A review of determinants for dairy farmer decision making on manure management strategies in high-income countries

Meredith T Niles, Catherine Horner, Rajesh Chintala and Juan Tricarico

1 Department of Nutrition and Food Sciences & Food Systems Program, University of Vermont, United States of America
2 Department of Plant and Soil Science & Food Systems Program, University of Vermont, United States of America
3 Nutrient Management & Stewardship, Innovation Center for US Dairy, Rosemont, IL, United States of America

E-mail: mtniles@uvm.edu

Abstract

The global dairy sector is a major source of human nutrition and farmer livelihoods, while also generating manure, an important nutrient for crop production, but one that must be managed to minimize environmental risk. Manure management—manure handling, processing, storage and application—is an important part of managing a dairy system. Rising awareness of environmental stewardship is increasing for dairy production that meets multiple sustainability goals. Importantly, a large body of research has identified a suite of potential manure management strategies (MMS) that can contribute to reduced environmental impact, and in some cases, provide additional benefits for farmers and society. Despite this growing body of technical and agronomically-focused research, there has been far less research on farmer decision making and adoption of MMS. To explore this gap, we conduct a systematic literature review of peer-reviewed articles exploring the drivers of farmer adoption and decision making related to MMS. We focus on high-income countries, where MMS strategies are more diverse and often involve advanced technologies. We find 36 articles across Europe, the United States, and Canada and focus on four key areas associated with MMS practices: (1) farm size and structural characteristics associated with MMS adoption including the relationship of certain MMS to each other; (2) existing adoption of MMS practices; (3) socio-economic and regulatory factors associated with MMS adoption; and (4) individual information, attitudes, and demographics associated with MMS adoption. We identify and discuss three gaps in the existing literature: (1) a dearth of studies exploring farmer adoption of MMS, especially from certain highly productive milk regions; (2) a lack of comparative studies across multiple regions and/or across time to identify more direct casual pathways of decision making; and (3) technical and other feasibility needs for future MMS adoption. These suggest a clear pathway for future research to better understand the myriad factors that influence dairy farmer decision making as it relates to MMS.

1. Introduction

Global dairy demand has grown steadily in the past several decades and is expected to continue to increase 2.1% annually for the upcoming decade (OECD and FAO 2017). Production is led by the United States, the largest producer of cow’s milk in the world (United Nations Food and Agriculture Organization 2014). At the same time, there is growing demand from consumers and policymakers for milk that is produced sustainably and with low environmental impact. Importantly, a large body of research indicates that significant potential opportunities exist to improve manure and nutrient management within dairy farming systems to reduce greenhouse gas (GHG) emissions and water quality impacts (Montes et al 2013, Holly et al 2018). This work has identified important environmental, technical and agronomic contexts that can affect the use of certain manure management strategies (MMS) in some regions, with varying environmental outcomes (e.g. the role of temperature and climate in driving GHG emissions from various MMS strategies, or farm size as a determinant for MMS). Furthermore, dairy manure represents an
important source of organic nutrients for crop production, which can provide agronomic and economic benefits to farmers, but also requires proper management to minimize environmental risks in water quality (Motew et al. 2018).

Dairy manure management involves multiple individual practices including manure collection, handling, processing, storage and application. There is now strong understanding, and in many cases scientific consensus, about how varying MMS may offer different environmental benefits and impacts across dairy farm systems and climates (Global Research Alliance 2014). Technical understanding is critical to quantify the benefits and impacts related to various MMS, and there has been a large body of research exploring the technical and agronomic components of MMS. However, understanding the non-technical drivers and barriers (e.g. farm or farmer characteristics, socio-economic and political factors, climate and environmental context) dairy farmers face to implement MMS is valuable to understand how and why dairy farmers make decisions about manure management and what kinds of technical, financial or other assistance could empower them to adopt new and existing MMS that increase environmental benefits and reduce risk. Although a significant body of research focused on farmer behavior and decision making exists, in addition to several broad review articles about farmer adoption of best management practices (e.g. Prokopy et al. 2008, Baumgart-Getz et al. 2012, Carlisle 2016), we are unaware of any review articles that specifically explore decision making and adoption of MMS by dairy farmers—despite the significant influence that manure management has on-farm profitability, structure and environmental impact. We aim to fill this gap in the scientific literature through this systematic review focused on the factors that influence the adoption of different MMS by dairy farmers in high-income countries. We focus on the many potential factors that have been shown to influence farmer decision making including farm size and structure, infrastructure, socio-economic and political factors, and individual-level farmer factors that can influence adoption.

2. Methods

2.1. Systematic approach
A systematic literature search was performed to identify all the peer-reviewed articles relevant to

| Location     | State/region     | Number of papers | World dairy production ranking (cow milk) | World production (tonnes, from 2017) (FAO 2017) |
|--------------|------------------|------------------|------------------------------------------|-----------------------------------------------|
| United States| Wisconsin        | 5                | 1                                        | 97 734 736                                    |
|              | Louisiana        | 3                | 1                                        |                                               |
|              | Florida          | 2                | 1                                        |                                               |
|              | New York         | 2                | 1                                        |                                               |
|              | Pacific Northwest| 1                | 1                                        |                                               |
|              | Pennsylvania     | 1                | 1                                        |                                               |
|              | Iowa and Missouri| 1                | 1                                        |                                               |
|              | California       | 1                | 1                                        |                                               |
|              | Connecticut      | 1                | 1                                        |                                               |
|              | Texas and Florida| 1                | 1                                        |                                               |
| United Kingdom| England         | 3                | 10 (United Kingdom)                      | 15 256 000                                    |
|              | Scotland         | 1                | 1                                        |                                               |
|              | England and Wales| 1                | 1                                        |                                               |
| Canada       | Ontario          | 2                | 19                                       | 8100 000                                      |
|              | Montreal         | 1                | 1                                        |                                               |
|              | National         | 1                | 1                                        |                                               |
| Denmark      |                  | 4                | 26                                       | 5557 160                                      |
| Netherlands  |                  | 3                | 11                                       | 14 297 361                                    |
| Denmark, Italy, Netherlands, Spain | 1 | 26, 14, 11, 24 | 5557 160 (Denmark), 11 380 094 (Italy), 14 297 361 (Netherlands), 7027 668 (Spain) |
| Ireland      |                  | 1                | 20                                       | 7478 160                                      |
| Italy        |                  | 1                | 14                                       | 11 380 094                                    |
| Austria      |                  | 1                | 31                                       | 3712 727                                      |
manure management on dairy farms within high-income countries as defined by the World Bank (World Bank 2019), whose dairy systems and industry are most comparable to those in the US. This was of particular interest given that the US is the largest producer of milk globally. While we recognize that high-income countries have varying socio-political contexts (Liu et al. 2018), which we explore as potential drivers, these regions share economic structures that enable technical capacity, are often large producers, and are dominant in the global export market (see table 1) providing commonalities for comparison. No temporal restrictions were imposed on the initial search to survey the full field of research on determinants of MMS. However, we later determined that articles published before 1980 were not relevant, given the evolution of regulatory and dairy landscapes over the past 35+ years.

