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SPECIAL SECTION: MANURESHEDS—RECONNECTING LIVESTOCK AND CROPPING SYSTEMS

The social networks of manureshed management

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Abstract

Manureshed management—the strategic use of manure nutrients that prioritizes recycling between livestock systems and cropping systems—provides a comprehensive framework for sustainable nutrient management that necessitates the collaboration of many actors. Understanding the social dimensions of collaboration is critical to implement the strategic and technological requirements of functional manuresheds. To improve this understanding, we identified aspirational networks of actors involved in manureshed management across local, regional, and national scales, principally in the United States, elucidating key relationships and highlighting the breadth of interactions essential to successful manureshed management. We concluded that, although the social networks vary with scale, the involvement of a common core set of actors and relationships appears to be universal to the successful integration of modern livestock and crop production systems necessary for functional manuresheds. Our analysis also reveals that, in addition to agricultural producers, local actors in extension and advisory services and private and public sectors ensure optimal outcomes at all scales. For manureshed management to successfully integrate crop and livestock production and sustainably manage manure nutrient resources at each scale, the full complement of actors identified in these social networks is critical to generate innovation and ensure collaboration continuity.

1 | INTRODUCTION

The specialization and concentration of agriculture has enabled great gains in food, fuel, and fiber production during the past century, but these forces have also contributed to long-term challenges, from dependence upon finite fertilizer resources to geographic nutrient imbalances that underpin the global expansion of water and air quality concerns (Ramankutty et al., 2018). In response, manureshed management—the strategic use of manure nutrients that prioritizes their balanced recycling between livestock and cropping systems—has been put forth as a potential solution to status quo management, which often results in geographic nutrient imbalances (Saha et al., 2018; Spiegal et al., 2020). The

Abbreviations: NGO, non-governmental organization.

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manureshed concept provides a comprehensive framework to weigh practical and theoretical aspects of manure recycling, with an eye toward environmental quality and economic prosperity. Importantly, neither the systemic drivers resulting in the "wicked problems" of uneven nutrient distribution nor the solution of manuresheds exists without the social dimension (Shortle & Horan, 2017).

Manureshed management occurs on a variety of spatial scales, from local, where crop and forage production on or near livestock operations utilize manure generated nearby, to national, where complex supply chain management may be required (Wieland, 2021). To effectively recycle manure nutrients from concentrated livestock operations onto lands where those nutrients are needed and can be used, numerous individual and institutional actors must be engaged, both directly and indirectly (Spiegal et al., 2020). The most obvious actors are livestock and cropping system producers, as well as their advisors and consultants, and those that treat manure (composters and other manure processors) or move it (contract manure applicators, haulers, and brokers). However, the web of actors integral to successful manureshed implementation is far broader in practice and may include governmental entities, non-governmental organizations (NGOs), fertilizer distributors, feed companies, housing/retail developers, scientists, consumers, and neighbors (Bryant et al., 2021; Dell et al., 2022; Meinen et al., 2020).

Moving toward functioning manureshed management requires inclusion of these diverse actors' perspectives and collective action. In this way, functionality relies on cross-boundary collaboration (e.g., Spiegal et al., 2021), such that separate actors work outside their typical area of influence and control in interacting with each other (Ferranto et al., 2013). There is a bounty of cross-boundary collaboration literature (Kark et al., 2015), but to date this scholarship has not focused on social interactions inherent to nutrient cycling across agricultural production types. To differentiate our aim, we propose "collaborative manureshed management" (terminology introduced in Spiegal et al. [2021]) as a form of cross-boundary collaboration between livestock and cropping system operations that often necessitates effective interaction between diverse, and sometimes geographically distant, actors.

The articles in this special issue characterize and evaluate manureshed components and present recommendations for producers, policy makers, consumers, and scientists to aid in manureshed management; however, their likelihood of success is greatly diminished if the relevant actors and their interactions within manuresheds are not considered and appreciated (Prokopy et al., 2019; Smith et al., 2018). Social network analysis is one way to examine relationships that enable collaborative manureshed management, helping identify the need for connections among seemingly disparate actors. Moreover, the explicit recognition of networks of actors may inspire and facilitate niche marketing opportunities for the products yielded from crop and livestock integration via manure recycling, thereby contributing to the livelihoods and economic prosperity of those managing production systems to meet multiple sustainability goals (Spiegal et al., 2020).

Core Ideas

- Manureshed implementation requires collaboration of many actors, often across multiple scales.
- Effective social interaction is needed to establish and maintain manureshed management.
- Nationally, manureshed networks engage at least 17 categories of actors.
- Local manuresheds require fewer actors but are still nested in larger socio-economic contexts
- Expanding engagement across manureshed networks can improve outcomes.

Our objective was to map the aspirational networks of actors involved in manureshed management across local, regional, and national scales. In doing so, we sought to elucidate key relationships and, ultimately, to identify the breadth of interactions needed for successful implementation of the manureshed vision.

2 | MATERIALS AND METHODS

We present theoretical network diagrams and relevant case studies across a spectrum of geographic scales (local, regional, national) using examples from the United States and, in one case, Denmark. The networks we describe are intended to present aspirational manureshed management because they reflect the actors needed for highly functioning manuresheds in which a diversity of goals (economic, environmental, production, social cohesion, and human quality of life) is simultaneously met.

Our analysis entailed categorizing actors into their roles in manureshed management as well as determining the nature of the connections among the actors (Table 1). Key actor groups were initially identified for inclusion in the networks via a literature review by the lead author. Additional actor groups were then added based on a modified, nonanonymous Delphi method in which each author considered the inclusion of additional actor categories based on their own personal experiences and literature reviews. While developing categories, we considered barriers to manureshed management (e.g., logistics, costs, land availability) and motivations for manureshed management (e.g., improvements in interper-

TABLE 1 Key actor groups within manureshed management. Each actor group's role is scale dependent

