Manure phosphorus produced by four confined livestock industries in 2012 (supplement 1.2). c) Major phosphorus flows in the United States, from mining of sedimentary deposits in the Southeast, to fertilization of Midwestern grains, to accumulation in several animal production regions.

1. Introduction

Recycling of nutrients from crops to livestock and back again facilitated the spread of agriculture through about 1950, when the Green Revolution and complementary Livestock Revolution fragmented longstanding nutrient cycles to promote sustained yields for the largest, healthiest human population to date (Ramankutty et al., 2018). Yet as agricultural systems have become more specialized and production practices more intensive, few concomitant structures have been developed to ensure that surplus manure nutrients from animal feeding operations are returned to the lands where feed is grown (Sidebar; Fig. 1a–c). As a result, manure nutrients have accumulated in and around feeding operations, with consequences for water quality, air quality, and quality of life (Davidson, 2009; Raudsepp-Hearne et al., 2010; Chadwick et al., 2011). At the same time, long-term reliance on commercial fertilizers has raised well-documented concerns about food production and environmental health alike (Fields, 2004; Galloway et al., 2008; Ravishankara et al., 2009; Edixhoven et al., 2014).

Sidebar: The specialization and concentration of US agriculture and fragmented nutrient cycles

US agriculture has become increasingly specialized, so that crop and livestock production have been disconnected, and concentrated, so that fewer, larger farms are producing the nation's overall food supply. In concert with vertical integration – which began in the 1950s for poultry and in the 1990s for hogs, and is now expanding in the finishing phases of beef production – specialization and concentration have contributed to intensive animal production being constrained to particular geographic regions of the United States (Dimitri et al., 2005; MacDonald and McBride, 2009).

Now, regions supporting particular livestock types do not necessarily overlap with regions that produce feed for that livestock – as is the case with corn that is produced largely in the upper Midwest (Fig. 1a) that is fed to, and excreted by, poultry and hogs in the South (Fig. 1b) (Layman, 2018). As few technologies, policies and incentives exist to return the manure from regionally-specific animal feeding operations to regionally-specific croplands to produce more feed for the animals, nationwide nutrient cycles are fragmented (Fig. 1c). The concept of a "manureshed" builds the understanding and the mechanisms for livestock manure nutrients to return to agricultural land where they are needed – across regions, county lines, and fence lines.

Agricultural producers in the United States commonly use manure as a source of crop nutrients (Russelle et al., 2007; Kleinman et al., 2011; Larney et al., 2011; Powers et al., 2019), and to address water quality concerns associated with the concentration of manure nutrients, community programs have been established that promote manure transport from areas of intensive animal production to nutrient-deficient agricultural lands (e.g., MacDonald, 2006; Herron et al., 2012; Dance, 2017; Pipkin, 2017). However, these programs have often faced, or even succumbed to, logistical and market challenges. To succeed, such programs require not only prudent guidance for producers and recipients, but also technologies that help overcome the challenges of using manures as fertilizer (Lory et al., 2008; Uutiset, 2018), infrastructures for transporting manure in a timely and safe fashion, and a supportive regulatory context (Kleinman et al., 2020). Improving understanding about *where* opportunities exist to relocate manure from areas of surplus to areas that can use the surplus is a critical first step for optimizing manure redistribution (Metson et al., 2016).

Our objective is to develop the concept of the manureshed – the lands surrounding animal feeding operations onto which manure nutrients can be redistributed to meet environmental, production, and economic goals (cf. Saha et al., 2018). Manuresheds can be managed at multiple scales: on farms with both animals and crops where the animals' manure is applied to the farm's croplands (Fig. 2a), among animal farms and crop farms within a county (Fig. 2b; Niskanen et al., 2020; Tomer et al., 2008), or even among animal and crop farms in neighboring or distant counties (Fig. 2c; e.g., Metson et al., 2016). The extent of a manureshed depends on the type of manure to be spread and the environmental, social, economic, and technological opportunities for spreading manure nutrients in the lands surrounding the livestock

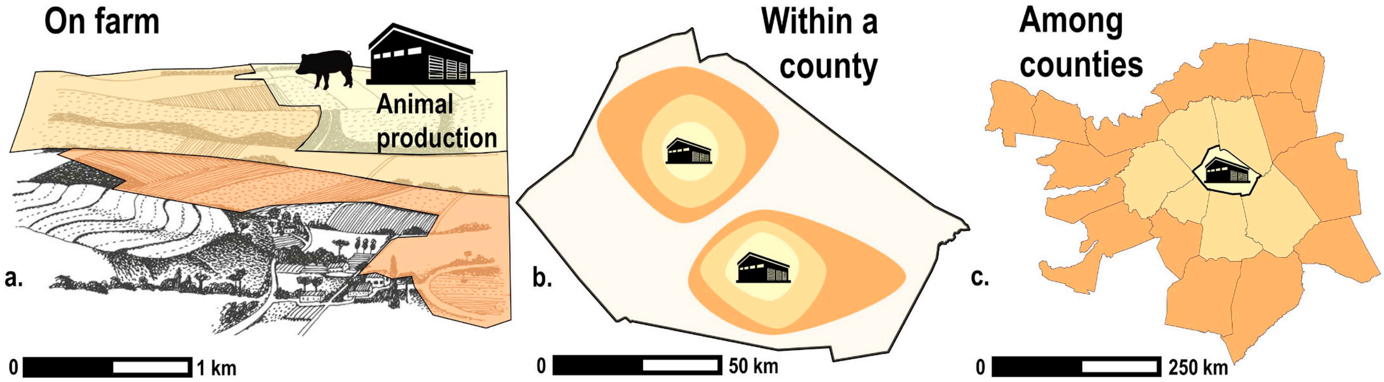


Fig. 2. A manureshed encompasses the lands surrounding animal feeding operations onto which manure nutrients can be redistributed to meet environmental, production, and economic goals. Manuresheds can be managed at multiple scales, for example: a) on-farm; b) among farms within a county; or c) among farms in different counties. Here, the darkening of buffers represents increased distance from the manure source.

operations. Over time, the size and shape of a manureshed may shift as producers relocate spreading in response to the build-up of manure nutrients (Brady and Weil, 2002), and emerging opportunities.

2. Materials and methods

We aggregated data from the Nutrient Use Geographic Information System (NuGIS; IPNI, 2012) and the 2012 United States Census of Agriculture (USDA-NASS, 2014) to first quantify nutrients in manure, farmland fertilizer, and crop removal in the 3109 counties of the 48 contiguous United States as of 2012; then classify counties as manure nutrient sources and potential sinks; and ultimately delineate inter-county manuresheds specific to particular livestock industries (sensu Fig. 2c). Finally, we use the manuresheds to discuss opportunities for advancing nutrient recycling in US agriculture.

Manuresheds were identified by connecting assemblages of counties where manure nutrients exceeded the assimilative capacity of farmland (sources) with nearby counties where manure could have been presumably used to fertilize farmland (sinks). We elected to delineate sources and sinks at the county level as opposed to finer scales (sensu Fig. 2a–b) or watershed scales (sensu Yang et al., 2016), because socioeconomic patterns and processes are key drivers of the production and recycling of manure nutrients, and many informative socio-economic and agricultural production data sets in the US are reported at the county level (sensu Raudsepp-Hearne et al., 2010).