A systematic review is defined by its application of repeated and iterative searches related to the research question at hand (Robin and Kathleen 2005, Sovacool et al. 2018). This process is intended to identify and explore studies that may exist across different bodies of evidence and contain heterogeneous methodologies (Greenhalgh et al. 2005). As Sovacool et al. explain, ‘a review becomes ‘systematic’ when it is based on a clearly formulated question or topic, identifies relevant studies, appraises their quality or relevance and then summarizes their evidence’ (Sovacool et al. 2018).

For this reason, qualitative systematic reviews such as this one have been indicated for exploring issues in which multiple and/or competing factors may interact in complex causal relationships (Tranfield et al. 2003).

2.2. Keywords and search terms

To systematically and thoroughly explore our research question, we used three online research databases: Agricola, Web of Science, and Google Scholar. These databases cast a wide net in collecting articles related to dairy manure management. Additionally, these databases enabled the inclusion of only peer-reviewed articles written in English. Keywords and terms used included ‘dairy farmer’, ‘manure management’, ‘nutrient management’, ‘manure application’, ‘adoption’, ‘manure’, ‘storage’, ‘application’, ‘behavior’, ‘injection’, ‘broadcast’, ‘side dressed’, ‘lagoon’, ‘liquid’, ‘solids’, ‘slurry’, ‘environment’, ‘sustainable’, ‘survey’, ‘anaerobic’, and ‘digester’. Searches included ‘dairy farmer’ grouped with various combinations of additional search terms related to dairy manure management. Iterative variations on search terms are used to return all literature that could be germane to the review (Greenhalgh et al. 2005). These search terms intentionally constituted a broad search to ensure that we did not exclude any potentially relevant articles. By intentionally including a broad range of studies, we sought to construct a more thorough view of the multiple factors that may influence farmers’ manure management decisions (Petticrew and Roberts 2006).

The initial search process yielded 910 articles, which includes double counts of articles that appeared in multiple searches. The initial search was followed by a secondary identification of relevant articles that referenced or were referenced by articles on the initial list. Article titles, abstracts, and keywords were assessed to determine relevance to the review topic and adherence to the geographic scope. In particular, we carefully assessed article abstracts to determine whether the article addressed our research question regarding the consideration of factors affecting the adoption and decision making processes on dairy farmers’ MMS choice. Given the small number of articles dealing explicitly with dairy farmers MMS adoption and decisions, we chose to include articles in which manure management was not the primary focus but rather, a subset of topics considered. Similarly, we felt it necessary to include articles that were non-dairy specific but that offered information relevant to the decision making of farmers’ MMS more generally. These decisions were deemed necessary to form a thorough picture of possible manure management behavior determinants.

2.3. Article types

A total of 36 articles were found for inclusion in this review. Of the 36 articles: 18 were US specific, 16 were based in Europe, and four were from Canada (note this includes studies with multiple locations), representing high-income regions with large global production (table 1). In terms of methodologies most commonly used in the included articles, 27 employed surveys, 6 conducted interviews, 3 analyzed case studies, and 2 applied modeling. Table 2 details the manure management focus, place of study, method, and number of farmers included.