Actor category	Description
Producers (crop/forage, livestock, integrated, operation's labor force)	produce livestock and/or crop/forage, responsible for managing either the manure and/or the crop/forage receiving manure.
Contract services	provide service (e.g., manure application, pest control, custom harvesting) to producers
Manure treatment industry (e.g., composting, pelletizing)	transform manure composition for hauling and field application
Manure haulers/brokers	connect livestock and crop/forage producers or other outlets for manure, haul manure, and in some cases convert to a value-added product and apply manure to crop/forage fields
Advisors/consultants (certified crop, nutrient management, livestock advisors, feed/nutrient consultants, veterinarians)	provide professional, often certified, advice to producers
Consumers	purchase crop or livestock products, including niche market purchases linked to responsible manure management
Regulatory/action agencies	develop and enforce governmental policy (e.g., USEPA, state regulatory agencies, and health departments)
Housing/retail development (including developers, residents, business owners)	convert primarily agricultural land to residential or commercial (retail) businesses, might have concerns about odor and air quality
Scientists	perform research to inform best manure management practices and identify technological advancements
Extension (land grant universities, USDA, and state/regional agency personnel)	conduct education and outreach bridging scientists and producers
Non-governmental organizations (e.g., environmental or conservation groups)	have an interest and stake in manure management and its effect on its member focus
Recreationists	use lands nearby primarily agricultural lands for recreational purposes (e.g., birdwatching, dirt biking, hiking)
Feed companies	buy grain/forage from producers and sell grain/forage/feed to livestock producers
Fertilizer distributors	manufacture and sell commercial fertilizers, synthetic and/or organic, for crop/forage production
Animal processors	slaughter or process livestock products
Alternative energy producers	produce energy in biogas or biomass plants in which livestock manure is an input
Retailers (e.g., supermarkets)	package, market, and sell final products of crop or livestock operations

sonal relations, air/soil/water quality, economic sustainability, food security). For the sake of network parsimony, we chose to maintain the same actor groups throughout each geographic scale, although we acknowledge there is much nuance to each actor category we identified. We attempt to illuminate the nuance with three specific examples of collaborative manureshed management. Undoubtedly, these actor categories will evolve over time, especially as collaborative manureshed management advances. In fact, it is our hope that this article will start conversations about what actors should be included in manureshed management that currently are not.

Next, aspirational connections between actors were determined by the Delphi method in which each author presented independent network matrices of hypothesized relationships between actors, demarcating each relationship as "must," "should," or "could" (Frewer et al., 2011). "Collaboration" was defined in the broadest sense, with a minimum of information flow between those actor groups constituting collaboration. Collaborations between actors were categorized into those that either (a) must occur at a particular scale for basic functionality, (b) should occur at that scale to ensure that manureshed implementation is sustained, (c) could be engaged to maximize the functionality of the manureshed

and allow for diverse perspectives, or (d) are likely peripheral on manureshed management for that scale. The authors then met and arrived at a consensus on what network matrices (i.e., actors, connections, strength of connections) represented aspirational manureshed functioning at each geographic scale.

Connections representing "must," "should," or "could" relationships were coded 1, 2, and 3, respectively. Connections not likely present between actors (peripheral) in the context of manureshed management were coded 0. Throughout the text we refer to core actors as those actors who have one or more critical (must) connection at the scale of interest. All connections are assumed to be bidirectional in that influence, or at least feedback, is being transmitted both ways. In one instance, we chose to include a reflexive tie between an actor category (producers) to highlight the presence of producers communicating among themselves and their labor force. In our network diagrams, a reflexive tie is visualized as an arc originating and terminating at the same node.

We visualized network diagrams within NetDraw using the agreed-upon matrices, and authors met again to make adjustments in actor categories and connections (Borgatti, 2002). Across all geographic scales, the nodes of each network diagram are stationary for the sake of interpretation. As such, the layout of the largest geographical scale (national) was used for the regional and local-scale networks because it showcases the nested nature of local manureshed management within the regional network and the regional management within the national. Spring-embedding was used in the layout of the national-scale network so that the nodes attract and repel each other dependent upon the number of connections they have to others. Connections not present at lower geographic scales but present at higher scales are represented as gray (peripheral) lines between nodes because they show the social context occurring in the background at higher scales even if the influence is only indirect at the scale of interest. The coloration scheme of connections is consistent among scales (black = must, purple = should, yellow = could, gray = peripheral).

3 | ASPIRATIONAL MANURESHED NETWORKS

Below, we describe opportunities for collaborative manureshed management at each of the scales of interest: local (on-farm), local (off-farm), regional, and national. At each geographical scale, we present the conceptual network, provide a figure from a real-world example depicting the relevance of manureshed management, and describe a case study that demonstrates or helps further define manureshed management at that scale. Each case study is unique to its socio-ecological context, which provides an opportunity to further examine the actors we identified in the aspirational networks and parse out subgroups of actors in our more general actor categories.

3.1 | Local-scale collaborative manureshed management

We assume that manureshed management at the local scale is coordinated either within the farm gates of an integrated crop/livestock operation situated on contiguous land (Figure 1) or between close neighbors working in respective livestock and cropping systems (Figure 2).

Integrated crop/livestock producers, following best practices, assess soil fertility and crop requirements, evaluate environmental risk, and consider factors including weather, labor or contractor availability, manure storage, field access, local knowledge, and off-farm manure demand, because they implement the "4 Rs" of manure application: Right Rate, Right Time, Right Form, Right Placement (Ehmke, 2012). Figure 1a displays the social system in which livestock producers with contiguous, integrated farmland make on-farm manure management decisions. At this scale, collaboration is not essential with other landowners; however, as depicted in Figure 1b, on-farm manureshed management would benefit from engagement of advisory and extension services and others to facilitate manure distribution to nearby off-farm areas with nutrient demands.

If livestock operations do not have sufficient crop and forage land to utilize manure generated onsite (i.e., manure surpasses the assimilative capacity), they then reach out to neighbors needing manure nutrients (Figure 2). These essential partnerships between local farmers are often long-standing. As depicted in Figure 2a, collaborations with manure brokers/haulers and other specialized services (e.g., composting or manure treatment) are not necessary at this scale, although they may exist, expanding manureshed management options. In many cases the producers utilize pre-existing partnerships when establishing manure utilization arrangements (Asai et al., 2014). Currently, manure transport by livestock producers, small and large alike, occurs primarily within 5–20 km of the manure source (Bartelt & Bland, 2007; Hadrich et al., 2010). For instance, a study of large beef feedlot producers in the United States found that most operations transport manure within 16 km of feedlots (Meredith et al., 2022).