Moreover, while we recognize innovative approaches to collecting and redistributing manure deposited diffusely across grazingland settings (Macintosh et al., 2018), we elected to focus on manure produced by confined livestock that is routinely collected and removed from built areas, because of the current challenges in collecting manure dispersed over landscapes (Kellogg et al., 2014). Our analysis covers only phosphorus (P) and nitrogen (N) because of their role as major fertilizer nutrients, the elevated environmental concerns associated with these elements, and a historical emphasis on their sustainable use in agriculture (Tilman et al., 2002). In addition, we approach the recycling of manure P and N in a general fashion, emphasizing the recovery of these nutrients for cropland or grazingland production that is feasible and responsible, rather than adhering to a strict sense of the term "recycling" in which manure nutrients would return to the very cropland where livestock feed is produced. Yet given our focus on recovering fundamental constituents of manure (P and N), we do indeed consider the goal here to be that of "recycling" – differentiating it from "reuse" in the common environmental lexicon (e.g., Liboiron, 2016).

2.1. Data aggregation and processing

NuGIS is a tabular and spatial database developed by the International Plant Nutrition Institute (IPNI) for the US (IPNI, 2012). We downloaded tabular, county-level data for the year 2012 and performed unit conversions to build our own data table comprising the following variables in tonnes per county: manure P, N; fertilizer P, N applied to farmland; P, N removed by crops, and N fixation by crops (details in supplement 1.1). The manure nutrient variables represented nutrient available for land spreading or other uses *after* accounting for losses from collection, spillage, volatilization (N only), and denitrification (N only) (called "recoverable" by IPNI). The nutrient removal estimates comprised 21 common crops including forages, and their production values at harvest in 2012. In total, NuGIS provided values of zero or greater for manure, fertilizer, or crop removal nutrients for 3068 counties in the contiguous US, with 3060 counties having at least one positive value for one or more of the variables. These data were used to classify counties as sources or sinks, and to calculate the surplus manure nutrient or sink "strength" of the counties for manureshed delineation.

The county-level manure estimates from NuGIS represented all confined livestock per county. For our manureshed delineation, we sought to quantify the respective contributions of the confined hog, poultry, dairy, and beef cattle industries. To do so, we obtained county-level inventory and sales data from the 2012 United States Census of Agriculture for seven livestock types (confined dairy cows, beef cattle on feed, broilers, layers, pullets, turkeys, and hogs) (USDA-NASS, 2014); used coefficients and equations provided by Kellogg et al. (2014) to calculate tonnes of manure P and N produced by each livestock type; and aggregated the manure P and N production to the level of industry (hog, poultry, dairy, beef) for each county (details in supplement 1.2). Like the NuGIS data, these industry-specific manure nutrient estimates represented nutrient available for use *after* accounting for losses from collection, spillage, volatilization (N only), and denitrification (N only) (referred to as "recoverable" by Kellogg et al., 2014). In total 3052 counties were represented in the sales and inventory data downloaded from NASS. After we removed counties because their entries were undisclosed by USDA-NASS to protect producer anonymity, 2990 counties with positive, non-zero values for at least one industry remained for analysis. Of the 2990 counties, 2225 had > 12 animal units (AU) of confined livestock in one or more livestock type – these were the counties for which industry-specific manure P and N were calculated (supplement 1.2).

We joined our NuGIS data table and industry-specific manure nutrient data table by unique Federal Information Processing Standard (FIPS) codes, using county names and codes recognized by the US Census Bureau as of 2012 as the definitive authority (Walker, 2019). The US Census Bureau recognized 3109 counties in the contiguous US, more than were reported in NuGIS and the downloaded Census of Agriculture data items. "Extra" counties were assigned to have zero generalized and industry-specific manure, fertilizer, and crop removal (41 counties were assigned all zeroes in the case of NuGIS; 119 counties were assigned all zeroes in the case of industry-specific manure P and N).

With regard to just manure P and N, NuGIS reported positive values for 3032 counties, whereas positive, industry-specific values were estimated for only 2225 counties. The discrepancy was due to methodological differences between IPNI (2012) and Kellogg et al. (2014), especially concerning non-disclosed data in the Census of Agriculture and the threshold at which to convert AU per county into manure nutrient estimates (supplement 1.2). As a quality-control check, we quantified the correlation of the sums of manure P and N from all industries per county and the general manure P and N derived from NuGIS per county – both on the basis of 3109 counties. Pearson's correlation was 0.9 ($p < .001$) for both P and N, and we deemed that using the datasets together was acceptable for our analytical purposes.

Data wrangling, county classification, manureshed delineation, and associated mapping described below were conducted in R 3.6.0 using the tidyverse set of packages (R Core Team, 2018; Wickham et al., 2019).

2.2. County classification based on nutrient source and sink potential

The 3109 counties of the contiguous United States were classified progressively (Table 1) as sources, sinks, or candidates for within-county transfers, using county-level estimates for P and N derived from NuGIS. Here we use estimates in terms of tonnes per county as inputs into the classification; the same classification conducted in terms of kilograms of P or N per hectare of harvested cropland per county is available in supplement 2.1. Values were rounded to two places for the classification analyses.

Counties in which manure nutrients exceeded crop nutrient removal were first classified as sources (step 1 in Table 1). Next, counties with < 500 ha of cropland that were not sources were excluded from further classification (step 2). Counties in which crop removal exceeded nutrients applied in manure and fertilizer were then classified as potential sinks for nutrients (step 3), as were counties in which fertilizer was applied at rates exceeding crop removal (step 4). The latter sink category (step 4) may reflect fertilizer rate adjustments due to lesser nutrient use efficiency, including build-up to maintain soil fertility recommendations (Raun and Johnson, 1999; Macnac et al., 2012). The remaining counties – where neither manure nor fertilizer alone exceeded cropland removal, yet cropland removal was exceeded by the sum of the two exceeded it cropland removal – were identified as candidates for within-county nutrient transfers. In those counties, the management focus would be transferring the manure nutrients to be used in place of fertilizer nutrients within the counties, with less focus on inter-county nutrient export or import.

The rules described above included a variety of assumptions, some of which were different for P and N. For both P and N, it was assumed that the manure nutrient was spread for recycling on all harvested cropland and grazingland per county. Whereas all P applied in manure and fertilizer was assumed to be assimilated and removed by the harvest during the course of 2012, only 50% of the N applied was assumed to be assimilated and removed (sensu Lassaletta et al., 2014). The lesser efficiency of N use by crops reflects N losses by volatilization, leaching, immobilization, and other pathways. Although N utilization varies with soils, management, climate, and scale of inference, average N use efficiencies for the US are often in the range of 30–80% (e.g., Lassaletta et al., 2014; Swaney et al., 2018). To capture the central tendency, a factor of 0.5 was applied to the manure and fertilizer terms for N in mathematical statements of Table 1. We evaluated the sensitivity of our results to this factor by comparing outcomes when 0.3, 0.5, or 0.8 were applied (supplement 2.2). Differences in conclusions were minor, so we deemed the factor of 0.5 to be appropriate for our ultimate purpose of delineating manuresheds.