2.4. Content analysis

We employed a summative approach within our qualitative content analysis to determine the relevant content within the articles identified through the primary and secondary searches. This approach involves identifying, counting and comparing keywords and other content themes, in order to interpret information themes across a broader context (Hsieh and Shannon 2005). Within this approach, we extracted and organized information regarding the methodology, main focus and key findings of each article. Information on the location and demographic insights of each study were also recorded. This process enabled identification and, ultimately, interpretation of themes relevant to farmer decision making within the body of literature on dairy MMS. We should note that many of the articles discuss the adoption of ‘best management practices (BMPs)’ or ‘best nutrient management practices’. Defining the suite of practices
| Authors, Year              | Manure management focus                                | Country or State | Method                  | Number surveyed | Farm type                          |
|---------------------------|-------------------------------------------------------|------------------|------------------------|-----------------|------------------------------------|
| Aguirre-Villegas and Larson 2017 | Impact of farm size on collection, storage and handling | Wisconsin        | Survey                 | 143             | Dairy                              |
| Anderson and Weersink 2014 | Economic feasibility of anaerobic digestion            | Ontario          | Real options economic model | N/A             | Dairy                              |
| Asai et al 2014a           | Partnerships for manure exchange- social aspects       | Denmark          | Survey                 | 644             | Dairy and pig                      |
| Asai et al 2014b           | Partnerships for manure exchange- farmer perceptions   | Denmark          | Survey                 | 644             | Dairy and pig                      |
| Barrington and Piche 1992  | Solid manure systems                                  | Montreal         | Interviews             | 25              | Dairy                              |
| Bishop et al 2010          | Adoption of anaerobic digestion                       | Oregon, Washington, Idaho | Survey            | 230             | Dairy                              |
| Brock and Barham, 2009     | Pasture-based dairy farm systems                      | Wisconsin        | Survey and interviews | 840             | Dairy                              |
| Buckley et al 2015         | Nutrient management practices                         | Ireland          | Survey                 | 271             | Dairy, beef and sheep              |
| Cabrera et al 2006         | Climate forecasting to mitigate nutrient pollution    | Florida          | Interviews and focus groups | 64              | Dairy                              |
| Case et al 2017            | Organic fertilizer usage                              | Denmark          | Survey                 | 452             | Dairy, beef, poultry, pigs and arable |
| Dou et al 2001             | Nutrient management practices                         | Pennsylvania     | Survey                 | 994             | Dairy                              |
| Filson et al 2003          | Manure management impact on quality of life           | Ontario          | Survey                 | 194             | Dairy                              |
| Gebrezgabher et al 2015    | Manure separation technology                          | Netherlands      | Survey                 | 111             | Dairy                              |
| Gedikoglu et al 2011       | Nutrient management adoption                          | Iowa, Missouri   | Survey                 | 1127            | Dairy, beef, pig, poultry and arable |
| Glenk et al 2014           | GHG mitigation                                        | Scotland         | Survey                 | 235             | Dairy                              |
| Hou et al 2016             | Manure treatment technology                           | Denmark, Italy, Netherlands, Spain | Survey            | 291             | Dairy, beef, pig and poultry        |
| Ingram 2008                | Soil management, farmer scientific knowledge          | England          | Survey and interviews | 81 (Int.), 163 (Sur.) | Dairy, sheep, pig and arable        |
| Meyer et al 2011           | Dairy housing, manure management                      | California       | Survey                 | 107             | Dairy                              |
| Oenema et al 2011          | Nutrient use efficiency                               | Netherlands      | Pilot farms            | 16              | Dairy                              |
| Ondersteijn et al 2006     | Perceived environmental uncertainty                   | Netherlands      | Survey                 | 103             | Dairy, mixed livestock and arable   |
| Paudel et al 2008          | Best management practices                             | Louisiana        | Survey                 | 49              | Dairy                              |
| Poe et al 2001             | Voluntary water quality practices                     | New York         | Survey                 | 470             | Dairy                              |
| Powell et al 2005          | Manure collection and distribution                    | Wisconsin        | Survey                 | 54              | Dairy                              |
| Powell et al 2007          | Nutrient management behavior                          | Wisconsin        | Interviews and mapping | 33              | Dairy                              |
| Rahelizatovo and Gillespie 2014a | Best management practices                           | Louisiana        | Survey                 | 124             | Dairy                              |
| Rahelizatovo and Gillespie 2014b | Best management practices                           | Louisiana        | Survey                 | 124             | Dairy                              |
| Sheppard et al 2011        | Nitrogen and manure management                        | Canada           | Survey                 | 523             | Dairy                              |
| Smith et al 2001           | Cattle manure management practices                    | England          | Survey                 | 986             | Dairy and beef                     |
| Southgate et al 1980       | Less polluting manure management systems              | Wisconsin        | Linear programming model | N/A             | Dairy                              |
| Strazzera and Statzu 2016  | Adoption of manure management technology               | Italy            | Survey                 | 82              | Dairy                              |
| Swindal et al 2010         | Adoption of anaerobic digestion                       | New York         | Survey                 | 418             | Dairy                              |
| Tao et al 2014             | Manure application                                   | Connecticut      | Pilot farms            | 4               | Dairy                              |
| Thurow and Holt 1997       | Dairy regulations                                     | Texas and Florida | Historical analysis | N/A             | Dairy                              |
| Tranter et al 2011         | Adoption of anaerobic digestion                       | England          | Survey                 | 384             | Dairy, beef and pig                |
| Welsh et al 2010           | Adoption of anaerobic digestion                       | New York         | Survey                 | 418             | Dairy                              |
| Wirth et al 2013           | Adoption of biogas technology                         | Austria          | Interviews and case studies | 35              | Dairy, energy crops and other       |
that this entails is not universal, and therefore may vary by the region of focus. The United States Department of Agriculture, in the context of nutrient management, has defined BMPs as, ‘soil and water conservation practices, other management techniques, and social actions that are developed for a particular region as effective and practical tools for environmental protection. Rarely does one single practice or action solve the pollutant concern, but often it is a combination of measures that is used… what works in one geographic region may not work in another because of variation in climate, soils, geology, and so forth’ (Sharpley et al 2006).

An overview of the articles, their geographic locations, methodology and manure management focus is provided first in the results section. The role of farm structure and characteristics on adoption of different MMS is provided in the second section including an overview of various MMS and their relationship to each other. This section includes details on the relationship between different management strategies to each other, and how they are often correlated with different management outcomes. Third, we review the adoption of different MMS across manure handling, storage, and application. Then, we focus on the socio-economic and political factors, including social networks, economic and cost factors, and policy and regulatory environments that can influence MMS. Finally, we detail the individual-level farmer factors that can influence adoption, including knowledge, attitudes and demographics. We follow the presentation of results with identified research gaps and opportunities for future research.

3. Results and discussion

3.1. Manure management practices in dairy farms and their relationship to each other

Dairy manure management involves multiple individual practices including manure collection, handling, processing, storage and application. MMS can be complex and vary widely across dairy farms since farmers can implement these practices in different ways (figure 1).

3.1.1. Manure collection

In manure collection stage, the manure is transferred to either storage or land application. The use of different manure collection systems is likely driven by a set of factors including both farm infrastructure as well as farmer priorities and goals. Importantly, manure collection systems appear to be significantly related to farm size (Powell et al 2005, Sheppard et al 2011) and go on to influence manure storage and application strategies. As noted previously, evidence suggests that small and medium-sized farms are more likely to collect solid manure while larger facilities are more likely to collect manure in slurry or liquid forms (Filson et al 2003, Sheppard et al 2011, Aguirre-Villegas and Larson 2017). The literature indicates that scrape and flush systems are the most common means of collecting slurry and liquid manures (Dou et al 2001, Meyer et al 2011, Aguirre-Villegas and Larson 2017). Bedded pack and gutter cleaners and other scrape systems were the most common collection methods mentioned for solid manure systems (Dou et al 2001, Filson et al 2003, Meyer et al 2011, Sheppard et al 2011, Aguirre-Villegas and Larson 2017).