At the local scale, livestock and cropping system producers often communicate directly to balance nutrient surpluses/deficits based on complex socio-economic factors; however, what may seem like a simple transaction or transfer of resources can be, in fact, much more complicated. Because these actors are embedded within larger social systems, even collaborative manureshed management at the local scale can be convoluted. For example, the quantity, timing, method, and location where producers spread manure may be guided by

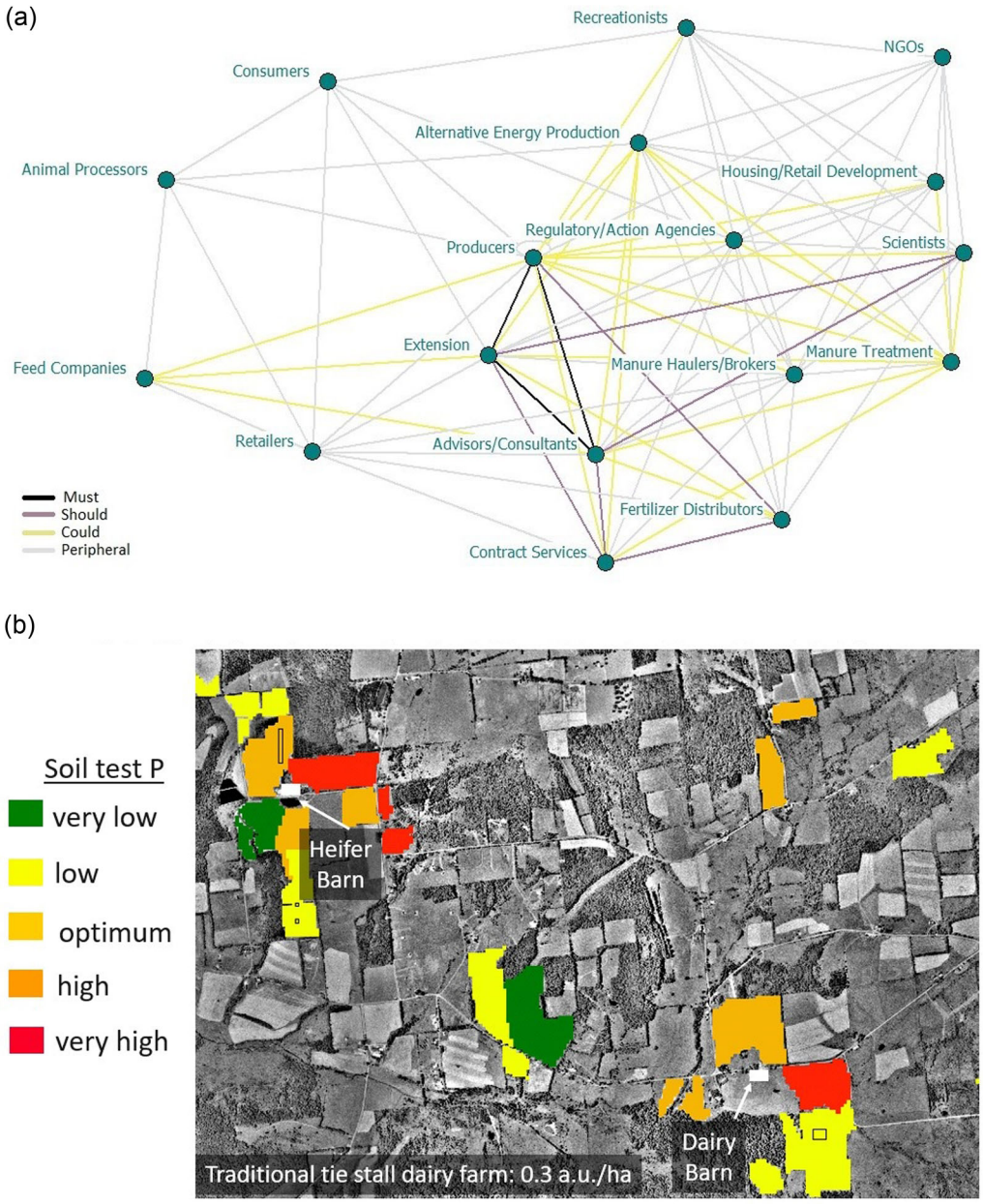

FIGURE 1 On-farm manureshed social system (i.e., the social system in which integrated livestock and crop/forage producers make on-farm manure management decisions). (a) Network diagram of actors directly or indirectly affecting livestock producers' nutrient management decisions for on-farm application. Nodes (circles) represent actors, lines represent a bidirectional influence, and arcs originating and ending at the same node represent a reflexive connection. Black lines represent critical manureshed interactions, purple represents connections that should be present ideally, yellow represents connections that could be present to improve functioning, and gray represents relationships present at larger scales. (b) On-farm manureshed management opportunity showing a traditional tie-stall dairy cattle operation with sufficient land to distribute manure nutrients but in which historical manure application practices have led to soil test P excess in some areas (near barns/manures sources) and have not met crop needs in others (adapted from Kleinman [1999])

regulations that policy makers put in place to protect water, air, and soil quality. In addition to extension and regulatory agents who help to interpret and implement these policies, advisors (e.g., nutrient consultants), NGOs, and local extension agents may serve as important actors. Further, manure may be processed (e.g., solid separation, de-caking, composting), including as recycled bedding in the dairy and poultry industries (Bryant et al., 2021; Church et al., 2020), affecting its availability and characteristics related to off-site transport (e.g., water content, pathogen content, odor). Contractors (e.g., manure application), custom haulers, regulatory/action agencies, retailers, and even specialized consultants (e.g., certified crop advisors) all contribute to manure processing. Also, the amount of land available for manure application is