Another assumption for both P and N was that counties with < 500 ha of total cropland should be excluded as potential sinks or candidates for within-county transfers. This decision reflects our experience and observation that investments in manure import and spreading are rare in counties with negligible extents of cropland. The exclusion decision was further supported by a known data anomaly in the NuGIS database, in which fertilizer estimates in several counties with negligible cropland greatly exceeded expected rates (supplement 2.3).

After classifying the 3109 counties, we mapped them in terms of quantiles in each class (after MacDonald et al., 2011), to illustrate their degree of surplus manure nutrient (source counties) or their sink "strength" (sink counties). Sink strength was calculated as either the amount of nutrient in deficit or the amount of commercial fertilizer in excess of crop removal. We also calculated the mean, standard deviation, and N:P ratio of the nutrients in the county-level manure, fertilizer, and crop removal within the county classes. N:P ratios ultimately informed the decision to delineate manuresheds only on the basis of manure P.

We evaluated the accuracy of our data sources and county classification by comparing the quantile maps and summary statistics against local knowledge and published data about typical P and N balances

Table 1

Step-wise rules for the county classification used to delineate manuresheds. Rules can apply to total mass or areal concentration of P or N per county.

Step	Rule	Class
Phosphorus (P)		
1	P in manure[a] – P removed by crops[b] > 0	Manure P Source
2	Total cropland in county < 500 ha	Excluded from further classification
3	P in manure + P fertilizer applied – P removed by crops < 0	Sink due to P deficit
4	P fertilizer applied – P removed by crops > 0	Sink due to P fertilizer surplus
5	P in manure – P removed by crops ≤ 0 & P in fertilizer – P removed by crops ≤ 0 & P in manure + P fertilizer applied – P removed by crops ≥ 0	Candidate for Within-County Transfers of Manure P
Nitrogen (N)		
1	0.5 * N in manure – (N removed by crops – N fixation) > 0	Manure N Source
2	Total cropland in county < 500 ha	Excluded from further classification
3	0.5 * (N in manure + N fertilizer applied) – (N removed by crops – N fixation) < 0	Sink due to N deficit
4	0.5 * N fertilizer applied – (N removed by crops – N fixation) > 0	Sink due to N fertilizer surplus
5	0.5 * N in manure – (N removed by crops – N fixation) ≤ 0 & 0.5 * N in fertilizer – (N removed by crops – N fixation) ≤ 0 & 0.5 * (N in manure + N fertilizer applied) – (N removed by crops – N fixation) ≥ 0	Candidate for Within-County Transfers of Manure N

[a] Manure nutrient produced by confined livestock and available after accounting for losses from collection, spillage, volatilization (N only), and denitrification (N only).

[b] Includes forages.

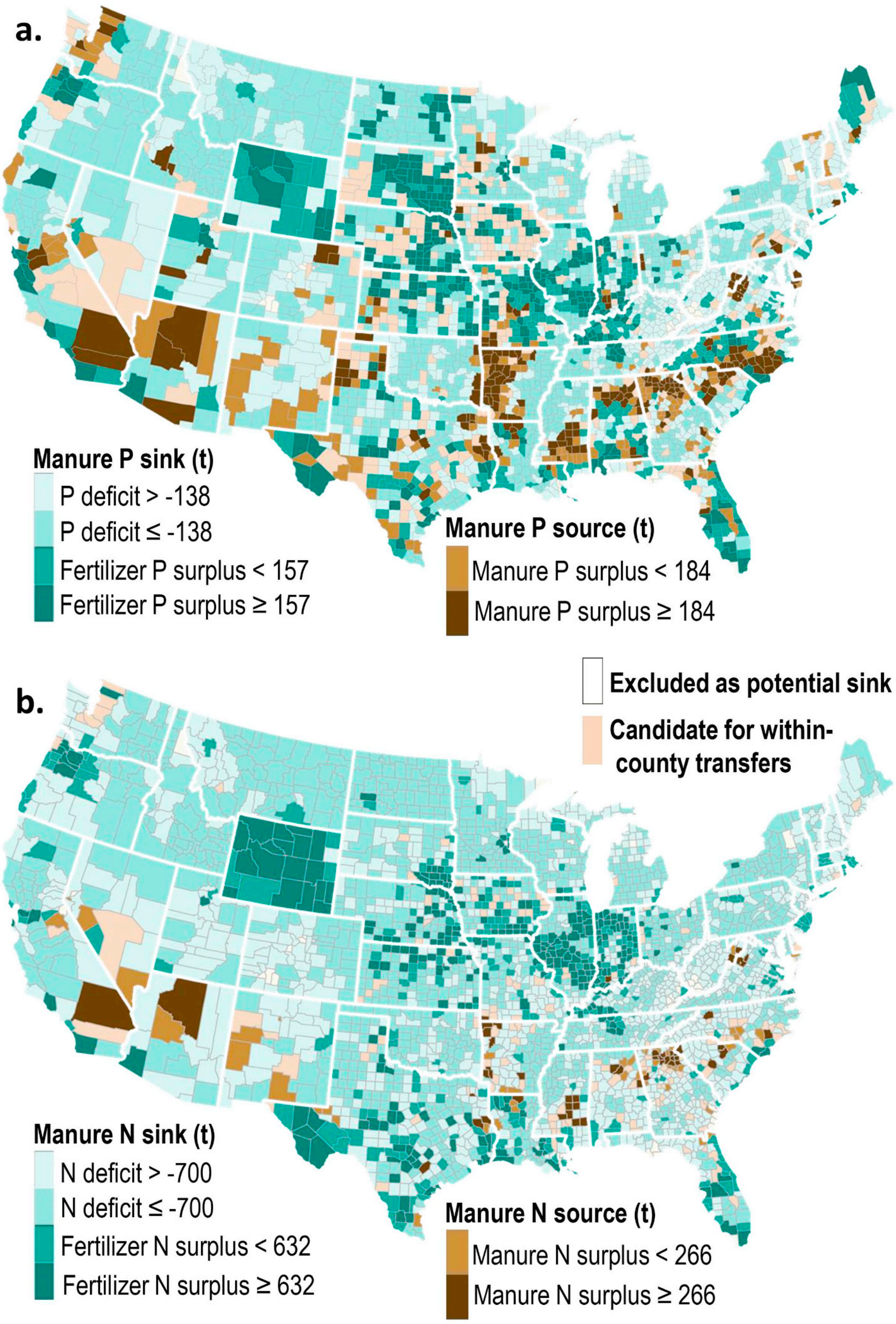


Fig. 3. Counties classified with respect to manure nutrient source and sink potential for a) phosphorus (P) and b) nitrogen (N) in 2012. Each class's shade of color (lighter vs. darker) represents a split at the median value of the class. See supplement 2.1 for maps in terms of kilograms of nutrient per hectare of harvested cropland per county.

(e.g., Pierzynski and Logan, 1993). We encountered a few surprises for some counties, but as we found reasonable explanations for them (supplement 2.3), we used the classes and nutrient balances as the basis for the manureshed analyses described next.