A recent study from dairy farms in Wisconsin finds that 70% of the small and medium farms used solid manure collection, while large facilities were more likely to employ slurry or liquid systems. These different collection and handling systems were correlated with the housing systems most common at small to medium and large scales (Aguirre-Villegas and Larson 2017). Manure collection was found to be more frequent among lactating cows and less frequent among dry cows and heifers, which could also be related to different housing systems for each type of animal (Dou et al 2001).

In Pennsylvania, farms collecting solid manure mainly did so via bedded pack, while 84% of farms collecting slurry, semisolid or liquid manure employed scrape collection techniques (Dou et al 2001). However, in California, larger farms also used manure as bedding, but did so following collection of corral scrapings and/or processing to separate out solids and liquids (Meyer et al 2011). This contradiction exemplifies a theme in the literature; namely, that there can be substantial variability in manure collection methods across farm size and regions (Powell et al 2005, Sheppard et al 2011).

3.1.2. Manure storage

Evidence indicates that manure storage is often a function of farm size and is related to the selection of other MMS. Existing data from Wisconsin indicate that large and medium farms are more likely to have long-term storage and treatment infrastructure than smaller farms (Aguirre-Villegas and Larson 2017). Another study examining Wisconsin dairy farms found that many small- to medium-sized operations employ pasture-based feeding systems, which do not require manure collection or storage and, consequently, avoid the time, labor and infrastructure costs associated with the storage and treatment systems necessary in confined feeding operations. Organic pasture-based dairy farms, however, were more likely to store manure in lined structures or piles than were larger confinement operations (Brock and Barham 2009). This could indicate that restrictions on chemical fertilizers might motivate more efficient use of manure nutrients and highlights the potential connection between farm-wide management systems and manure storage strategies (Brock and Barham 2009). An earlier study in Pennsylvania correlated specific manure storage strategies with either dry (non-milk
producing due to age or seasonal reproductive cycles) or lactating cows, highlighting the interconnectivity of manure storage and other farm-level factors such as breeding and housing systems. At that time (2001), there were few instances of alternative manure collection and storage systems, such as methane digesters or treatment lagoons, and in fact 30% of farmers reported no manure storage system at all (Dou et al. 2001). In contrast, a study from the late 1990s in Ontario found that the majority of farmers stored manure in an outdoor pile, while the largest farms reported using liquid systems with storage lagoons (Filson et al. 2003). In a survey of Louisiana dairy farmers, management of wastewater and runoff from cow housing facilities had the highest rate of adoption amongst a suite of BMPs related to manure storage (Rahelizatovo and Gillespie 2004a). Glenk et al. found that covering stored manure, using anaerobic digesters and removing manure frequently as GHG mitigation strategies, were less frequently adopted compared with other GHG mitigation strategies in Scotland (Glenk et al. 2014). Later findings from Canada suggest farms typically stored slurry between 1 month and 1 year, with 97% not agitating manure, and only 10% of farms separating liquids and solids (Sheppard et al. 2011).

3.1.3. Manure processing

Many studies found that there is significant potential for adoption of more environmentally sound manure processing strategies. In Europe, manure solid–liquid separation and anaerobic digesters have the greatest adoption potential (Hou et al. 2016). In New York, more than half of farmer respondents expressed some or great interest in a community-level manure digester (Swindal et al. 2010). Another study of New York dairy farmers found that interest in anaerobic digester technology is not inherently scale-based, and that the impact of farm size on interest is mediated by other farm-scale variables, such as reliance on pasture or interest in biotechnology (Welsh et al. 2010). More recently, Strazzera et al. found that 77% of dairy farmers in an agricultural region of Sardinia, Italy were interested in the potential for biogas/anaerobic digesters at their farms (Strazzera and Statzu 2016). However, in England the potential adoption rates were much lower in one survey, where only 9% of farmers indicated they would consider investing in a digestor; 30% responded maybe and 60% indicated they would not consider investing (Tranter et al. 2011). Similarly, a Pennsylvania study found that only 8 out of 944 farms used manure processing strategies such as methane digesters or treatment lagoons. In Wisconsin, only 7 out of 143 farms processed manure via anaerobic digester (Aguirre-Villegas and Larson 2017). Heterogenous findings are reaffirmed by a study across four regions of Australia, which found high variability of adoption of biogas technology across the different regions (Wirth et al. 2013).

Aside from digester technology, another manure processing technique discussed widely in the literature is solid–liquid separation. Meyer et al. concluded that dairy farms in California’s Central Valley increased the use of solid–liquid separation from 54% in 1994 to up to 70% in 2007 (Meyer et al. 2011). However, in Wisconsin, less than 17% of farms utilized manure separation technology, via either solid–liquid separation or sand separation (Aguirre-Villegas and Larson 2017). In the Netherlands, one study found that farmer attitude and the compatibility of current manure application technologies were significant factors influencing farmers likelihood of adopting manure separation technologies (Gebrezgabher et al. 2015).

3.1.4. Manure application to agricultural crop lands

Application of manures is connected with how manure is stored and is often related to farm size as well. Larger Wisconsin dairy farms typically land applied seasonally in spring and fall and used multiple application techniques as compared to smaller farms, which applied weekly or even daily due to a lack of longer-term storage structures (Aguirre-Villegas and Larson 2017). Early evidence from Pennsylvania in 2001 found that most manure application was done by surface spreading (95%), and incorporation was not
practiced by most farms (Dou et al. 2001). In the Netherlands, shallow manure injection was common among farmers surveyed (56% of farms), while 22% used trailing shoe injector and 12% used drag bars (Gebrezgabher et al. 2015). In Canada, however, one study found that most slurry manure was broadcast and not injected at the time farmers were surveyed (Sheppard et al. 2011).

3.1.5. Summary

In summary, various farm-level factors—including farm size, feeding system, housing system, and breeding system—were identified as influencing adoption of specific manure collection, storage and treatment systems. There was an indication that management decisions around the storage and treatment of manure may offer the greatest opportunity to reduce GHG emissions associated with dairying. However, farmer interest in adopting new storage and treatment technologies varied. Certain manure processing strategies and treatment methods, such as anaerobic digesters and solid–liquid separation, were more common and were generally adopted by larger farms that also applied manure less frequently than smaller farms thanks to their greater long-term storage capacity. The literature presents consistent evidence indicating that substantial heterogeneity exists across farm sizes and geographic locations regarding the most common methods of manure application.

