frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 22 January 2024
DOI 10.3389/fsufs.2023.1292326

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OPEN ACCESS

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RECEIVED 11 September 2023
ACCEPTED 29 December 2023
PUBLISHED 22 January 2024

CITATION
Deviney AV, Classen JJ and Bruce JA (2024) Pathways to sustainable transitions in a complex agricultural system: a case study of swine waste management in North Carolina. *Front. Sustain. Food Syst.* 7:1292326. doi: 10.3389/fsufs.2023.1292326

Pathways to sustainable transitions in a complex agricultural system: a case study of swine waste management in North Carolina

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North Carolina has a high density of swine farms with nearly half of the commercial operations located in two eastern counties. Lagoon and sprayfield (LS) is the dominant method of swine manure management despite pressure to transition to environmentally superior technologies. LS is an efficient and cost-effective method of waste management but has negatively impacted the environment and local communities from both discreet events (breeches, flooding) and ongoing issues (odor, disease vectors). The Multilevel Perspective Theory (MLP) is a frame for understanding the relationships between a sociotechnical regime, its surrounding landscape, and emerging niches for sustainable technology development to help align these different levels of perspective and support transitioning toward more sustainable practices. Here, a farm level is added to represent the user perspective of regime technology in complex agriculture systems (MLP + F). We demonstrate how change may influence the North Carolina swine waste management (NC SWM) system through alternative scenarios applied to a conceptual model developed with the MLP + F frame in a methodology for analyzing complex agricultural systems with input from a diverse panel of experts. This case study demonstrates how the methodology can be applied through two NC SWM model scenarios analyzed with fuzzy cognitive mapping techniques. The first scenario explores whether panel recommended changes generate a shift toward sustainable manure management. Inference results suggest that experts have a broad understanding of how these goals may be achieved, but strategies are needed to enhance the specificity of proposed changes. Testing scenarios with more targeted interventions within specific subsystems could provide greater guidance with regard to policy, economic factors, farm practices, or societal demands. The second scenario considers the systemic effect of introducing a manure dewatering process on swine operations, with and without landscape support. Results from this scenario indicate that the more landscape support is engaged, the greater the impact on desirable outcomes. However, contradictions emerged between different versions of this scenario such as increased negative public perceptions despite positive community outcomes. This may require further investigation to tease out potential misalignment between perceptions of a complex system and actual system behaviors.

KEYWORDS

agriculture, complex systems modeling, fuzzy cognitive mapping, lagoon and sprayfield, multilevel perspective theory, swine waste management

1 Introduction

There is an assumption among researchers and design teams that the information needed to appropriately define a problem and its solution space is available and accessible. For engineering and technology applications where the system of interest behaves in a well-defined and logical way this is true. However, this assumption is not applicable for a problem that is ill-defined, symptomatic, has conflicting requirements, or the solution space contains multiple potential options whose outcomes cannot be anticipated without implementation at scale. These are the "wicked problems" described by Rittel and Webber (1973) involving complex systems.

The case of North Carolina's swine waste management (NC SWM) system is a complex agricultural system that provides an example of how the traditional approach to technology design limits adoption when focused too narrowly on "environmentally sustainable" solutions. Nearly a third of U.S. swine are housed in barns that use the lagoon and sprayfield (LS) system for waste management (Putman et al., 2018). Because LS is a wet waste treatment system, each North Carolina farm must maintain a permit with the NC Department of Environmental Quality (NC DEQ) that incorporates a nutrient management plan to limit the potential for discharge. North Carolina has over 2,500 permitted commercial swine operations that depend on LS with nearly half of these operations located in just two counties. Most of these swine farms operate under contracts with an integrator company for feed and animals, but they are individually responsible for their own waste management and permits. However, the cumulative impact of swine farms competing with poultry operations or encroaching development for manure application acreage means the total nutrients in animal waste can exceed the local available land capacity for application. This creates negative effects to the environment and to human health from over-applying manure, run-off, leaching, surface-water pollution, ammonia volatilization, reduced air quality and odor near farms. Lagoon breaches or flooding caused by extreme precipitation events compound these impacts (Wing et al., 2002, 2008; Casey et al., 2015; Heaney et al., 2015; Ogneva-Himmelberger et al., 2015; Balas et al., 2016).

Despite its value as an organic fertilizer and soil conditioner, swine manure is not as strong a competitor to commercial fertilizers as dry poultry litter in North Carolina, in part because of the high liquid volume and low nutrient concentrations resulting from the wet treatment process (Key and Kaplan, 2007). To date, and despite significant financial investments, "sustainable" replacements to the LS system of waste management have not been broadly adopted. Historically, technology design was focused on the perceived need to reduce environmental impacts from swine operations by replacing the anaerobic lagoon. In 1997 the North Carolina legislature placed a moratorium on permitting new or expanded swine operations that do not meet five performance standards with their waste treatment systems (N.C. General Assembly, 1997). These performance standards include eliminating the discharge of animal waste to surface and groundwaters, and substantially eliminating ammonia emissions, odors, disease-transmitting vectors, and nutrient or heavy metal contamination of soil and groundwater. More than two decades later, few technologies are able to meet all five criteria, while any that do still fail to be adopted at scale because (1) the technologies do not assimilate well into the existing infrastructure that supports the established LS system, (2) developers have not been able to tap into viable markets for the value-added products the technologies create, and (3) the technologies are untested, expensive, and too complicated for application on the individual farms. None of these issues are environmental problems.