2.3. Delineating manuresheds

We delineated four manuresheds as representative examples of major confined livestock industries in the United States: poultry, hog, dairy, and beef. Manuresheds were delineated only on the basis of P source and sink strength, because statistical analyses of our county classes revealed that N-based redistribution of manure surplus from source to sink would over-apply P relative to crop demand (section 3.1). Relatedly, with the exception of one county, all source counties for manure N were also source counties for manure P, and thus it was assumed that calculating manuresheds on the basis of P would also encompass manure N redistribution.

We selected source areas for the manuresheds by first identifying assemblages of counties that comprised the largest available count of neighboring P source counties dominated by one livestock industry (hog, poultry, dairy, or beef) and then expanding the boundaries to include all adjacent P source counties. Industry dominance within each assemblage was assessed using the relative proportion of manure P produced by each industry, per our county-level estimates derived from the 2012 Census of Agriculture (USDA-NASS, 2014; Kellogg et al., 2014). Due to methodological discrepancies between the NuGIS and

Census of Agriculture data sets explained above, we had industry-specific estimates for about 90% of our source counties.

We performed cluster analysis to assess the cohesiveness of livestock industries in the delineated source areas (supplement 3.1), for purposes of accurately describing the composition of the source areas. In addition, we sought to verify that each selected assemblage of source counties had sink counties in its vicinity. To do so, we quantified, for each county nationwide, the spatial autocorrelation between county-level manure P surplus and county-level sink strength for P, with respect to ten nearest neighbor counties (Getis and Ord, 1992; supplement 3.2).

Once satisfied that our selected assemblages of source counties were adequately cohesive in livestock industry composition and were locally spatially correlated with sink counties, we conducted the manureshed analyses. First we unioned each assemblage into a source area polygon. Manure P surplus (in tonnes) was summed across all counties in each source area polygon. Next, Euclidean distance was calculated between the centroid of each sink county nationwide and the nearest edge location of each source area polygon (Pebesma, 2018). We then cumulatively summed the sink strength of sink counties at progressively longer distances from each source area edge. The set of nearest sink counties with a cumulative sink strength that equaled the surplus manure nutrient in the source area was designated as the set of "requisite" sink counties to assimilate the surplus from the source area.

Manuresheds were named for their general geographic location and their dominant and – if present – subdominant livestock industries. We calculated summary statistics for each manureshed: the tally of county types within the manureshed (count of counties), the relative contribution of livestock industries to the total manure P in the source area (percent), the total wet weight of manure produced in the source area (tonnes), and the average minimum distance required to travel from source area counties to requisite sink counties for manure nutrient recycling, in terms of Euclidean distances between source and sink county centroids (kilometers).

3. Results

3.1. County classification

Manure source counties were identified in 40 of the 48 contiguous United States, with a substantial concentration in the southern part of the country (Fig. 3; data available at Spiegal et al., 2020). Source counties for manure P greatly outnumbered those for manure N, with counts of 390 for manure P (~13% of all counties) and 100 for manure N (~3% of all counties). Ninety-nine of the 100 source counties for manure N were also source counties for manure P, the sole exception being Clark County, Nevada, which was a candidate for within-county transfers for P, but a source county for manure N. Clark County cropland was dominated by alfalfa hay production in 2012 (Fig. 1a), such that county-level N-fixation rendered manure N to be in excess of the assimilative capacity of county cropland [0.5 * 87 t manure N – (297 t N removed by crops – 267 t N fixation) = 13.5 t manure N surplus] (step 1 in Table 1 for N).

One hundred counties with < 500 ha cropland were excluded from the pool of counties to be classified as sinks or candidates for within-county transfers of P from manure stocks to fertilizer stocks; 106 were excluded for N. The discrepancy between P and N consisted of six counties with < 500 ha cropland that were source counties for manure P but not for manure N (Alpine County, California; Clayton County, Georgia; Dekalb County, Georgia; Duke County, Massachusetts; Philadelphia County, Pennsylvania; and Storey County, Nevada).

Counties representing net nutrient sinks outnumbered manure nutrient sources by 6-fold for P and 28-fold for N. Arkansas and Georgia were among the states with the greatest proportion of source counties with surpluses of both P and N. Notably, in Tennessee, a state located between Arkansas and Georgia, the majority of nutrient sink counties were classified as sinks for both P and N – highlighting an interstate opportunity for manure nutrient recycling. All of the counties in Montana and Wyoming were potential sinks for P, due mainly to P deficits and fertilizer surpluses, respectively. For N, all of the counties in five states were potential sinks, either due to a crop N deficit or a fertilizer N surplus: New Hampshire, North Dakota, Utah, Vermont, and Wyoming.

Overall, 449 more counties were classified as potential sinks for N than for P. N deficit counties were more numerous than P deficit counties (2181 for N vs. 1642 for P). However, counties that were sinks due to a surplus of annual fertilizer application were roughly comparable for the two nutrients, with 675 counties for P and 585 counties for N. The sinks due to fertilizer surplus were clustered in the Midwest, but they were also distributed in the Southeast (e.g., Florida, Alabama and North Carolina) and the West (e.g., Texas, California, Oregon and Wyoming).

The number of counties identified for within-county transfers of manure nutrients to substitute for fertilizer nutrients was similar to the number of manure source counties for each nutrient: 302 counties for P and 137 for N. Notably, in the counties classified as candidates for within-county transfers of manure P, the mean N:P ratio in manure was below the stoichiometric range reported for crop removal in those counties (Table 2) – suggesting that supplemental N fertilization would be required to support within-county transfers of manure for fertilizer due to the greater N demand of crops when manure reuse is driven by manure P content.

The stoichiometry of nutrients in manure has been identified as a key factor leading to the accumulation of P in farmland soils (e.g., Sharpley et al., 2013). Indeed, the N:P removed by crops greatly exceeded the N:P in manures in all county classes (Table 2). In strong

Table 2
Amount of agricultural nitrogen (N) and phosphorus (P) in county classes in 2012. Mean and standard deviation are followed by range in parentheses.