3.2. Influence of on-farm and off-farm factors on dairy manure management decision making

3.2.1. Farm size

Farm size and its influence on farmer adoption of technologies has been widely studied, especially in cropping systems; however, no universal conclusions have been reached about the role that farm size plays in technology adoption, particularly BMPs (Prokopy et al. 2008). We find similar evidence for MMS; namely, that there are no consistent effects of farm size on MMS. There is, however, more evidence to suggest that large farms have greater propensity for adopting MMS best practices (although in some cases these associations are not significant, i.e. Buckley et al. 2015). In a survey of Louisiana dairy farmers, larger farms with higher milk yield show greater adoption of BMPs (Rahelizatovo and Gillespie 2004a). These facilities were more likely to adopt erosion control practices and more capital intensive waste management systems, but less likely to adopt best nutrient management practices (Rahelizatovo and Gillespie 2004a). Other evidence suggests that larger farms are more likely to store manure and/or process manure in multiple ways, in part because larger dairy farms collected slurry or liquid manure whereas a majority of smaller farms collected solid manure. Regardless of manure solids, scrape systems—including alley scrapers, barn cleaners, and skid steers—were common across all farm sizes (Aguirre-Villegas and Larson 2017). Larger farms are also more likely to use processed manure (Case et al. 2017) and adopt modern technologies for manure management (Brock and Barham 2009). Others found that larger farms in the Netherlands were more likely to use separation technology, though such relationships were not deemed statistically significant (Gebrezgabher et al. 2015). One study found that larger farms were more likely to be owner occupied, and thus more likely to adopt anaerobic digesters, suggesting the importance of farm size in relationship to other variables of interest (Tranter et al. 2011).

Conversely, in some studies, smaller and medium-sized farmers were associated with less frequent adoption of MMS with environmental benefits. Powell et al. (2005) found that small farms in Wisconsin were more likely to have difficulty adequately collecting and utilizing manure in environmentally friendly ways (Powell et al. 2005). Similarly, evidence from Connecticut dairy farms indicated that medium-sized farms were more likely to over apply manure on fields close to their manure storage as compared to larger farms; however, this was likely related to the fact that larger farms had access to equipment better suited to efficiently transport manure longer distances (Tao et al. 2014). Dairy farmers in New York with fewer than 250 cows also indicated less interest in anaerobic digesters on their farms than did larger dairy operators (Swindal et al. 2010). However, Welsh et al. find that farm size was mediated by other factors related to manure management, such as access to pasture and attitude towards biotechnology, suggesting that farm size itself had little to no influence on farmer interest in anaerobic digester technology and that other factors should be considered (Welsh et al. 2010).

One important limitation to note in considering size as a variable mediating dairy MMS is heterogeneity across the literature. Size often being relative, definitions of what constitute small, medium or large vary by context. For example, one paper defines small farms as under 99 animal units (which is equivalent to approximately 76 full-grown Holstein dairy cows), while another paper from the same region applies under 200 cows as the definition for a small farm. This inconsistent definition of the variable further complicates discerning its potential impacts on MMS.

3.2.2. Farm infrastructure

Outside farm size, other factors have also been explored as possible drivers of dairyman farmer adoption of MMS. The existing infrastructure on a dairy farm encompasses the physical structures and equipment as well as operational and organizational systems that enable production. Infrastructure plays a significant role in MMS; for example, manure handling, storage and application strategies are all connected and co-determined by operational infrastructure. In many cases manure storage benefits cannot be realized unless they are accompanied by manure incorporation.
and consideration of quantity and timing aspects when applying it (Dou et al. 2001). The types of manure application possible for a given farm are, in turn, inherently influenced by whether the farm separates manure into liquids and solids (Gebrezgabher et al. 2015). For example, Buckley found that the use of solid manure storage was correlated with lower adoption of nutrient management practices as compared with farms using liquid storage. They conclude that this may be related to solid storage being associated with older facilities that are less structurally compatible with the adoption of more modern nutrient management technologies. This conclusion indicates that conversion to liquid systems could increase adoption of nutrient management practices (Buckley et al. 2015).

Results from Iowa and Missouri make similar conclusions, as farmers with liquid systems were more likely to adopt record keeping and manure injection systems (Gedikoglu et al. 2011). Importantly, however, research indicates that the cost and feasibility of transitioning to new MMS can be highly variable across farms (Bishop et al. 2010).

Other studies found similar results indicating a substantial influence of existing systems or infrastructure on adoption of new MMS. Early modeling studies suggested that the adoption of systems with less potential nutrient leaching depends on equipment and storage capacity (Southgate et al. 1980). More recently, 30% of Ontario dairy farmers indicated that their existing MMS was a limiting factor for both expansion of their farm and potential adoption of new technologies (Filson et al. 2003). Given that MMS’s become rather ‘fixed systems’, Cabrera et al. (2006), found that such inflexibility in their systems prevented some farmers from using climate and weather forecasts that could assist them with nutrient management planning (Cabrera et al. 2006).

3.2.3. Summary
While we find there is no universal effect of farm size on MMS identified across the literature, there was, however, a notable trend indicating that larger farms are more likely than smaller farms to adopt certain MMS, particularly storage and treatment strategies that require substantial investment in technology or infrastructure. The literature further indicates that farm size interacts with other farm-level factors to impact the likelihood of a farmer choosing specific MMS.

In terms of farm infrastructure, the literature again indicated the prevalence and influence of interconnected systems related to MMS. Some systems were more conducive to adoption of certain MMS; for example, liquid systems were associated with greater adoption of manure nutrient management practices. The literature also indicated that infrastructure can inhibit improvements to manure management. Because every stage of manure management interacts with the other stages, the infrastructure associated with each is often mutually dependent, making it hard to change only one component of MMS. This is related to the finding that MMS often become fixed systems, which impedes adoption of new strategies or technologies.