To manage swine waste more sustainably requires a holistic systems thinking approach to understand how a new technology or practice might interact with the overarching sociotechnical system. A methodology was developed to integrate multiple stakeholders' expertise in the construction and utilization of a conceptual model to support a more robust understanding of a system of interest (Deviney et al., 2023). We will refer to this methodology as Multi-Perspectives Modeling, or MPM. The goal of MPM is to identify as many relevant system elements as possible and the known cause-effect relationships between them. When applied to the multilevel perspective (MLP) framework, these elements and relationships enable the researcher to gain meaningful insights into the complex system. The MLP framework represents the sociotechnical system across three levels: the landscape (external influences), the regime (the system of current practice) and the niche (technological interventions). Because in agricultural systems the farm itself is the end user of many applied technologies, the farm was added to the MLP framework (MLP + F). This level provides necessary context to the model and gives agency to the farm as a decision-maker for sustainable technology adoption. The methods used for data collection and analysis (Delphi, fuzzy cognitive mapping) are well established across multiple disciplines (Okoli and Pawlowski, 2004; Papageorgiou, 2014).

The conceptual model of the NC SWM system developed using MPM determined how well the system aligns for transitioning to a more sustainable regime and what types of barriers might exist (Deviney et al., 2023). However, it is still unknown whether certain changes to the system might achieve desired goals. This case study uses the NC SWM model to further investigate two alternative scenarios by activating concept nodes and performing inference to analyze possible outcomes based on changes to those concepts. These scenarios include panel-recommended changes to improve sustainable manure management and the integration of a manure dewatering technology into the system. Such scenarios can illustrate potential unexpected consequences of change, as well as the types of landscape support needed to enhance the potential for technology adoption.

2 Materials and methods

The NC SWM conceptual model used in this case study was constructed from information provided by a diverse panel of 17 experts using the three-step MPM methodology developed by Deviney et al. (2023). The steps include: (1) applying MLP + F to the system of interest and identifying assumptions, information gaps and related expertise, (2) using a modified two-round Delphi approach to collect, validate and map information about the system from the expert panel to develop a list of system concepts and relationships, and (3) analyzing potential system behavior through the alignment of system perspectives across the MLP + F levels. The Delphi approach was used for data collection to preserve participant anonymity while allowing all participants to comment on the model as it was being developed. The model consists of 549 system concepts with 1,185 weighted and directed cause-effect relationships between them. These concepts and relationships are divided into 11 subsystem fuzzy cognitive maps, with each map containing only the outgoing inter-map connections with other subsystems to avoid duplication.

For this case study, the NC SWM system is used to explore two alternative scenarios through fuzzy cognitive mapping inference to determine if specific goals can be achieved by "activating" certain concept nodes within the system. Key elements of the modeling process related to the case study scenarios are highlighted below. Each scenario activates one or more of the model's concept nodes. Inference for the alternative scenarios was performed with the fcm package in R (Dikopoulou and Papageorgiou, 2017) using the Kosko clamped inference function and the hyperbolic tangent forcing function with $\lambda = 1$ and $e = 0.01$ as inference parameters. Test simulations indicated this combination of functions provided the strongest agreement in both expected outcome and inference output values. A subset of the whole system model was used for each alternative scenario.

2.1 Applying MLP + F

The sociotechnical regime being investigated is the LS system of swine waste management. The anaerobic lagoon is a large open-air and typically earthen structure used to biologically treat and store animal waste that is flushed from barns at daily or weekly intervals. Properly designed and managed lagoons are an economical and functional treatment method similar to that used in some municipal wastewater treatment plants (Office of Water, 2002), without the need for added energy or chemical inputs. The products of anaerobic digestion are methane, carbon dioxide (CO_2), and soluble plant-available nutrients that can be irrigated onto nearby sprayfields growing hay or crops. Open lagoons in an LS regime release the methane and CO_2 – both greenhouse gasses – into the atmosphere. Odorous compounds and ammonia-nitrogen are also emitted from both the lagoon and in the field, which reduces the nitrogen to phosphorus ratio of the irrigated effluent and causes excess soil phosphorus at the permitted nitrogen application rates (Adeli and Varco, 2001). Recalcitrant material and insoluble nutrients settle at the bottom of the lagoon as sludge. Sludge may accumulate for years before removal and land application as a soil conditioner and fertilizer. However, the high phosphorus and metals (zinc, copper) content of sludge limits where it can be applied as these nutrients accumulate in soil and cause crop toxicity or other environmental challenges. Aside from the technology itself, the regime also includes all of its shared rules, embedded institutions, and infrastructures that contribute to the regime's current trajectory and stability (Rip and Kemp, 1998; Geels, 2011). For the LS regime this includes regulatory aspects related to obtaining and maintaining compliance with a general permit for swine operations, maintenance processes and related equipment for pumping and irrigation, and technical assistance through Cooperative Extension or consultants in swine waste management.