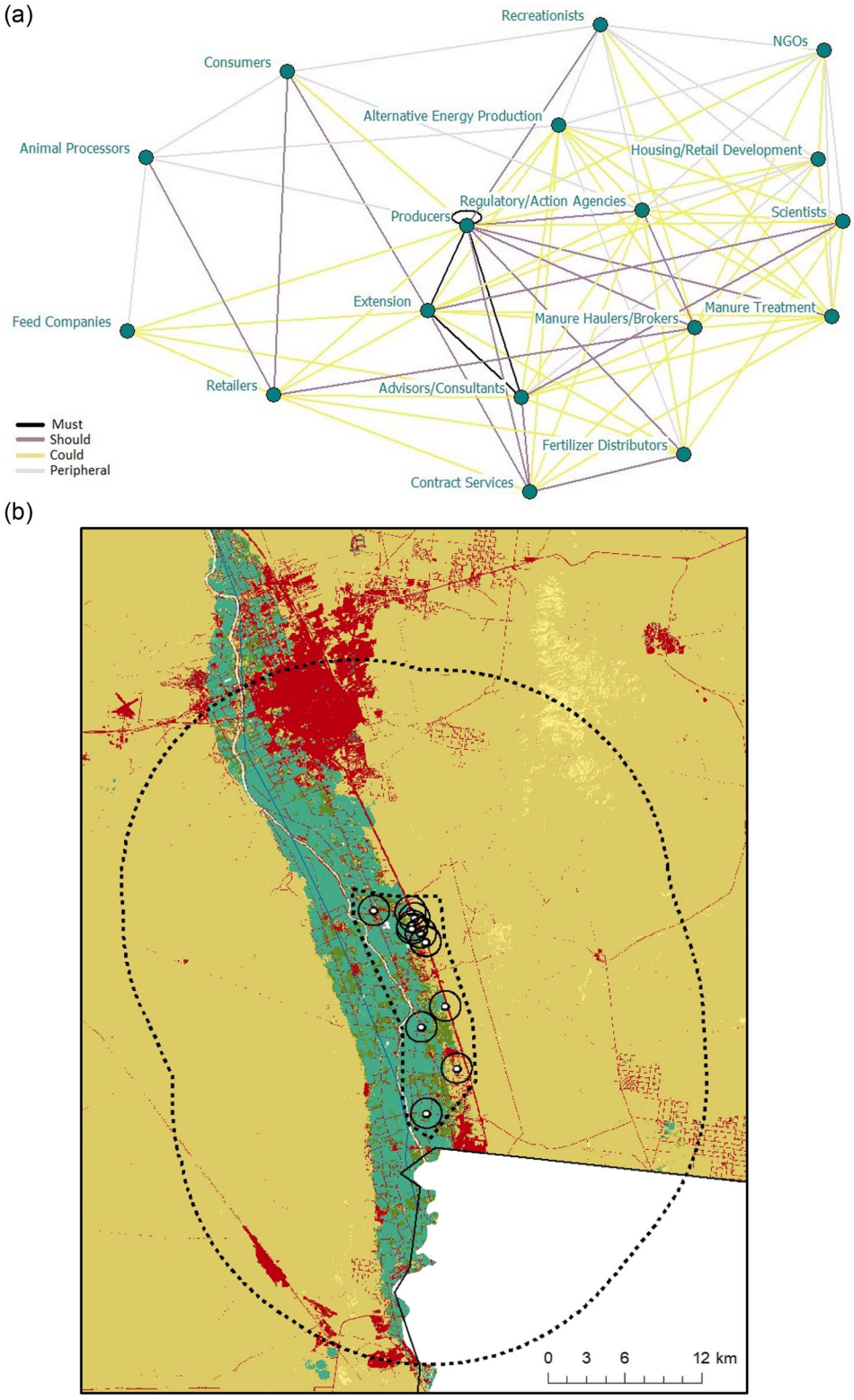

FIGURE 2 Local (off-farm) manureshed social system (i.e., the social system in which local-scale [off-farm] manuresheds operate). (a) Network diagram of actors directly or indirectly affecting livestock and crop/forage producers' nutrient management decisions. Nodes (circles) represent actors, lines represent a bidirectional influence, and arcs originating and ending at the same node represent a reflexive connection. Black lines represent critical manureshed interactions, purple represents connections that should be present ideally, yellow represents connections that could be present to improve functioning, and gray represents relationships present at larger scales. (b) A dairy manureshed in New Mexico including crop/forage land where dairy manure could be exported and urban development that could hinder land application. White dots are dairy farms nested in or near areas of crop/forage production (green), whereas urban zones where neighborhood sensitivities to manure are a concern are depicted in red (Spiegal et al., 2021)

affected by the presence and relative proportion of agricultural land to housing/retail development in the surrounding area (Figure 2b). Furthermore, manure application on lands adjacent to housing developments, especially marginalized communities, presents an ethical dilemma concerning odor and air quality (Nicole, 2013). Labor availability, including the aforementioned contractors and consultants, and community organizations may constrain manure hauling and land application potential. In addition, veterinarians, herd managers, feed supplement companies, certification systems (e.g., organic), and integrators influence how much N and P is fed to animals and subsequently excreted.

Even at the local scale, manure transfer to nutrient deficient crop and forage production areas can be a logistical challenge; however, word-of-mouth, local bulletin boards (physical or virtual), and newspaper postings can be effective means to connect producers. Notably, manureshed management at the local scale does not necessarily require advanced technology to be successful; existing collaborations and manure management infrastructure common to today's crop and livestock systems are often adequate.

3.1.1 | Local-scale manureshed example: Danish partnerships

A well-documented example of local-scale manuresheds and collaborative connections inherent to their functionality comes from a survey conducted in Denmark following a key shift in policy. Concern over excess N in aquatic environments led Denmark to designate all lands as "nitrate vulnerable zones," which resulted in collaborative manureshed management that offers insight into local-scale actors and interactions. In 1991, Denmark instituted mandatory farm N quotas determined from the assimilative capacity of crops and the N content of livestock manure or commercial fertilizer (Kronvang et al., 2008). To comply, crop producers must provide to regulatory authorities detailed records on manure and commercial fertilizers produced, received, provided, and applied. The regulations prompted livestock producers who were exceeding their lands' assimilative capacity to partner with crop and forage producers needing nutrients. In this case, mandatory top-down regulations resulted in collaboration among producers but did not mandate with whom to partner. Key actors involved in this local-scale manureshed example include regulatory agencies along with livestock and crop producers. Although scientists, consumers, fertilizer distributors, and other actors are doubtlessly affecting nutrient management choices, the focus of this local-scale example is on relationships between individual livestock and crop producers.

A survey of Danish manureshed partnerships found four different types of collaborative arrangements: business partnerships, stable partnerships, neighbor partners, and local network partners. As Asai et al. (2014) reported, business partnerships focused on economics were formed mainly via professional networks. Communication between partners was minimal, but manure traveled longer distances than in the other arrangements. Stable partnerships refer to close social relationships, mainly via family or close neighbors. Communication was frequent in such partnerships, and manure tended to travel shorter distances. Neighbor partnerships were the most common and were characterized by relatively infrequent communication and manure traveling shorter distances. Local network partnerships were recent relationships with more frequent communication than neighbor partners and manure traveling further distances but not as far as manure transfer in business partnerships. All partnership types were mainly local in that 70% of producers reported that the manure traveled to fields <5 km away from where manure was produced. Additionally, most producers knew their partners prior to establishing the collaborative arrangement. This Danish example (Asai et al., 2014) goes a step further than our aspirational networks by showcasing the type of local-scale partnerships that can be established between producers. Our aspirational networks do not portray "partnership type," but in a real world setting collaborative relationships can take many forms (e.g., cooperation vs. collaboration) (McNamara, 2012). This case study also highlights the role regulatory/action agencies can have on producers' manure management decisions.