3.3. Role of socio-economic factors
While farm infrastructure and size can influence MMS, there is also recognition that social and economic factors can affect MMS adoption. These factors are diverse and include everything from a farmer’s social network or information sources to the debt ratio at the farm, the profitability or cost of the MMS, and the regulatory and policy environment. Below we detail the existing research on how these socio-economic factors relate to MMS adoption.

3.3.1. Social networks
Several studies have explored the multiple ways in which social relationships and networks may affect MMS adoption by farmers. Social networks at varying scales appear to influence the adoption of practices and manure management by farmers. Contact with agricultural advisors, researchers or other farmers led to more nutrient management and BMPs adopted in Ireland (Buckley et al. 2015), the Netherlands (Oenema et al. 2011) and Louisiana (Rahelizatovo and Gillespie 2004a). Contact with government agencies, especially the Natural Resources Conservation Service in the United States, is also associated with increased adoption of BMPs among dairy farmers in Louisiana. Social relationships among dairy farmers were critical for successful implementation of manure exchange programs (i.e. exchanging manure between farms that have excess to those that need manure), particularly as they helped to foster respect and communication across farmers (Asai et al. 2014a, 2014b).

Perceived social costs and benefits to society and neighbors is another social determinant that can drive adoption of MMS by farmers. Bishop et al. found that social motives and the social costs of avoided adoption of anaerobic digesters were significant predictors of anaerobic digester adoption (Bishop et al. 2010). Having non-farmer neighbors is also a significant predictor of anaerobic digester adoption in New York, with the potential to reduce odors and promote good neighbor relations being a primary driver (Swindal et al. 2010, Welsh et al. 2010).

3.3.2. Economics, cost and profit
Several articles explored the role of economic factors in adopting MMS. Some studies have found that economic barriers and/or costs are the primary driving factor influencing MMS adoption. In Europe, Hou et al. found that economic factors were the largest barriers to technology adoption for manure treatment, with a lack of investment capital (60%), high processing costs (52%), and long payback periods (45%).
being the major reasons cited by farmers (Hou et al 2016). Relatedly, a model based on dairy farmer survey responses in the Pacific Northwest of the US indicated that even profit seeking farmers are unlikely to adopt anaerobic digester technology due to uncertainty regarding the profitability of this major investment. The model further indicated that even farmers that recognize the social benefits of anaerobic digester adoption may be averse to adoption because of economic reasons (Bishop et al 2010). One possible explanation may be the option value of waiting, whereby there is an economic benefit in farmers delaying adoption of a significant technology investment as the technology may become cheaper or more efficient in the future (Anderson and Weersink 2014). Economic barriers were found to be particularly important for adoption of manure processing infrastructure for small farms, who have less income and potentially fewer economic resources (Aguirre-Villegas and Larson 2017). The impact of MMS costs in general can have reaching impacts, with 16% of farmers surveyed in Ontario citing that MMS costs were adversely affecting their quality of life (Filson et al 2003).

Other studies found that economic barriers and costs have different effects on MMS adoption. For example, Paudel found that those technologies that were adopted by dairy farmers had on average the highest costs, but such MMS were eligible for cost-sharing incentives funded through the federal government up to a cost threshold (see policy section below for additional information) (Paudel et al 2008). Barrington found that cost was not consistently reported as the primary factor for farmers shifting towards liquid MMS, but it was often second (Barrington and Piche 1992). Instead, some technology shifts may be influenced by debt to asset ratios, with lower levels associated with increased adoption of best management MMS (Paudel et al 2008). Further, some technologies require consideration of both payback periods and income impact assessments. Longer payback periods for adoption of anaerobic digesters were associated with less likely adoption (Strazzera and Statz 2016), while potential for increased income through energy generation via anaerobic digesters is a significant predictor of adoption across multiple regions (Swindal et al 2010, Strazzera and Statz 2016).

3.3.3. Policy and regulatory influences
How and why farmers adopt MMS can be significantly influenced by policy and regulatory structures in a given region. For example, in Europe, dairy farmers cited the policy and regulatory environment as having the most significant impact on their MMS adoption (Hou et al 2016). Others found that awareness of government regulations related to water quality had a significant impact on adoption of nutrient BMPs (Rahelizatovo and Gillespie 2004a). Incentive programs or government funding support for MMS were explored across multiple regions. The potential cost-share of incentive programs or economic impacts were shown to have significant impacts on potential or actual adoption of MMS (Southgate et al 1980). Low cost-shares are a hindrance to producer adoption of BMPs (Paudel et al 2008), and even nominal costs for voluntary participation in incentive programs can significantly reduce participation rates (Poe et al 2001). Further, additional grant funding from policies could help shift the return on investment portfolio for particularly expensive MMS such as anaerobic digesters (Anderson and Weersink 2014). While studies do suggest that farmer participation in incentive programs is important to drive adoption of expensive MMS (Paudel et al 2008), in at least some cases, previous participation in government incentive programs actually resulted in dairy farmers being less likely to adopt a BMP (manure injection) (Gedikoglu et al 2011). Further, Poe et al found that 22% of dairy farmers would not participate in voluntary water quality programs even if 100% cost-shares were provided for adoption of practices (Poe et al 2001), demonstrating that some farmers simply will not participate in government programs regardless of the potential benefits or costs.

Importantly, some studies indicate caution around incentive programs and regulations overall, as farm and farmer heterogeneity means that policies may not work everywhere for everyone (Powell et al 2007, Oenema et al 2011). This may be particularly true for nutrient management plans and other manure application technologies since these may be field dependent (Tao et al 2014) and have different impacts on nutrient cycling and GHG emissions, suggesting an inherent need for flexibility in policy (Glenk et al 2014). Others advocated that policies need to consider different types of farmers, not just those that might be innovators or early adopters. Further, since farmers are often dual-motive (i.e. making decisions based on multiple drivers or outcomes), policies that address multiple priorities could also be critical (Bishop et al 2010). This may be particularly important as non-adoption of a practice was found to be due to a perceived non-applicability of a specific practice to a specific farm (Rahelizatovo and Gillespie 2004a), which may not be addressed by policy.