Both the farm and the landscape were initially supportive of the adoption of the current LS regime as an efficient and cost effective technology for swine waste management. A key driver was the expansion of the pork industry itself, which shifted how pigs were raised from small herds to large, confined swine housing operations. This transformation was coupled with another industry shift from independent farms to contract farming with integrator companies that control the pork processing infrastructure (MacDonald and McBride, 2009). Other factors that led to a rapid expansion of North Carolina's pork industry through the late 1990s include a relatively flat geography, a subtropical climate that supports lagoon function, and the need for a new agricultural focus due to declining tobacco production (Furuseth, 1997). Over time, these supportive landscape factors began to compete with social and environmental justice challenges, particularly with regard to odor and negative health impacts experienced by low-income and minority residents in proximity to swine operations (Wing et al., 2000). Despite this brewing discontent, a succession of disruptive and high-profile environmental crises, including major lagoon breaches and repeated significant flood events from hurricanes, are credited with eventually halting pork industry growth. The 1997 moratorium on new or expanded swine farms using the anaerobic lagoon became permanent in 2007, although farms permitted prior to the moratorium are allowed to continue to use anaerobic lagoons.

To date, North Carolina continues to be among the top three pork producing states in the United States (USDA NASS, 2021). Since poultry production was not included in the new rules for wet waste management because most poultry operations use a dry litter system, the poultry industry has also expanded and North Carolina now ranks among the top three states for total poultry production (North Carolina Poultry Federation, 2021). The poultry and swine industries in North Carolina utilize a contract system between individual farmer-producer operations and integrator companies that coordinate and control the overall production system, including animal breeding, distribution, feed, and processing. Lawsuits against a major pork integrator have increased landscape awareness of the impact the high density of animal operations has on rural low-income and minority communities, continuing to highlight environmental justice concerns. However, a history of agriculture-friendly policy and right-to-farm legislation in North Carolina often hinders the effectiveness of these legal pressures (Smart, 2016).

A niche development in swine waste management is using covered digesters for renewable natural gas (RNG) production on swine farms, introducing a novel change to the landscape and regime (Align RNG, 2020). Although the technology recovers energy and significantly reduces greenhouse gas emissions from swine waste, a special permitting process has been developed because greenhouse gas recovery does not explicitly satisfy the performance standards imposed by the moratorium. Additionally, covered digesters do not manage nutrient recovery from animal waste differently than the LS regime. Digestate – the residual waste that remains after biogas recovery – is typically returned to the old open lagoon for storage until land application, so that potential environmental impacts from excess nutrient application and flooding remain. Thus, a niche space exists for economically viable nutrient recovery technologies for swine operations with or without covered digesters to reduce nutrient overloading and resulting negative environmental impacts in high production areas.

Because swine operations almost exclusively use the LS regime in North Carolina, the farm level is focused on commercial agricultural operations that include raising or growing swine as part of their enterprise. In 2020, the NC Department of Environmental Quality listed 2,133 state general permits for swine covering 3,501 lagoons (NC DEQ, 2020). The average North Carolina swine farm has approximately 50 acres of permitted sprayfields. Most North Carolina farms with gross revenues over $150,000 have been in operation for more than 10 years, although more than half of small farm holders do not list farming as their primary occupation. Often swine farms generate additional income from other farming operations (e.g., crops, poultry, cattle) and/or other employment by the operator and family

TABLE 1 Researcher assumptions regarding North Carolina's pork production and swine manure management regime, with associated MLP + F levels.

#	Assumption	MLP + F level(s)
1	More nutrients are imported into than exported from regions of high-density livestock production, causing an excess of nutrients to build up in the environment.	Landscape
2	Compliance with and enforcement of environmental regulations will ensure environmental sustainability of animal operations.	Landscape
3	The lagoon and sprayfield waste management regime is associated with air and water pollution, particularly in areas of high-density livestock production.	Landscape, regime
4	Producers and local community members will benefit from a reduction in environmental impacts of swine farms.	Landscape, farm
5	The excess water introduced by the lagoon and sprayfield system dilutes and devalues manure nutrients, contributing to the treatment of swine manure as a waste byproduct rather than valuable fertilizer.	Landscape, regime, farm
6	Alternative technologies exist that can replace the current regime and reduce environmental impacts of swine operations.	Landscape, regime, niche, farm
7	Alternative technologies exist that will create value added products from swine waste.	Regime, niche, farm
8	Markets currently exist or could be quickly developed for manure byproducts to help offset financial costs of treatment and processing.	Landscape, niche, farm
9	There is a desire among multiple stakeholder groups, including producers, to find cost-effective alternatives to lagoon-sprayfield waste management.	Landscape, regime, niche, farm
10	Producers will use alternative technologies for manure management if they are technically and economically feasible.	Regime, niche, farm
11	Policy incentives exist or could be developed to facilitate development and utilization of sustainable manure management technologies and manure-based products.	Landscape, niche, farm

members. This diversity in farm types influences farmer responsibility and the kinds of decision-making related to risk aversion, diversification, management style, and interest in innovation, among other factors (Karan, 2011). Farmer values also play a key role in the decision-making process and reach beyond just economic or business considerations to include such values as tradition, ethical behavior, community pride, and personal traits (O'Connell et al., 2017).