3.2 | Regional-scale collaborative manureshed management

Manureshed management at regional scales involves many of the same actors as the local scale; however, the burden of forming connections across nutrient surplus and deficit areas falls primarily upon manure processors (e.g., composting, pelletizing), manure haulers/brokers, and contract manure applicators (black lines in Figure 3a) (Dell et al., 2022; Meinen et al., 2020; Spiegal et al., 2021). The extent and arrangement of residential or commercial land in the region limits the area available for manure application (Figure 3b). Additionally, the ratio of livestock to crop/forage producers affects manureshed dynamics and can create competition for manure nutrients. Meredith et al. (2022) documented several instances of large-scale beef feedlot companies, citing high demand by local farmers as a key limitation to manure transport distance. Because manure nutrients are perceived as a limited resource, at least one prominent feedlot company chose to arrange manure transfer only to farmers who either sell them grain or have cattle fed with them. Conversely, when there are relatively few local crop and forage producers, manure is less valued, and livestock producers may either

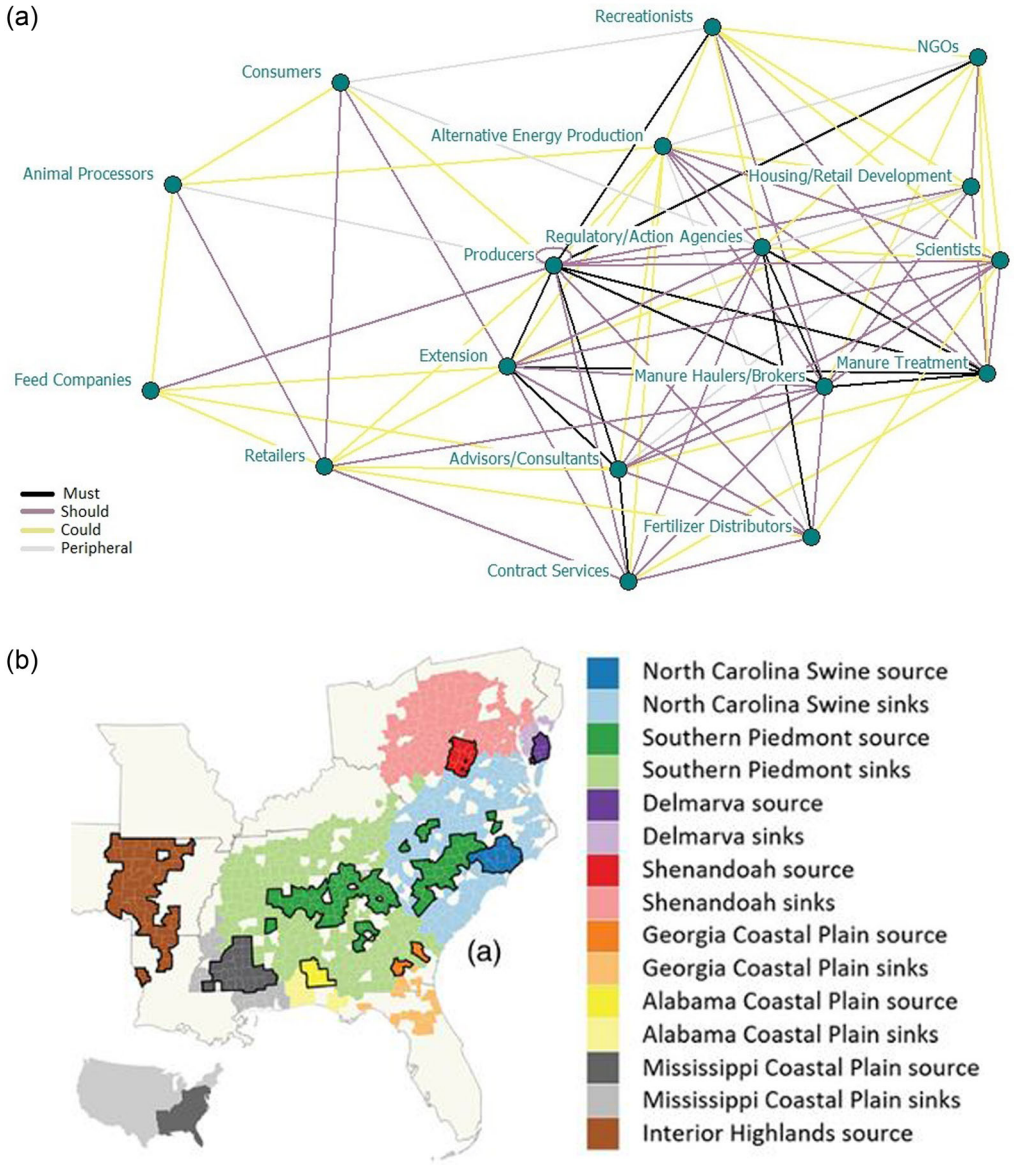

FIGURE 3 Regional manureshed social system (i.e., the social system in which regional-scale manuresheds operate). (a) Network diagram of actors directly or indirectly affecting producers' nutrient management decisions. Nodes (circles) represent actors, lines represent a bidirectional influence, and arcs originating and ending at the same node represent a reflexive connection. Black lines represent critical manureshed interactions, purple represents connections that should be present ideally, yellow represents connections that could be present to improve functioning, and gray represents relationships present at larger scales. (b) Example of regional manuresheds in the southeastern United States, principally driven by the concentration of poultry production with major contributions from swine and beef sectors. Source and sink areas of manure nutrients for each manureshed are represented by gradations of a particular color (Bryant et al., 2021)

pay crop producers to take the nutrients or haul to crop and forage production areas further away. Similar to local-scale manuresheds, regulatory agencies can directly influence management in regional manuresheds, and policy makers do not act within a vacuum. The connection is two-way. Producers, recreationists, NGOs, developers, and consumers all influence economics and rules governing manure utilization and therefore should be included in collaborative manureshed management.