	N (t)	P (t)	N:P ratio[a]
Manure P source counties (390 counties)			
Nutrient in manure[b]	1586 ± 2263	842 ± 1300	2.0 ± 0.5
	(0–16,324)	(0–10,557)	(0.07–4.2)
Fertilizer nutrient applied to farmland	1869 ± 3396	220 ± 411	9.8 ± 4.0
	(0–28,491)	(0–3661)	(2.1–25.5)
Nutrient removed by crops[c,d]	1617 ± 3086	355 ± 669	5.2 ± 1.1
	(0–34,282)	(0–6152)	(1.0–8.4)
Manure P sink counties due to P deficit (1642 counties)			
Nutrient in manure	149 ± 317	98 ± 188	1.9 ± 3.1
	(0–6245)	(0 – 3011)	(0.04–96.0)
Fertilizer nutrient applied to farmland	3790 ± 6701	472 ± 753	9.2 ± 8.8
	(4–161,079)	(0–8069)	(1.0–171.6)
Nutrient removed by crops	3404 ± 4339	859 ± 1080	4.3 ± 1.1
	(18–46,366)	(3–8657)	(1.0–8.4)
Manure P sink counties due to fertilizer P surplus (675 counties)			
Nutrient in manure	203 ± 297	139 ± 209	1.6 ± 0.7
	(0 – 2102)	(0–1724)	(0.4–9.3)
Fertilizer nutrient applied to farmland	8097 ± 7887	1296 ± 1367	7.0 ± 3.5
	(34–41,472)	(3–13,970)	(0.6–40.9)
Nutrient removed by crops	3426 ± 3743	918 ± 993	4.3 ± 1.3
	(17–29,459)	(3–5959)	(1.4–8.5)
Candidates for within-country transfers of P (302 counties)			
Nutrient in manure	750 ± 1391	458 ± 697	1.7 ± 0.7
	(0–15,697)	(0–6569)	(0.5–7.0)
Fertilizer nutrient applied to farmland	7081 ± 7820	1007 ± 1158	7.8 ± 3.0
	(42–39,223)	(6–5783)	(2.3–20.8)
Nutrient removed by crops	4946 ± 6148	1269 ± 1442	4.3 ± 1.1
	(30–60,167)	(9–11,320)	(0.9–8.4)

[a] Counties with values of zero for N or P were not included.

[b] Produced by confined livestock and available after accounting for losses from collection, spillage, volatilization (N only), and denitrification (N only).

[c] Includes forages.

[d] N removed by crops = N removed by crops – N fixation.

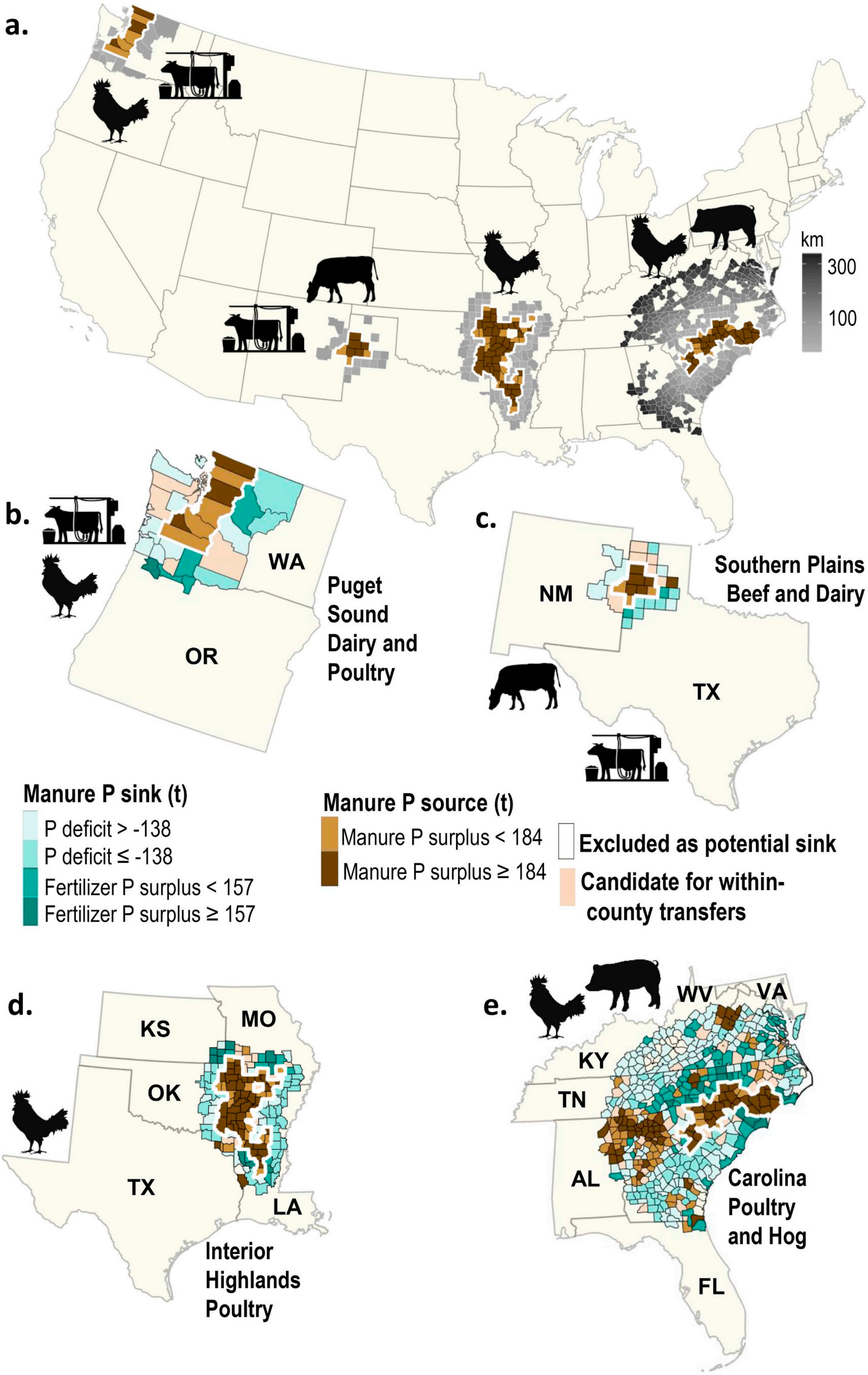
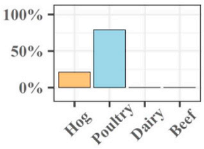
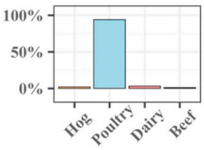
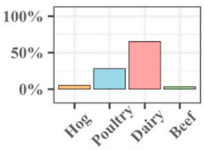
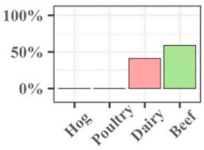


Fig. 4. Manuresheds in the contiguous United States with a) source counties in browns and sink counties required to assimilate the manure phosphorus (P) surplus from the source counties in grays; and all county classes in the manuresheds for b) dairy and poultry, c) beef and dairy, d) poultry, and e) poultry and hogs.

Table 3
Characteristics of manuresheds delineated for manure phosphorus (P) produced by US confined livestock industries in 2012.

Manureshed	Counties in source area	Manure in the source area[a]	Contributions of industries to total manure P in the source area[b]	Requisite sink counties Average minimum transport distance from sources to requisite sinks[c]
Carolina Poultry and Hog	36 counties: 23 in North Carolina 13 in South Carolina	Wet weight: 24.28 mil t Manure P: 53,897 t Surplus manure P: 39,566 t		297 counties: 220 with P deficit 77 with fertilizer P surplus 368 ± 140 km
Interior Highlands Poultry	55 counties: 38 in Arkansas 7 in Missouri 5 in Oklahoma 5 in Louisiana	Wet weight 12.58 mil t Manure P: 42,840 t Surplus manure P: 32,176 t		74 counties: 56 with P deficit 18 with fertilizer P surplus 283 ± 122 km
Puget Sound Dairy and Poultry	7 counties: All in Washington	Wet weight: 2.04 mil t Manure P 3396 t Surplus manure P 1628 t		12 counties: 10 with P deficit 2 with fertilizer P surplus 178 ± 68 km
Southern Plains Beef and Dairy	8 counties: 7 in Texas 1 in New Mexico	Wet weight 8.96 mil t Manure P 12,937 t Surplus manure P 4826 t		14 counties: 12 with P deficit 2 with fertilizer P surplus 147 ± 51 km

[a] Wet weights derived from the 2012 United States Census of Agriculture (USDA-NASS, 2014) and coefficients and equations from Kellogg et al. (2014). Manure P and surplus manure P derived from NuGIS (IPNI, 2012). Estimates account for losses from collection, spillage, volatilization (N only), and denitrification (N only).