2.2 System assumptions and knowledge gaps

Assumptions associated with researcher understanding of the NC SWM regime are listed in Table 1, spanning the MLP + F levels. Environmental impacts of swine operations that use the regime are recognized as a key driver of change across all levels. Environmental impacts are assumed to be the result of high nutrient inputs (assumption 1, Table 1) and a lack of regulatory compliance by swine operations (assumption 2, Table 1), coupled with functions of the regime itself (assumptions 3,5, Table 1). It is assumed that landscape agents such as policy makers and community members, as well as the farmers who use the regime are motivated to transition to an alternative technology (assumptions 4, 9–11, Table 1). It is also assumed that such technologies exist and are feasible (assumptions 6–8, Table 1).

2.3 Stakeholder groups and subsystem identification

An initial list of stakeholder groups was developed from researcher prior knowledge, assumptions, and literature about the system (Deviney et al., 2021). This list and a list of correlated subsystem categories were iterated throughout the interview round of data collection. The goal was to refine included stakeholder groups such that enough perspectives were captured to ensure a relatively comprehensive representation of the system without overlap – especially across the landscape – while keeping group identity broad enough to safeguard participant anonymity. Through the interview coding process, concepts were categorized into subsystems of the overarching model. These subsystems helped to consolidate similar concepts and allowed the panel experts to assess the parts of the system that correlated to their expertise. Table 2 lists the stakeholder groups, including a self-reported group on bioenergy production, the correlating subsystem categories based on the concepts identified by panelists, the associated MLP + F level for system analysis, and the number of participant views associated with the stakeholder group/subsystem pairing. Generally, participant self-ranking from some knowledge to extremely knowledgeable of their domain of expertise was used to determine their affiliated stakeholder group(s), except where a participant made significant contributions to a subsystem they did not explicitly identify with in their initial participation survey or where they confirmed knowledge during the interview. In the interview, each panelist was asked to describe the NC SWM system from their perspective and what changes, if any, they would make to the system. The system descriptions were coded into concepts with cause-effect relationships and translated into the 11 subsystem maps. Changes were used to develop alternative scenarios. Each panelist was provided two to three subsystem maps related to their expertise to review and assign values to the concepts and cause-effect statements, based on how easily they perceived a concept would be to change through human intervention and how much influence each cause concept would have on an effect concept.

2.4 Alternative scenario development with fuzzy cognitive mapping techniques

Fuzzy cognitive maps consist of a set of nodes (concept variables) and weighted, directional edges between nodes (relationships). This

TABLE 2 Stakeholder groups, associated subsystem categories, MLP + F level, and number of panel experts assigned to each category/group.

Stakeholder group	Subsystem category	MLP + F level	Panel experts*
Agriculture-related industry (excluding swine)	(A) agriculture (livestock and crop production)	Landscape	6
Community residents or business near swine operations	(C) communities (neighbors, local businesses, activists)	Landscape	9
Academic research and outreach (incl. Extension)	(E) education (science research, Cooperative Extension)	Landscape	13
Grower/producer	(F) swine farm	Farm	10
Regulatory agencies; policy making bodies	(G) government (rulemaking, regulation, support)	Landscape	8
Social/environmental activism	(L) land (environment, natural ecosystems, climate, weather)	Landscape	4
Grower/producer	(M) manure management	Farm	5
Bioenergy production, consulting, academic	(N) niche (novel manure management tech and strategies)	Niche	5
Pork industry representative	(P) pork industry (integrators, processing, marketing)	Landscape	6
Swine production / grower	(R) regime (lagoon and sprayfield system)	Regime	9
Social/environmental activism	(S) society (land use, consumers, general public, expectations)	Landscape	5

Panelists self-identified their stakeholder group affiliation(s).
*Note that most panel experts identified with more than one stakeholder group.

mapping structure allows for the propagation of change through a system by "activating" one or more concept nodes, which causes an increase or decrease in adjacent nodes, that in turn affects nodes adjacent to those, and so on (Kosko, 1986). A concept can be increased or decreased (activated) to prompt a change in the system, and inference is conducted to analyze how activating one or more nodes (alternative scenarios) might influence the other concepts in the system (Dikopoulou et al., 2018). To perform inference with fuzzy cognitive maps, the concepts and their signed relationship values are translated into a mathematical weighted adjacency matrix which, when interacted with an activation vector using inference rules, propagates the change throughout the system until a steady state is achieved (Papageorgiou and Salmeron, 2014). Values are constrained through forcing functions to a range of [0,1] or [−1,1] to make interpreting the outcome more manageable. The relative differences in final concept values allow users to infer how a change in the activated concept(s) may affect the system as a whole (Özesmi and Özesmi, 2004).

The first alternative scenario is based on the expert panel's most frequently cited goal of increasing sustainable manure management (N36). N36 is a receiver node in the niche subsystem with seven drivers, including voluntary adoption of BMPs and innovation (F33) at the farm level and policy incentives for change in manure management practices (G59), with the remaining five drivers also niche concepts. Panelists suggested a number of ways to support increasing N36. The recommendations and related concept nodes are listed in Table 3. These are the nodes activated in the alternative scenario. Criteria for selecting a recommended change included having an associated concept node in the system, being of a driver or ordinary type (not a receiver), representing a decision variable as opposed to reflecting the state of the system, and having at least a "high" level of alignment in panelists' perception of how easy the node would be to change through human intervention. Several recommendations, including "improve leadership to facilitate solutions," "more efficient utilization of existing policy and funding," and "implement incremental change" did not have a direct correlation to concepts in the NC SWM model and were not included in this scenario.