For regional-scale manuresheds, connecting livestock and cropping system producers is more challenging than at the local scale because word-of-mouth, local bulletin boards, and newspaper posting are often ineffective. Instead, manure brokers are needed to make these connections, and continued effort is needed to sustain these services and connections (Cox, 2020). Thus, support for manure brokering, as well as policy-based mandates and incentives as described for Denmark above, is an essential priority for that scale.

3.2.1 | Regional-scale manureshed example: The Arkansas poultry litter export program

In the early 2000s, burgeoning poultry operations in northwestern Arkansas led the City of Tulsa, Oklahoma, and the Attorney General of Oklahoma to file lawsuits against upstream poultry producers in Arkansas. Imposition of P management standards via a court settlement agreement required lesser rates of poultry litter application to farmland in the litigated watersheds, resulting in at least 33% of the litter being exported from the watersheds (Sharpley et al., 2012). Due in part to poultry litter's low moisture content and high nutrient content per weight, a successful manure export program was created that moved over 85% of the litter produced in the Eucha-Spavinaw watershed to nonlitigated areas. Additional innovations, which improved the quality (i.e., sanitation, nutrient density) of manure for transport (Macklin et al., 2007; Penn et al., 2011) and ensured that litter could be stored on-site and readily used by crop farmers (Carreira et al., 2007) also contributed to program success.

Initially, concern existed that the litter export mandate would force poultry operations out of the watershed due to onerous paperwork requirements, high litter transport costs, and the loss of the income from litter sold as fertilizer. However, US$1.3 million from government grants and matching funds, along with contributions from NGOs, helped poultry operations overcome the associated costs (Herron et al., 2012). Further, a litter brokering program provided coordination between poultry producers, trucking companies, as well as crop and forage producers, removing much of the logistical burden. Thus, a great deal of litter was transported to farms in eastern Arkansas, Kansas, and Oklahoma, often beyond the regional manureshed.

The export of litter from the Illinois River and Eucha-Spavinaw watersheds did result in unintended collateral outcomes. In particular, cow-calf producers in the litigated watershed lost a cheap and plentiful source of pasture fertilizer (Kleinman et al., 2015). With the continued export of poultry litter out of the litigated watershed, pasture productivity declined, leading to decreases in beef herd size and a decline in pasture conditions. Despite such drawbacks, the mandated nutrient management changes achieved their intended purpose of lessening P runoff within the Illinois River (Herron et al., 2012). One insight gleaned from this manureshed is the need for comprehensive engagement of manureshed actors within the larger social network to understand concerns, consider options, develop technical innovations, and implement programs, all of which highlight the importance of extension, outreach, education, and research (Hightower, 2014).

3.3 | Toward national-scale collaborative manureshed management

In comparison to both local- and regional-scale manureshed management, transport of nutrients from distant ends of the supply chain requires multiple interactions and engagement with numerous actors (Figure 4). National-scale manureshed management would require the interaction of geographically distant actors to redistribute manure from areas of concentrated livestock production to nutrient deficient croplands potentially several states apart. Although clear examples of highly functioning national-scale manureshed management do not yet exist, there are ambitious efforts to distribute nutrient resources across large areas, including manure-to-energy conversion (MacDonald, 2008), composting (Happel, 2012), or other processes, such as nutrient extraction (Easymining, 2020; Kinsley, 2017). Thus, the aspirational national-scale network (Figure 4) emphasizes the relative importance of alternative energy production, regulatory/action agencies, fertilizer distributors, and retailers. On the retail end of the value chain, there is a special role for marketing "recycled nutrient" products.

3.3.1 | A regional manureshed example with national potential: Delmarva peninsula

The integration of broiler chicken production began on the Delmarva peninsula, adjacent to the Chesapeake Bay, the largest estuary in North America. In 2021, the Delmarva chicken production community raised 567 million chickens (Delmarva Chicken Association, 2022). With smaller and smaller land footprints, many broiler operations increased the export of litter off-farm (Kobell, 2015). Stringent environmental regulations, public scrutiny, and frequent litigation (including an ongoing, precedent-setting lawsuit on ammonia emission controls) have simultaneously galvanized collective action around manureshed management, engaged a wide range of stakeholders, and, unsurprisingly, polarized individuals and communities.

In support of manure relocation from poultry farms to offsite land needing manure nutrients, a manure processing plant was established in Seaford, DE, in the early 2000s. The plant was a private-public sector venture that received state and federal government subsidies and was managed by the poultry industry. The Seaford plant began as a pelletizing facility, and in its height pelletized and packaged poultry litter, hatchery byproducts, and poultry processing byproducts that were composted on site. The pelletized litter was marketed as an organic fertilizer and shipped to major garden store distributors and end users across the country, including greenhouses

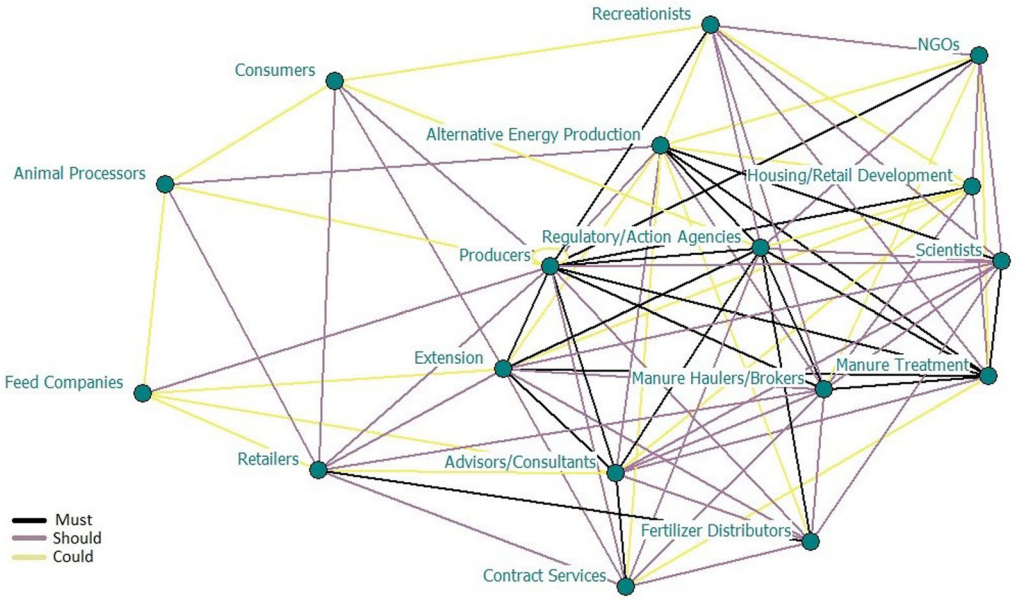

FIGURE 4 National manuresheds social system (i.e., the social system in which national-scale manuresheds operate). Nodes (circles) represent groups of individuals/organizations. Lines between nodes represent a bidirectional influence; arcs originating and ending at the same node represent a reflexive connection. Black lines represent the most critical relationships necessary for functional manuresheds at the national-scale, purple represents connections that should be present, and yellow represents connections that could be present to improve functioning. Gray lines (peripheral) connections are not present at the national scale