Farmers also often cite regulatory uncertainty as a driver of their on-farm behaviors, as this uncertainty can lead to a perception of hostility towards farmers (Ondersteijn et al 2006). Thurow and Holt suggest that policy and regulatory uncertainty influence farmers’ propensity to postpone investment in environmentally friendly management practices. Such uncertainties are associated with shifting guidelines, compliance and timeframes, as well as dissonance between federal and state regulations (Thurow and Holt 1997). Finally, at least one study found that just because regulations require a certain practice does not mean that such
practices are fully incorporated into farm-level management. Buckley et al. found that while farmers in Ireland were doing soil testing to comply with regulations, they were not actually using the results to inform better nutrient management outcomes on their own farms (Buckley et al. 2015).

3.3.4. Summary
Throughout the literature, contact with agricultural advisors, researchers and other farmers was consistently found to increase adoption of best practices related to manure management. Farmer attitudes toward non-farm factors, such as societal benefits and neighborliness, were also found to be important drivers of adopting certain MMS, especially adoption of digester technologies.

In contrast, economic barriers were consistently found to be one of the most influential factors in farmer decision making related to MMS. Cost was found to be especially prohibitive for smaller farms in the context of adopting manure treatment strategies. Besides the cost of MMS, cost-share programs, debt to asset ratio, payback period and the opportunity for additional income were found to impact farmers’ decisions to adopt or not adopt certain MMS.

Finally, the policy and regulatory landscape was consistently found to be an important factor influencing farmer adoption of MMS. Multiple studies identified the need for flexibility within policies to accommodate farm and farmer heterogeneity. It was also found that farmer uncertainty around regulations negatively impacted farmers’ decision to adopt improved MMS.

3.4. Individual characteristics
Factors related to individual farmers—including farmer attitudes and perceptions, knowledge and information, and demographics—are important to consider in their relationship to MMS. Indeed, some even concluded that how farmers apply manure and nutrients on their farm is more linked to individual farmer perspectives and behaviors than to specific operational features of a farm (Powell et al. 2007).

3.4.1. Knowledge/information
Studies explored the many ways that information and knowledge about MMS can influence on-farm behavior, with varying outcomes. Gebrezgabher et al. found that knowledge of manure separation technologies had no significant impact on farmers wanting to use it. The authors thus conclude that knowledge is not a determining factor for future adoption of this MMS (Gebrezgabher et al. 2015). Conversely, others concluded that in fact it is a lack of specific technical knowledge related to nutrient content in manure that has prevented farmers from adopting better nutrient management strategies (Smith et al. 2001, Tao et al. 2014). Still other results suggest a disconnect between what farmers understand and know, and what others think they understand and know. Ingram found that many farm advisors think that farmers lack technical knowledge of soil management and that this lack of knowledge explained, at least in part, why farmers fail to use more sustainable nutrient management practices (Ingram 2008). Instead, Dou et al. find that one of the barriers for farmers to use better MMS specific to nutrient management is not because they do not know about manure nutrient testing, but rather, that they do not trust the test results (Dou et al. 2001). In the case of anaerobic digesters, one study concluded that the lack of adoption was not about knowledge of the MMS itself, but rather a lack of knowledge about the potential suite of co-benefits that the practice could offer (Strazzera and Statz 2016).

3.4.2. Attitudes
Individual farmer attitudes toward technology, risk profiles or perceptions of challenges in agriculture are shown to have notable impacts on farmer adoption of MMS. As Wirth et al. describe it, these ‘cultural’ factors can often mediate the policy, institutional, and farm system in which farmers exist and can explain the difference in MMS adoption (Wirth et al. 2013). In the studies we identified, there was a consistent finding that receptiveness and a positive attitude towards the potential technology/MMS in question is important for potential adoption (Bishop et al. 2010, Swindal et al. 2010, Gebrezgabher et al. 2015). But attitudes towards factors beyond the practices themselves also have important impacts. Farmers that expressed high concern for environmental impacts were more likely to want to adopt anaerobic digesters (Strazzera and Statz 2016) and nutrient management practices (Buckley et al. 2015). Additionally, farmers with production-oriented and stewardship mindsets were also more likely to adopt more nutrient management practices (Buckley et al. 2015). Conversely, Swindal et al. found that farmers were typically motivated by more tangible and financial concerns, including the need to control odors and capitalize on manure, than to do the ‘good environmental or public good thing’ (Swindal et al. 2010). A study of Florida dairy farmers found that many felt that other sources of pollution (e.g. human waste) were a greater contributor to nutrient management issues within the region, which could lead to a lack of adoption of practices to mitigate the problem (Cabrera et al. 2006). Counter to other studies, risk averse dairy farmers in Louisiana were more likely to adopt BMPs, which the authors concluded could be a form of risk management (Rahelizatovo and Gillespie 2004a). The role of attitudes for driving adoption of MMS (at least exclusively) should be considered somewhat cautiously though. Gedikoglu et al. found that farmer’s attitudes about potential impacts of manure injection on water quality had no effect on adoption. This led the authors to recommend that a focus on farmer
profitability might be a better strategy (Gedikoglu et al. 2011).

3.4.3. Demographics
Farmer and farm-family demographics were correlated with varying levels of adoption of MMS. Research exploring how the age of farmers influences their MMS decision making had mixed results. Older dairy farmers were found to be less likely to adopt nutrient management practices (Buckley et al. 2015), to want to use processed (i.e. acidified or anaerobic digestion) manure (Case et al. 2017), and to want to use manure separation techniques (Gebrezgabher et al. 2015). Relatedly, Paudel et al found that impending retirement was the most frequent reason for farmers not to adopt BMPs (Paudel et al. 2008). Conversely, however, Gedikoglu found that older farmers in Iowa and Missouri were more likely to want to adopt manure injection (Gedikoglu et al. 2011). Education levels among farmers were also found to have varying impacts on MMS perceptions and adoption. While studies found that farmers with higher levels of formal education were more likely to adopt manure injection, keep manure records (Gedikoglu et al. 2011) and adopt BMPs for manure management (Paudel et al. 2008), Gebrezgabher et al instead found that farmers with less formal education were more likely to have positive attitudes about manure separation technologies (Gebrezgabher et al. 2015). Finally, the influence of off-farm income, or the income that a farm household draws from non-farming activities, on farmer decision making about MMS also has mixed results. In the context of manure injection technologies, total off-farm income was not correlated with greater likelihood to adopt. Off-farm seasonal employment, however, which more specifically refers to off-farm work pursued by the individual farm operator during seasonal downswings in farming activities, was correlated with greater likelihood to adopt manure injection technologies. This may indicate that income earned by other members of a farm household does not influence manure management decisions, whereas off-farm income earned by farmers themselves does influence these decisions. In the context of labor intensive MMS strategies, such as record keeping, off-farm income had a negative impact on adoption, likely because of the time management associated with such practices (Gedikoglu et al. 2011). Buckley et al found similar results in Ireland, where off-farm income was negatively correlated with adoption of nutrient management practices (Buckley et al. 2015).