The second alternative scenario added a new concept, swine waste dewatering process (M44x), as a novel node to the NC SWM conceptual model. M44x was inserted into the manure management subsystem as a driver node that directly increases or decreases other manure management nodes. Figure 1 illustrates the connections from M44x, which were given a positive or negative weight of 0.5 to indicate a "moderate" amount of influence to receiver nodes on a scale of [0,1]. This moderate value was used to simulate the possible impact of adding a dewatering technology to the LS system.

In addition to analyzing the effect of introducing a dewatering process to the system, M44x was also activated with different combinations of two additional concepts that panelists indicated could act as leverage points within the system to support technology adoption. One concept is targeted funding for innovative technologies (G64), which aligns with the panel's assertion that it is necessary to subsidize the shift to sustainable manure management technologies. This assumption is reflected in very high agreement among panelists regarding the influence of this node on farmer decision-making, new waste treatment technology research, and pairing nutrient recovery with biogas production. Panelists also focused strongly on communication between stakeholders as a necessary driver for sociotechnical regime change. To accommodate this recommendation, a second leverage point of multiple stakeholder engagement as a mechanism for information exchange (S29) was also included in the scenario. Although panelists gave S29 a modest amount of influence on the system, there was strong disagreement regarding how easily this node could be activated. Yet, a possible outcome of activating this driver is fundamental to MLP + F theory for sustainability transitions, in that improving communication could lead to greater alignment among stakeholder groups. If greater alignment is achieved by activating S29, it should be reflected in positive changes to the environmental and social issues underlying the need to transition the current regime toward more sustainable behavior.

3 Results and discussion

Inference results should be interpreted as the relative values of concept nodes to each other when the propagation of change through

TABLE 3 Expert panel recommended changes to the NC SWM system to increase sustainable manure management, associated concept nodes, subsystem, mean value assigned by panelists, alignment, and node type.

Recommended system change	Associated concept node(s)	Subsystem	Mean value	Alignment	Type
Identifying reasonable goals for sustainable manure management	C7. stakeholder input to legislation, regulation, and rule-making for animal operations	Communities	0.14	Total	Ordinary
Increase technical, operational, and financial support for swine producers	G27. funding and technical assistance for swine producers (e.g., requirements, applications)	Government	0.64	High	Ordinary
Incentivize pork industry support of technology adoption	G59. policy incentives for change in manure management practices	Government	0.57	High	Ordinary
Foster political motivation to change/ update policies	G60. political motivation to move toward sustainable manure management	Government	0.36	High	Ordinary
Increase state and federal funding programs	G64. targeted state and federal funding programs for innovative technologies (e.g., NRCS, USDA, NCDA, NC DEQ, EPA)	Government	0.64	High	Ordinary
Develop viable manure-based products	N3. manure management technologies that create value-added manure products	Niche	0.61	High	Ordinary
Develop novel waste management strategies that work with the existing regime	P25. utilizing existing infrastructure	Pork Industry	0.52	High	Driver
Increase technical, operational, and financial support for swine producers	P28. integrator buy-in with financial support / cost-sharing	Pork Industry	0.33	High	Ordinary
Increase public support for funding improvements	S41. public support for funding improvements (payments for nutrient recovery, technical assistance)	Society	0.29	High	Ordinary