[b] Mean contribution of industry per county in the source area, derived from the 2012 United States Census of Agriculture (USDA-NASS, 2014) and coefficients and equations from Kellogg et al. (2014).

[c] Average Euclidean distance between the centroids of source counties and centroids of requisite sink counties in each manureshed.

contrast, commercial fertilizer nutrients tended to possess N:P at least four-fold greater than manures in the same counties, and nearly two times more than the N:P removed by crops, likely reflecting fertilizer rate adjustments related to low use efficiencies for N and "build-up/ maintain" philosophies for P.

3.2. Manuresheds

Three of four manuresheds contained secondary livestock industries that contributed, on average, at least 20% of the manure P in their source areas: Carolina Poultry and Hog, Puget Sound Dairy and Poultry, and Southern Plains Beef and Dairy (Fig. 4; Table 3; data available at Spiegal et al., 2020). Within the fourth, Interior Highlands Poultry manureshed, there were only minor contributions from other industries. Among all manuresheds, substantial differences existed in the transport distances required to recycle surplus manure P from source areas in sink counties (Fig. 4a; Table 3). The average minimum distance ranged from 147 ± 51 km (Southern Plains Beef and Dairy manureshed) to 368 ± 140 km (Carolina Poultry and Hog manureshed).

The most extensive manureshed was the Carolina Poultry and Hog manureshed, with necessary transport distances extending well into the mid-Atlantic and southeastern United States (Fig. 4a). This manureshed spanned 512 counties in total (Fig. 4e): 36 in the source area, 297 requisite sinks, and 179 other counties within the matrix of requisite sinks (40 candidates for within-county transfers, 88 source counties for manure P that did not fit the definition for the source area in the manureshed, and 51 counties that were excluded from classification due to minimal croplands, many in West Virginia and Kentucky). Thus, the large size of the Carolina manureshed can be explained in part by the geometries of its counties: as in the other three manuresheds (Fig. 4b–d), the centroids of the requisite sink counties in the Carolina manureshed were, by design, as close as possible to the source area edge; however, the perimeters of the requisite sink counties had irregular geometries, so other classes of counties were interspersed between them. The scope of the Carolina manureshed also reflects a combination of factors related specifically to production in the region: the nationally significant concentration of hogs in the area (Fig. 1b), the surfeit of nutrients generated by hog farms in eastern North Carolina and by poultry farms throughout the greater source area (39,566 t surplus P from 24 million tonnes of wet weight; Table 3), the large extent of forested land without the assimilative capacity of croplands for manure nutrients, and the relatively low crop nutrient demand of many Appalachian counties (light shading of the "P deficit" quantiles in Fig. 3e).

Extending from the Ozarks region of southern Missouri through western Arkansas to the Gulf Coastal Plain of northern Louisiana, the Interior Highlands manureshed (Fig. 4d) now encompasses one of the largest concentrations of broilers nationwide (> 1.1 billion birds), trailing broiler production in only Georgia (~1.4 billion birds) and roughly equivalent to Alabama (Fig. 1b; USDA-NASS, 2019). Despite the large extent of the Interior Highlands source area, we estimated that its 32,176 t of surplus manure P could be assimilated by crops in a relatively tight radius of sink counties, dominated by croplands along the Mississippi Delta region (Fig. 4d).

At 29 counties total, the Southern Plains Beef and Dairy manureshed contained the fewest counties of all the manuresheds, with only 8 source counties, 14 sink counties required to assimilate the surplus from the sources, and 7 other counties interspersed in the matrix of requisite sink counties (Table 3, Fig. 4c). The relatively small size of this manureshed is a function of the high assimilative capacity of croplands on farms surrounding the beef and dairy feedlots of the region, as well as the low concentration of P per unit mass of beef cattle manure compared with that produced by other types of livestock (Kleinman et al., 2005; Kellogg et al., 2014). Indeed, several counties in Texas that support high-volume beef feedyards did not even have a surplus of manure P. For instance, Potter County, Texas, which contains high-profile beef feeding operations around the city of Amarillo, was not classified as a source county, but instead as a candidate for within-county transfers of P.

The Puget Sound Dairy and Poultry of Washington state was not the most extreme in terms of surplus P from dairy or poultry manure (e.g., the county of San Bernadino in southern California alone had approximately 3080 t of dairy manure P in excess of the county's cropland assimilative capacity), but it did comprise the *highest count* of adjacent source counties for dairy manure P. Notably, in the region around the Puget Sound, the surplus of 1628 t of manure P from dairy and poultry, in addition to smaller beef and hog industries, could be absorbed by crops produced in 12 neighboring sink counties in Washington and Oregon (Fig. 4b).

4. Discussion

4.1. Manuresheds: Tools to advance nutrient recycling in US agriculture

The manuresheds presented here elucidate factors critical to advancing nutrient recycling in four major livestock industries that have inherently different structures. The vertical integration of poultry and hog production organizes feed and animal production management within single institutions, providing a decision-making structure that may be conducive to implementing manureshed recycling. For instance, Tyson Foods recently announced sustainable nutrient goals for their feed producers that could be tied to a manureshed framework (Tyson Foods Inc., 2018). Consolidation within the dairy industry and organization around regional cooperatives and processing facilities also provide opportunities for the aggregate, industry response implicit in a manureshed. Beef production, in contrast, includes diffuse production stages (cow-calf) in which nutrients are largely returned to land by grazing animals, although the later stages of production (backgrounding, finishing) offer the concentration of animals and connection to transportation infrastructure required for wholesale manure transport (Drouillard, 2018).

Nutrient density, a key issue affecting practical transport to distant operations, is particularly limiting in manuresheds circumscribing dairy and hog feeding operations. In general, high-liquid manures are considered to have a practical transport limit of < 10 km (Bartelt and Bland, 2007; Hadrich et al., 2010), making solid-separation a critical step in converting liquid manures into transportable components. Conversely, solids such as poultry litter can be moved much farther (Herron et al., 2012). Ratios of N:P are another critical consideration for both liquid and solid manures (Kleinman et al., 2005). For manures with lesser N:P ratios (e.g., dry poultry manures where considerable ammoniacal N has been lost in storage and handling), the application of manure to meet crop N requirements accelerates the accumulation of P in soils relative to fertilizers and other manure sources. Here we use our four example manuresheds to briefly review the opportunities and constraints for optimal manure use and recycling in the four major confined livestock industries of the United States.