as far away as Oklahoma (nearly 2,000 km). A unique partnership of regulators (USEPA, State of Maryland), private industry (Perdue Farms), and local haulers worked to meet the plant's capacity, which, at the time, was equivalent to 14% of the Delmarva's litter production (Kleinman et al., 2012). However, high operating costs and an unreliable supply of poultry litter resulted in less pelletized litter production than anticipated. For instance, U.S. commodity and fertilizer prices skyrocketed in 2008 at the onset of the Great Recession, temporarily reducing litter supply to the plant as poultry producers and their neighboring crop producers retained the litter for its fertilizer value. To save pelletizing costs, the Seaford plant converted to only composting litter. In 2019, the plant was purchased by a bioenergy company that installed anaerobic digesters to produce biogas and fertilizer products. Although the plant still serves an essential role in regional manureshed management, the departure from value-added organic fertilizer pellets that were easy to handle and ship nationally to distant end users, to compost that is less nutrient dense, and now to energy and mixed byproducts (including 30,0000 tons of slurry; Cox [2021]) has undoubtedly restricted the geographic scope of this once national manureshed. The plant's evolution from pelletizing to composting facility, and, today, to manure-to-energy generator, however, is a testimony to the potential for long-term success through adaptation, innovation, and determination in large-scale manure management.

In this example, a host of national, regional, and local actors were engaged, revealing the necessity of numerous actor interactions in national manureshed management. Undoubtedly, core roles at this manureshed scale include a vertically integrated corporation (including livestock producers, manure haulers/brokers, and animal processors from Figure 4) with capacity to plan strategically across multiple components of the manure life cycle, federal and state government actors who provide regulatory and subsidy incentives, and NGOs who help connect local and national stakeholders. Notably, manure brokering was essential to connect Delmarva poultry producers with manure end users (e.g., crop producers, mushroom growers) with a gamut of opportunities available, from relying on professional networks (Cox, 2020) to direct marketing/digital services (https://littr.io). Today, groups such as the Delmarva Land and Litter Cooperative persist in organizing the network of manureshed actors, including poultry integrators, crop/forage and livestock producers, regulatory and action agencies, NGOs, and others (https://delmarvalandandlitter.net). Although this example did not engage the full panoply of stakeholders that would ultimately be involved in national manureshed management, it does offer insight into which actors must be engaged to sustain manureshed management as well as the challenges with operating at this scale.

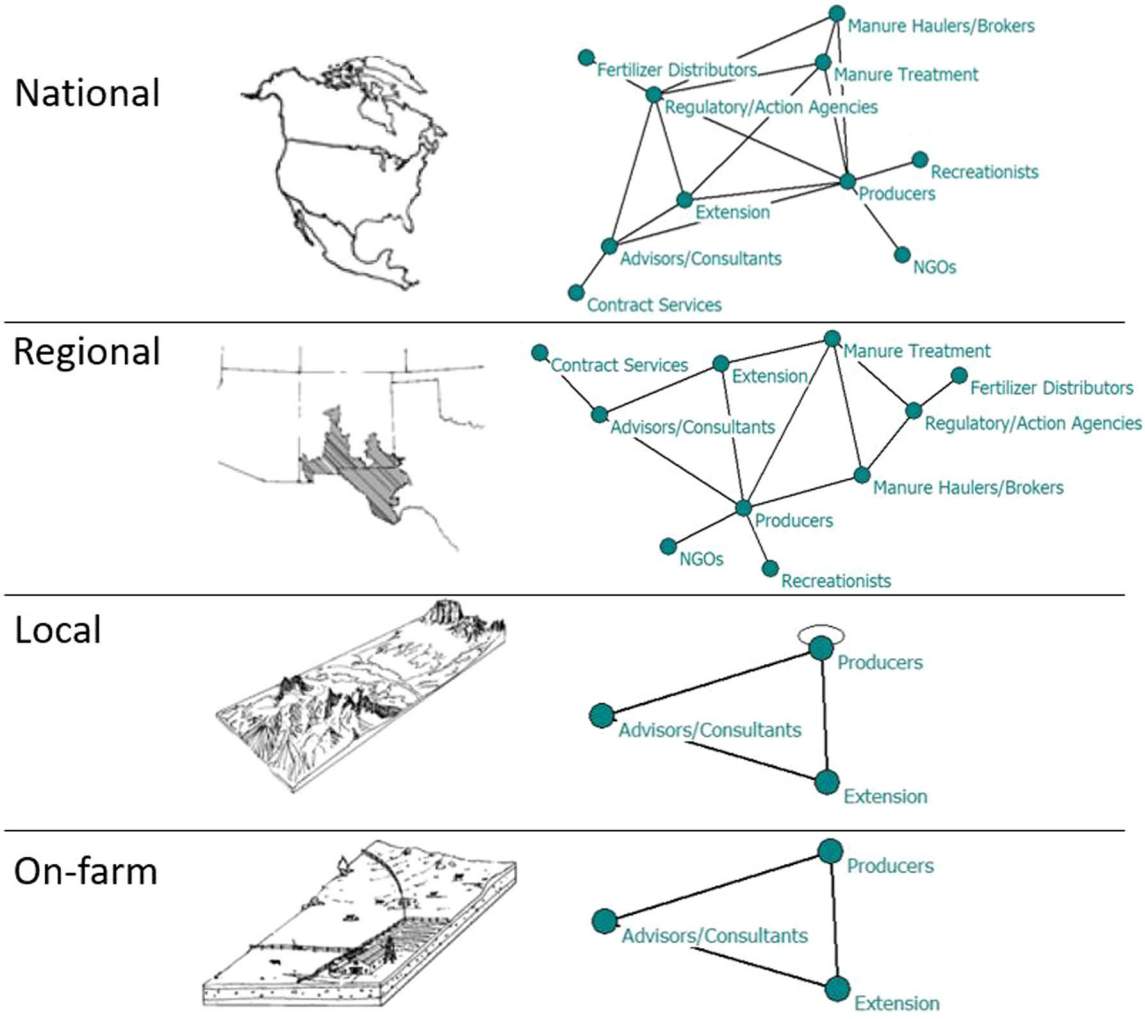

FIGURE 5 Network diagrams of crucial (must) actors at each geographic scale, highlighting how the networks are cumulative. Artwork courtesy of Matthew M. McIntosh