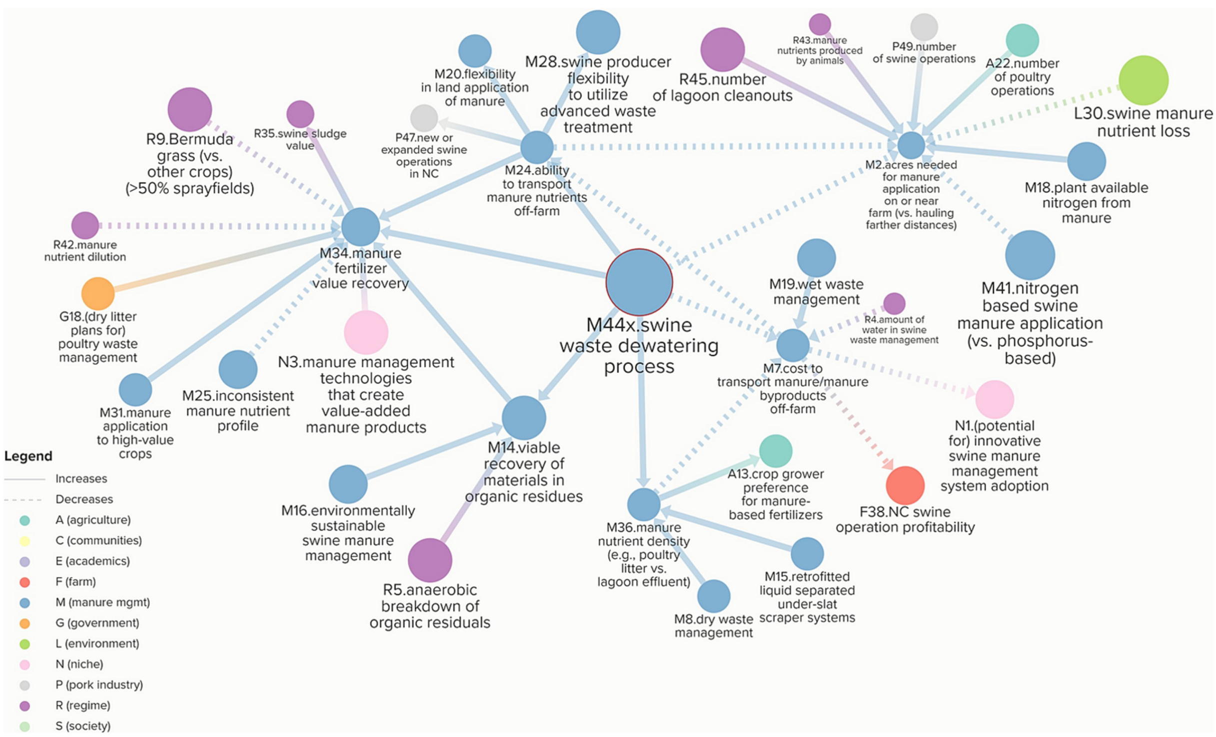

FIGURE 1
Addition of the driver node M44x.swine waste dewatering process to the manure management subsystem map through six connections, each with a weight of +0.5 or − 0.5 to indicate an increase or decrease of the receiving node.

the system has reached a "steady state." For this model, inference results are based on the expert panel's collective perception of system relationships and the averaged influence values assigned to those relationships.

3.1 Alternative scenario 1: panel recommended goals and drivers

The purpose of this scenario was to learn whether changing certain drivers across the MLP + F levels will lead to the goal of increasing sustainable [swine] manure management. Panelists believed achieving this goal requires identifying reasonable goals for sustainable manure management and utilizing existing infrastructure, increasing technical, operational and financial support for swine farms, and incentivizing policy makers, the pork industry, and the general public to support advanced technology development and adoption.

Figure 2 illustrates a subset of the simulation results across all four MLP + F levels. The full inference results are available in the Supplementary material. The increase in the value of the node N36 from zero to the highest possible value of 1, suggests that the nodes activated in this scenario collectively achieved the panel's goal of sustainable manure management. It is worth noting that both the nodes selected for change in the scenario (Table 3) and the subset of nodes illustrated in Figure 2 all have high or total alignment among panel experts regarding how easily these nodes could be changed by human intervention. This alignment suggests that the model adequately represents a collective view of system behavior, so that the scenario outcome is a useful analysis of potential change.

Although the panel's input to this scenario is well-aligned with their shared goals and expected outcomes, the drivers implemented do not as a group create a single or simple path toward transitioning away from the LS regime. Rather, the recommended system changes are broad goals in themselves and lack specificity for how they could be applied. Furthermore, although the experts agreed on how easily some of the concepts could be changed by human intervention, their collective assessment of the ability to change some concepts was low, with a mean value of less than 0.5 for four of the nine nodes activated. Additionally, the lack of nodes representing certain recommendations such as the need for strong leadership or incremental change suggest these shortcomings are potential barriers to sustainability transitions as they were not included in the current state of the system.

There are several strategies that could be used to enhance the specificity of proposed changes for sustainable manure management and overcome the challenges noted above. For example, points in the system where stakeholder perspectives are most aligned provide common ground to begin identifying where leverage points exist to support successful interventions. The NC SWM conceptual model can also be used to help identify barriers to change without forcing stakeholders to "choose a side" because the model represents the integration of multiple perspectives. Additionally more targeted interventions within specific subsystems or combinations thereof could help tease out the root causes of the negative environmental impacts associated with swine operations and provide greater guidance with regard to policy and regulation, economic factors, farm practices, or societal demands.

Some expected outcomes from more sustainable swine manure management include a reduction in soil degradation for excess nutrient application (A1) and a decrease in commercial fertilizer use (A8) as manure fertilizer value recovery (M34) and the economic feasibility of nutrient conservation practices (F12) both increase. There is also a significant decrease in negative public perception of swine operations (C10), suggesting that manure management is perceived as a key driver of the discord between swine operations and their local communities. Interestingly, there appears to be a correlation between an increase in sustainable manure management and a reduction in the need for appropriately designed air quality and odor control standards for animal operations (G46), as well as reduced public acceptance of science-based information (S38). These decreases are likely artifacts of the decrease in C10 and also a decrease in environmental and social justice concerns related to swine operations (C13). Thus, with a reduction in these negative perceptions, less public demand for regulation or the need for social justice are expected.

Another contradictory outcome is a decrease in the ease of swine manure management (M9) coupled with a decrease in swine farm operator responsibilities (F69) and a decrease in the cost of installation, operation and maintenance of alternative manure treatment technology (N18). In the manure management subsystem map, the decrease in M9 is driven by an increase in manure production, which would occur if swine production expands as a result of more sustainable manure management. The current system as described does not accommodate improved management strategies with an increase in the number or size of swine farms so that changes to the system can allow these concepts to act independently. A review of the subsystem maps could be warranted to identify these and other potential missing relationships between concepts that might explain such contradictions in scenario output.