4.1.1. Carolina Poultry and Hog manureshed

The large poultry-hog manureshed presents (Fig. 4e) some of the greatest challenges for connecting nutrient cycles in animal and crop production. First and foremost, this manureshed extends into hotspots of the Chesapeake Bay watershed, a region which is responding to the imposition of a Total Maximum Daily Load (TMDL) under the US Clean Water Act, and is grappling with its own need for manure export for local animal production systems (e.g., poultry in the Shenandoah Valley and the Delmarva Peninsula of Delaware, Maryland, Virginia, and mixed animal production in Lancaster, Pennsylvania) (Kleinman et al., 2012). Secondly, most hog manures are liquid, stored in uncovered lagoon storage systems with only limited, periodic clean-outs that would remove the manure solids that are more conducive to transport (liquid fractions from hog lagoons are typically applied near barns, often through irrigation systems; i.e., fertigation). A third challenge to connecting hog and crop production is that the solids extracted from liquid hog manure contain the highest relative concentrations of both total and water extractable P compared with other major livestock categories (Liu et al., 2018).

Nonetheless, there are opportunities to extend the transport of hog manure nutrients even farther than presented here. Innovations in nutrient recovery from hog manures have moved beyond the realm of research and development to commercialization, albeit still being in a nascent stage. The on-farm treatment system of Vanotti et al. (2005, 2010) employs a nitrification bioreactor, followed by the addition of $Ca(OH)_2$ to precipitate calcium-based P. Manure solids containing $> 90\%$ of the P in hog manure are exported for end uses in compost or low-solubility fertilizer. A co-benefit of this system is the removal of odors and pathogens. While tradeoffs for this technology exist, not the least of which involve the cost of establishing on-farm treatment plants and the undeveloped nature of markets for the fertilizer products, early prototypes offer opportunities to better understand and resolve such barriers. Moreover, the poultry component of this manureshed presents a variety of opportunities for manure transport that are not found with the hog industry, as described in the following section.

4.1.2. Interior Highlands Poultry manureshed

At a national scale, more poultry-dominated counties were identified as sources of manure nutrient than for any other industry (Table 3); yet, because poultry litter is generally solid (i.e., $< 30\%$ moisture), and because production of poultry is vertically integrated, from hatchery to house to feed to slaughter, opportunities for coordinated storage and relocation are more readily available than for other manure types. In the Illinois River Watershed of northwestern Arkansas, which overlaps with part of our poultry manureshed (Fig. 4d), in-house and land management of poultry litter are regulated through mandatory nutrient management plans that have evolved from historical litigation between Arkansas and Oklahoma. There, the five largest poultry integrator companies developed the Illinois River Watershed Initiative in 2005 to export 200,000 t of poultry manure out of the watershed to less sensitive watersheds in Oklahoma and Kansas over three years (Herron et al., 2012). As a result, much of this litter was transported to nutrient sink counties in the Delta of eastern Arkansas, consistent with the identification of nutrient sinks presented herein.

Central to the success of the Illinois River Watershed initiative were litter brokering programs that connected poultry and crop farmers, as well as key innovations, particularly the baling and plastic wrapping of litter to enable storage and timely use by recipients. Unsurprisingly, a variety of partners were required for success, as well as a mix of federal, state, and local funding sources. Private companies are continuing litter redistribution now that the grant funding has ended (Herron et al., 2012). In addition, Arkansas has subsequently designated Nutrient Surplus Areas with more restrictive rules for manure application and management that favor litter export (Arkansas Natural Resources Commission, 2010). It is noteworthy that states other than Arkansas are establishing poultry litter export programs, including West Virginia

(Collins and Basden, 2006), Georgia (Mullen et al., 2011), and Maryland (Dance, 2017). Indeed, of the four livestock industries reviewed here, the poultry industry has been the focus of the most effort to redistribute manure nutrients.

4.1.3. *Puget Sound Dairy and Poultry manureshed*

Different strategies will be required to transport manure from the dairy and poultry industries that dominate the Puget Sound manureshed. Acknowledging that real challenges exist (see discussion on Interior Highlands Poultry manureshed), most modern poultry manure management systems are better suited to the vision of distributing manure nutrients within a manureshed due to the dry nature of litters and belt-dried feces. In the case of dairy farming systems, many are land-extensive in comparison with other animal production systems. However, in the Puget Sound area, topography and suburban expansion have helped to constrict the cropland area where manure can be recycled, shifting many potential sinks for manure nutrients to productive croplands in eastern Washington and Oregon (Fig. 3). Thus, although as of 2012, much of this manureshed was contained within the boundaries of a single US state (Washington), future opportunities may exist for interstate transport of manure into northern Oregon, similar to other case studies presented here.

High profile lawsuits in Yakimaw County – a candidate for within-county transfers of manure P in the Puget Sound manureshed – have intensified focus on dairy manure management in the region, from compliance with existing standards to innovations around processing liquid dairy manures (Jenkins, 2019). To enable transport of manure within the Puget Sound manureshed, the dairy industry in particular is challenged with the large fraction of liquid manure that it generates. Overall costs and compatibility of dewatering and solid separation technologies for dairy varies widely (Kleinman et al., 2020). Current dairy infrastructures and management strategies present farm-specific constraints upon the adoption of different technologies.

Many larger dairy operations already separate solids from the manure stream for reuse as bedding in cattle housing, although the nutrient content of these separated solids is generally less than half of the total content of the manure, with most P and N associated with remaining fractions (Church et al., 2016). A variety of liquid manure processing technologies have been tested on Washington's dairies, from energy-intensive distillation filters to vermicomposting systems, all of which offer opportunity to export manure solids (Jenkins, 2019). Washington State University's struvite recovery plant demonstrates the feasibility of generating a concentrated P and N fertilizer from dairy manures that recovers 60–80% of nutrients, greatly extending the potential for transporting these nutrients well outside of the local manureshed (Washington State University, 2018).

4.1.4. *Southern Plains Beef and Dairy manureshed*

Substantial similarities exist in manure management of beef and dairy production systems of the Southern Plains manureshed. Dairies are constructed around open lots or, in some cases, Saudi barns, with manure management resembling beef feedlots of the region more than dairies in more humid regions, such as the Puget Sound Dairy and Poultry manureshed (Holly et al., 2018).

Most manure from confined beef cattle in the United States is the product of a geographically extensive supply chain connecting grazinglands to feedlots concentrated in states with ready access to rail and truck transport of cereal grain and grain byproduct. Roughly 70% of US beef cattle are transported, also by truck, to be finished in feedlots in Texas, Colorado, Iowa, Kansas and Nebraska (Swanson and Morrow-Tesch, 2001; Saitone et al., 2016). Historically, distant export of manure from both beef and dairy feedlots has been limited, as has manure-spreadable cropland contained within the largest feedlot farms that account for the majority of beef finishing (Amosson et al., 1999; Koelsch et al., 2000). Nonetheless, a large fraction of feedlot manure is in dry form favorable for off-site transport, especially in this region. Composting has been a preferred means of further improving export potential for dry feedlot manure, as it reduces nuisance odors and pests. Precedent even exists for profitable contractual efforts that oversee composting and marketing of composted material (Kryzanowski, 2017). Indeed, a variety of options for improving the value of feedlot manure have been explored (Larney et al., 2011; Parker et al., 2018), but an abundance of feedlot manure and limited markets within reasonable transport distance have deterred manure transport along the Southern Plains region's well-established distribution networks.