4 | A NETWORK OF NETWORKS: SETTING THE STAGE FOR COMPREHENSIVE MANURESHED MANAGEMENT

At the heart of all these spatial scales is a core set of relationships between manureshed management actors needed to integrate livestock and crop production through the transfer of manure resources and to make strategic adjustments in cropping systems and fertilizer management strategies. These actors must operate within a complex set of regulations, interpersonal relationships, and various priorities that increasingly require experts, advisors, and specialists to navigate and leverage as the scale increases (Figure 5). The relative importance of collaboration between any two sets of actors largely increases with geographic scale. This is visibly apparent in the network diagrams, with more connections classified as critical (black) or important (purple) as you scale from local to national contexts.

Our application of aspirational social networks points to the nesting of core actors from the local scale to the national scale and suggests connections between these actors at the broader scales that relate back to the local scale. In other words, connections in the lower geographic scales are the foundation of each successive geographic scale. Engaging the core actors at a given scale is critical to success at that scale but should not exclude the potential for interactions and opportunities that stem from relationships with other manureshed actors. Adding another level of complexity is that each geographic level of scale is not isolated from the others (Bodin & Crona, 2009); there is continuous cross-scale interaction between the local-, regional-, and national-scale manureshed networks. For instance, if national-level manureshed management was embraced that would almost certainly change how partners are managing manuresheds at local scales.

Recent history is replete with many sobering reminders of the difficulties of collaborative manureshed management. For instance, Minnesota's Minnwatt plant opened in 2007 as the first power plant in the United States designed to burn poultry litter. During its operation, the plant was an outlet for half of the state's turkey litter. However, the plant was shut down due to cheaper alternative energy sources and was eventually demolished in 2019 (Dunbar, 2017). Maintaining flexibility in manureshed networks helps to maintain the overall resilience of the network, so if there are disruptions, like the closing of a composting or biomass energy plant, alternative collaborations in place can be pivoted toward.

5 | OPPORTUNITIES, MOTIVATIONS, AND CHALLENGES FOR MANURESHEDS AT VARIOUS SCALES

Our analysis of social networks at the local, regional, and national scales showed that although some relationships are crucial to manureshed management, other interactions (e.g., between feed companies and recreationists) may not be needed or are not feasible, depending on the geographic scale in question. Thus, technical agro-environmental expertise and solutions will not alone solve nutrient challenges; socio-economic aspects are necessary for sustainable solutions (i.e., successful manuresheds). For example, in regional and national manuresheds, several actors (e.g., manure haulers/brokers, fertilizer distributors) are essential to establishing a sufficient valuation of manure as a soil amendment and mechanisms of efficient, profitable delivery of nutrient resources across the agricultural production system. This is seen in the movement of manure within manuresheds because interpersonal relationships dictate these transfers. Even at local scales where the status quo is to transport manure on-farm or between near neighbors, socio-economics guide these relationships and manure transfers. Then as scale increases, socio-economic trade-offs increasingly affect the success and applicability of technological solutions. In areas of increasing population, surrounding arable land is being converted to other uses. With this conversion, less land is available for manure spreading and more land is proximate to communities, which spurs concerns about manure odor. Thus, as scale increases, manure brokers who identify and connect buyers and sellers of manure and who can facilitate logistics of manure processing, trucking, and storage are increasingly important. Once transport distances are not economically feasible, additional actors (e.g., fertilizer distributors and scientists designing manure processing techniques/equipment) are needed to process manure into lighter, standardized products, and further actors (e.g., retailers and their marketing departments) are needed to ensure the products meet the needs of diverse markets (e.g., niche, organic). Biogas and biomass energy plants ("alternative energy production" in Figures 1–5) are another potential outlet for manure that distributes concentrated nutrients to wider service areas. However, as evidenced by the closed plant in Minnesota, favorable market conditions or incentives must be in place to make alternative energy production a feasible long-term solution.

A combination of "top-down" and "bottom-up" approaches is likely needed in regional manuresheds and certainly at the national scale. Again, considering socio-economic factors and including all relevant actors are essential in developing any manure-related incentives or regulations. In other words, crafting policies that ignore crucial actors (e.g., manure brokers) have limited utility and will ultimately fail. Additionally, technical experts and scientists must be included to develop cost-effective technologies to harvest P and N from manure, lessen subsequent hauling costs, consider alternatives (e.g., biosolids), and develop and evaluate value-added products. Modelers and economists are also vital to evaluate the complex interaction of transportation and macro-economic factors. Last, but not least, time is required for a foundation of trust to be established among actor groups for collaboration building.

6 | CONCLUSIONS

The present study mapped the networks of actors involved in manureshed management across local, regional, and national scales. This socio-economic component, specifically the social dimensions of actors and their interactions, is a critical component of successful manuresheds that ensure sustainable use of manure through the integration of livestock and crop production systems and utilization of manure resources. Our analysis revealed that even though the social networks vary with scale, the involvement of certain core actors (Figure 5) appears to be universal to the successful integration of modern livestock and crop production systems within manuresheds. However, networks at each successive geographic scale are constructed upon the connections active in the lower scales. When building manureshed functionality, it is important to keep in mind this full complement of actors. Future research should be conducted on how the aspirational networks presented here vary from what is currently present.

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AUTHOR CONTRIBUTIONS

Gwendwr Rhiannon Meredith: Conceptualization; Investigation; Methodology; Visualization; Writing – original draft; Writing – review & editing. Sheri Spiegal: Conceptualization; Investigation; Writing – review & editing. Peter J. A. Kleinman: Conceptualization; Investigation; Writing – review & editing. Daren Harmel: Investigation; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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