3.2 Alternative scenario 2: adding a manure dewatering technology

In this alternative scenario, a concept node for an unspecified swine waste dewatering process (M44x) was incorporated into the manure management subsystem of the conceptual model through six new connections. The dewatering technology was added at the farm level as opposed to the niche level as it is not in itself a method of sustainable manure management, but could contribute to more sustainable practices without necessarily eliminating the current LS regime. Inference was run with this scenario activating M44x with and without the support of two additional landscape nodes, targeted funding for innovative technologies (G64), and multiple stakeholder engagement as a mechanism for information exchange (S29). Table 4 shows the relative impact of these driver combinations on four system goal nodes in the niche, landscape and farm levels that were used to indicate whether adding a dewatering technology would lead to an improvement in these goals. The full inference results can be found in the Supplementary material.

The addition of a dewatering technology positively impacted landscape issues driving the need for a regime shift in swine manure management, including negative environmental and social impacts. The addition of M44x alone and combined with the support of landscape nodes (G64, S29) did improve the four goal nodes in Table 4, however the combination of M44x, G64 and S29 together had the greatest impact on all four goals. This outcome is similar to the Scenario 1 results for the same nodes (Figure 2). However, other

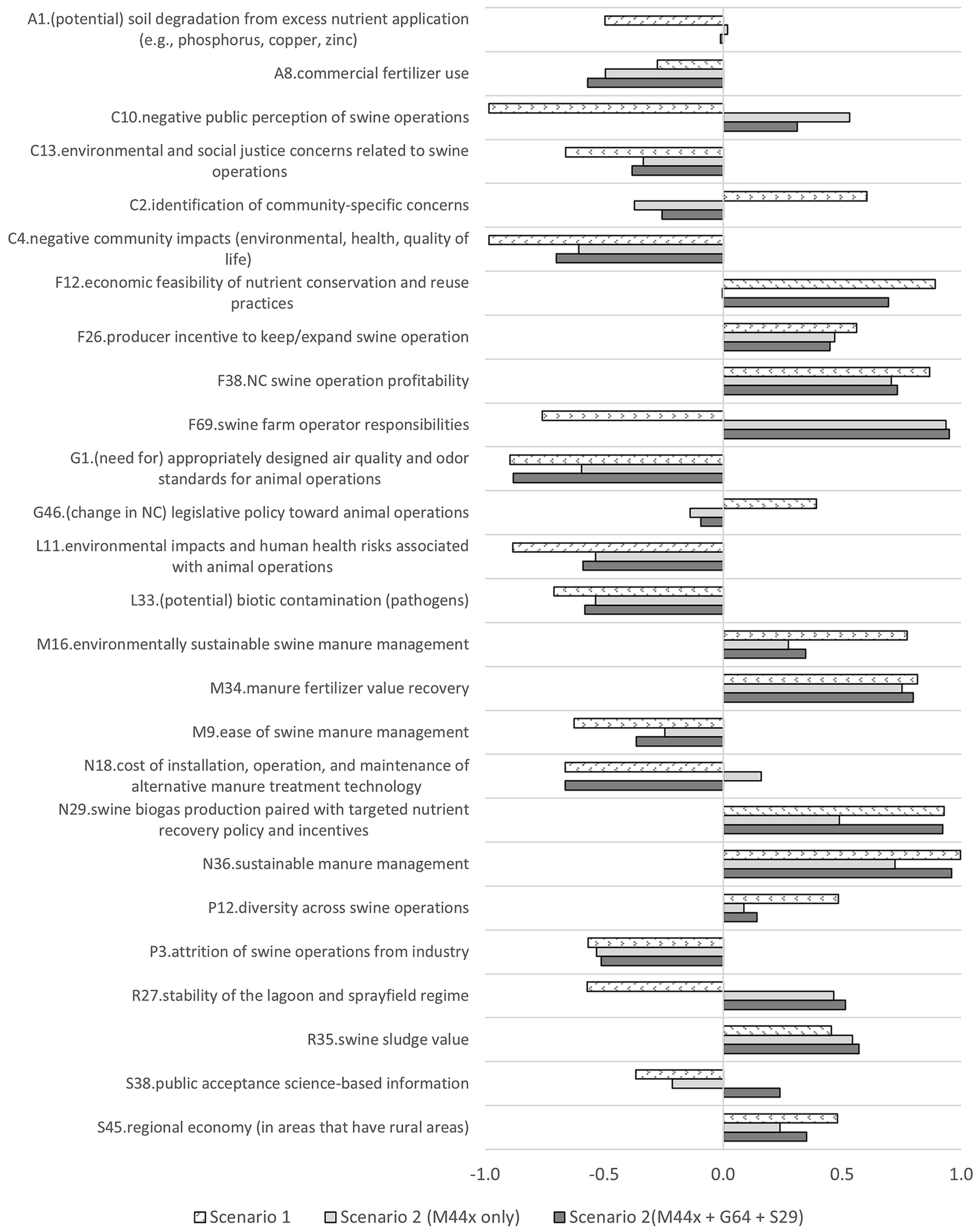

FIGURE 2
A subset of the inference output for scenario 1, scenario 2 adding M44x only, and scenario 2 coupling M44x with landscape nodes G64 and S29.

outcomes differ significantly between Scenario 2 and Scenario 1 and in contradictory ways. For example, negative public perception of swine operations (C10) actually increases, despite community benefits such as a decrease in negative community impacts (C4) and a decrease in environmental and social justice concerns related to swine (C13). This outcome can be traced through the subsystem maps, to find a circular argument, where improved manure management leads to an increase in swine farms, which in turn leads

TABLE 4 Comparison of the relative impact of dewatering process (M44x) and landscape interventions* on niche, farm, and landscape nodes.