Notably, a diversity of lands contribute to the production of feedlot beef manure, but not all are viable candidates for manure application. While recycling feedlot nutrients to produce more feed in croplands or intensively managed pastures can be readily envisioned, applying feedlot manure to rangeland is relatively uncommon due to the extent, water limitations, and native biodiversity considerations of most rangelands. However, opportunities may be expanding for recycling of manure nutrients in rangeland *reclamation* settings (Wilcox et al., 2012).

The rangelands and pasturelands that supply cattle to feedlots provide a suite of valued ecosystem services (Havstad et al., 2007; Sanderson et al., 2012). Accordingly, the complement of costs and benefits of feedlot manure management cannot be understood unless the full supply chain is considered. An important first step would be a nationwide assessment of the geographic flows of weaned calves and stockers from grazinglands to feedyards; however, data compilation for such an assessment is complicated by the lack of a comprehensive tracking system that records movements of cattle through the US beef supply chain (Skaggs et al., 2004).

4.2. *A need for systemic adjustment*

The simplistic goal of balancing manure nutrients among counties belies the complexity of implementing the manureshed vision. For the concept to advance nutrient recycling, changes would be required in farm, market, and regulatory systems, by a multitude of actors, on cascading geographic scales and levels of social organization (Reganold et al., 2011). For confined animal producers, comprehensive manure management strategies are required that reflect the value of the resource as well as its liabilities, and the interaction of many farm management decisions on manure yield and quality (Kleinman et al., 2020). Without innovations in storage, dewatering, and nutrient recovery, export of manure nutrients will not expand. However, the capacity to oversee nutrient export cannot reside with the producer alone and will require, by necessity, external entities whose business is manure translocation (e.g., AgMap, 2019). Similarly, transformation is required in grain and forage production, which has come to rely on commercial fertilizers instead of manure nutrients. While some nutrient recovery systems do produce concentrated fertilizers from manures, those such as struvite are rarely used in modern production systems. Sometimes, the effort may be in dispelling perceptions that manure will adversely interfere with production. Other times, cropping systems may need to be adjusted to account for differences between manures and commercial fertilizers. No single approach can prevail, as all have tradeoffs.

Arrangements among farmers with excess manure nutrients and farmers who could use them are a form of collaborative adaptive management (Klerkx et al., 2010). Research from Denmark, where redistribution of manure nutrients is regulated nationally to address water quality concerns, shows that most collaborative manure managers knew each other socially or professionally before they established their manure transfer arrangements (Asai et al., 2014). Some producer arrangements are already underway in the United States. For instance, truckers from western Pennsylvania haul low-grade hay to the mushroom industry in the eastern part of the state, and they pick up poultry litter for the return trip west. This "back-hauling" effectively exports poultry litter nutrients from the sensitive Chesapeake Bay watershed in the east, and several small companies specialize in this service (AgMap, 2019). Characterizing social networks that enable such manuresheds for the United States is a new field of research which may ultimately help to advance collaborative adaptive manure management and identify new pathways for niche marketing by the collaborative manure managers.

These new frontiers of farm- and community-level manure management will require incentivization. For instance, forgiveness on toll roads for back-hauling poultry litter from eastern to western Pennsylvania (as discussed above) could improve cost effectiveness. Further incentivization may come in the form of collective marketing through a vertical integrator (e.g., Tyson poultry and pork, Niman Ranch beef and pork, Organic Valley dairy), so that producers engaging in manureshed approaches are adequately compensated for putative or quantifiable societal benefits (Honeyman et al., 2006). Incentivization through regulation is already occurring in different ways across the country. In Minnesota, for example, permitting requires that each dairy have an adequate land base for the manure it produces (Minnesota Pollution Control Agency, 2019). In Pennsylvania, farms with surplus manure nutrients are mandated to export those nutrients, and the exported nutrients are to be land-applied to balance the needs of importing operations (Pennsylvania Nutrient Management Program, 2017). The state of Maryland has adopted a similar approach, while also incentivizing farther transport distances (Maryland Department of Agriculture, 2016). The Nutrient Surplus Areas (NSAs) designated by Arkansas (Arkansas Natural Resources Commission, 2010) promote a manureshed approach. While these state-based regulatory infrastructures are promising for advancing nutrient use on a case-by-case basis, a standardized, nationwide regulatory infrastructure as seen in other nations is not yet in place (e.g., Asai et al., 2014). The interplay of management planning and regional planning is a frontier that can actualize aspirational manureshed visions. Herein we provide critical data that can help inform such developments.

5. Conclusions

Recycling nutrients is a hallmark of sustainable production systems, but ensuring viable, longstanding redistribution in the partial free market economy of the United States requires that all components be economized and scalable. In many places, the experience, technologies, and policies needed to support *local* transport already exist. However, for the full, national-level manureshed vision to reach fruition, manureshed management would extend beyond localities. The advance of nutrient recovery technologies (e.g., solid-separation) can help to extend nutrient recycling from local to national levels, but importantly, the potential value of manures as fertilizers also depends on their liabilities. Therefore, management and technologies from scraping to storing to hauling to land spreading will need to minimize concerns such as odors, pathogens, and weeds/pests.

Recycling manure nutrients on lands where they have not been previously used would require profound changes not only in manure processing and transportation, but also in the realms of agronomy, bioenergy, cropping systems, and – depending on the nature of the sinks and sources under consideration – horticulture, landscaping, and even biosolid management. However, as a first step, the work presented here illuminates how the manureshed concept can build the cross-disciplinary understanding needed to recouple crop-livestock agricultural systems. This work also illuminates needs for future research. For instance, delineating manuresheds from individual confined animal feeding operations (e.g., Tomer et al., 2008) could help to identify intra-county pathways for redistribution of manure nutrients, taking into account the legacies of past management of confined livestock and fertilizer application (Sharpley et al., 2013) that are not addressed in our analysis. A nationwide spatial analysis, using road networks in conjunction with network analyses and economic costs of manure transport, would facilitate a least-cost path analysis-based optimization of manure nutrient redistribution from sources to sinks.

Strategies to redistribute manure will vary widely, so national networks of scientists and other stakeholders who understand their local systems as well as national-level opportunities for manure nutrient redistribution are well-poised to advance the systematic development of these strategies (e.g., the Long-Term Agroecosystem Research (LTAR) network; Kleinman et al., 2018). Extending the results of this research to all stakeholders is needed so that producers, consumers and other decision-makers can understand the benefits and tradeoffs of using manure nutrients as an alternative to fertilizer use where it is warranted. Ultimately, nutrient redistribution requires solutions at the societal scale. We believe that individual producers are willing participants, but the scope of the problem is beyond individual or, in some cases, local control.

Declaration of Competing Interest

None.

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Appendix A. Supplementary information

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