	C4. negative community impacts (environmental, health, quality of life)	F38. NC swine operation profitability	L11. environmental impacts and human health risks associated with animal operations	N36. sustainable manure management
M44x	−0.61	0.71	−0.53	0.72
M44x + G64*	−0.64	0.73	−0.54	0.96
M44x + S29*	−0.69	0.72	−0.59	0.74
M44x + G64 + S29	−0.70	0.73	−0.59	0.96

*Landscape interventions include targeted federal funding for innovation (G64), multiple stakeholder engagement (S29).

to negative community and social impacts, which are in turn resolved by sustainable manure management. As with Scenario 1, reviewing the subsystem maps for missing relationships could help identify the source of these contradictory outcomes.

Regarding the feasibility of dewatering swine waste, less water-intensive management strategies do exist and have been implemented on swine farms that use the LS system. For example, as partial fulfillment of its court order, Premium Standard Farms installed scrapers beneath the barn floor as an alternative to flushing manure (Nowlin, 2013). This strategy not only reduced the overall waste volume, but has had the added benefit of improving indoor air quality in barns (Lim and Parker, 2018). In 2000, as part of an industry-government agreement (the "Smithfield Agreement") in North Carolina to develop alternatives to the LS regime, a pilot-scale belt system was tested also to eliminate flushing and for solid/liquid separation of manure (Humenik et al., 2004). However, neither technology has been broadly adopted on North Carolina swine farms. One reason is the high cost of retrofitting an existing operation with limited benefit compared to the current regime, based on the assumption that all manure produced will still be land applied on the farm (Task 1 Team, 2005). There is also a related concern for small-acreage farms regarding the potential conservation of nitrogen in some nutrient management technologies, including covered digesters for biogas production, that may require additional land to meet nutrient management requirements. To mitigate the high costs of retrofitting swine barns with a new technology, financial and policy support at the landscape-level could include a number of strategies. For example, helping growers reduce the risk of implementing unproven technologies through investment grants, insurance programs, and provisional permitting could encourage early adoption. Additionally, developing markets for manure-based products through nutrient-trading programs coupled with enhanced nutrient management planning options for farms could generate new farm income and reduce the burden of nutrient overapplication in areas of high-density production. These types of scenarios could be developed and tested with stakeholders using the NC SWM model. However, without landscape support including financial incentives, regulatory flexibility and specific markets for manure-based products to address these concerns it will be difficult to overcome the status quo.

4 Conclusion

Implementing change in complex agricultural sociotechnical systems is a wicked problem. Researchers or design teams that work on technology development in the niche space often do not have access to the empirical data needed to fully define the system and its constraints across all of the MLP + F levels. Stakeholder experience and expert knowledge can remedy this shortcoming by (1) providing necessary context to understand the system expectations, (2) identify user needs for viable technology design, and (3) to recognize potential barriers and opportunities for adoption.The success of innovation emerging from the niche spaces depends not only on an appropriate technological solution, but also on such actions as supportive government policies, economic viability, and social acceptance, as illustrated by the scenarios used in this case study. When the landscape, regime, niche and farm levels are aligned – that is, their behaviors, processes, and outputs function in harmony toward a common goal – the "stage is set" to support a sustainable sociotechnical transition. Future research could further refine pathways to more sustainable manure management practices by developing specific strategies for incorporating landscape support with farm needs to identify the types of technologies that are both feasible and likely to achieve the desired environmental benefits. These strategies can then be explored as scenarios in the NC SWM model.

It is important to note that the results of this case study using the NC SWM conceptual model do not offer any probabilistic or statistical outcomes. However, inference results using fuzzy cognitive mapping techniques with data developed from a body of diverse expert knowledge can help model users better understand the drivers that affect complex system behaviors. To address conflicting outcomes, future work with the NC SWM model could include a review of the subsystem maps to refine and identify either duplicate or missing concepts and connections. The current iteration of the model is a "snapshot in time" of experts' understanding of the system designed to identify where misalignment exists in their collective perception of system behavior. Thus, updating the model periodically through the modified Delphi process used in MPM could provide further insight into the evolving relationships between the MLP + F levels and where advancements in technology development affect adoption.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by the North Carolina State University Institutional Review Board for the use of human subjects in research. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

Author contributions

AD: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. JC: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. JB: Conceptualization, Methodology, Supervision, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

This article includes work from the corresponding author's doctoral dissertation (Deviney, 2022). The corresponding author would like to acknowledge the Foundation for Food and Agricultural Research and Waste 2 Green, LLC for supporting the doctoral program.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1292326/full#supplementary-material

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