3.4.4. Summary
There was substantial heterogeneity across the literature regarding the impact of farmer knowledge, information and attitudes on adoption of MMS. Overall, there was more consistent indication that a farmer’s positive attitude towards a specific MMS was important for adoption. Other attitudinal factors, such as towards the environment, were found to play a role in farmers’ decision making. Farmers more concerned with environmental issues and stewardship were more likely to adopt nutrient management and manure treatment strategies. However, the literature also indicated that attitudes and knowledge interact with a complex suite of other factors that may mediate manure management decisions. Similarly, the impact of farmer demographic variables seems to interact with other variables in a complex way, making it difficult to discern the impact of demographic variables on MMS within this small body of literature.

4. Identified knowledge gaps/future research
Through this systematic literature review, we identified three key knowledge gaps and research priorities, both from our own assessment of the literature as well as the recommended gaps and future research of the studies examined. These gaps include: (1) a lack of studies overall focused on dairy farmer decision making and behavior as it relates to MMS; (2) a need for comparative studies across places and time to capture comparative data and potential behavioral changes; and (3) additional technical and data needs that could assist in driving farmer adoption of best MMS. We detail each of these further below.

4.1. Lack of social science studies and data
Our review found a total of 36 articles that met our criteria for being published after 1980 and in high-income countries. Of these 36 articles, only 12 were published within the past five years, despite a large body of recent literature published in the agricultural sciences and focused on better understanding MMS from a technical standpoint. For example, multiple review papers exist exploring the technical, environmental, and agronomic details of MMS, especially from the perspective of GHG emissions (e.g. Montes et al. 2013, Owen and Silver 2015). These papers collectively cite hundreds of papers published on the topic (for example, Montes et al cites 220 articles and Owen and Silver utilize 38 specific field-based studies for comparison). This suggests that despite the growing focus of research on MMS, especially from an environmental perspective, there has been far less research conducted on the social factors underlying dairy farmer behaviors and decisions as they relate to MMS. It should be noted that there are potentially reports or other gray literature in many regions and countries that have explored these topics further; however, given the multiple ways in which such reports are or are not made public and in what way, such reports were outside the scope of this review. This is a critical oversight in both our scientific understanding of MMS as well as the capacity for enabling support systems for farmers to implement BMPs.
Our results also suggest that the geographic distribution of research is sparse, even across multiple high-income countries. In the United States, where slightly less than half of the studies were published (18 total), only 12 states (California, Connecticut, Florida, Idaho, Iowa, Louisiana, Missouri, New York, Oregon, Pennsylvania, Washington, Wisconsin) were represented in the available data, despite dairy having a presence in all 50 states. Furthermore, some states were clearly a significant focus of study across multiple authors and time periods, such as Wisconsin where five of the 18 studies were published, and Louisiana where three out of the 18 studies were published. While this focus makes sense in Wisconsin since it is the second largest producer of milk in the United States, other foci were less clear such as Louisiana, which ranked 40th in milk production in 2015 (Progressive Dairyman 2016). Furthermore, some states that were in the top ten producers of milk in 2016 in the United States were not represented at all, including Michigan (5th largest producer), Minnesota (8th largest producer), New Mexico (9th largest producer), and Texas (7th largest producer) (Progressive Dairyman 2016). This suggests that we know very little about on-farm manure management decisions farmers make in some of the key milk producing states in the US. Instead, research foci on certain regions appears to be driven by individual programs or authors, rather than a broader systematic effort to understand dairy farmer decision making for MMS across many regions.

We find similar trends in Europe, with only eight countries represented in the existing literature. Half of these studies were in the Netherlands, three in England and Denmark, two in Italy and one each in Austria, Ireland, Spain, and Scotland. These results also suggest a lack of connection to dairy production as Germany and France were the number one and two European producers of milk in 2016, neither of which were represented in our review. While the Netherlands, England, Denmark, Italy, and Ireland were all among the top ten producers of milk in Europe in 2016 and represented in this analysis, we did not find any studies from Poland (5), Ukraine (7), or Belarus (9), which also ranked in the top ten producers of milk in Europe in 2016 (FAO 2017). Similar to the US, this suggests that we know very little about dairy farmer manure management decisions in several key dairy-producing countries in Europe. It should also be noted that we found no articles exploring the decision making or adoption processes of MMS in other high-income countries including Japan, Australia, and New Zealand, although in some of these regions pasture-based dairy production is far more common and may minimize the need to study MMS decision making.

Finally, across all studies we also find that multiple years of data across a single region do not exist. All studies were single attempts at gathering data at one point in time, without surveying or interviewing farmers over multiple years or conducting follow up studies. For social science research, this point is especially important for multiple reasons. First, a lack of time series data means that observations are purely correlational and cannot make any causal inferences about the factors that are associated with observed behaviors. Second, and related, is an inability to understand how adoption has changed over time, and what these changes might be attributed to. Asking farmers about their likely MMS behaviors or the kinds of technologies they may adopt does not provide insight into whether these behaviors actually happen. Recent evidence suggests that what farmers intend to do versus what they actually do do not closely track to each other, and different factors affect actual behavior change as compared to potential behavior change (Niles et al 2016). There is a clear need to conduct social science research with dairy farmers across multiple years to enable more detailed analysis of causal factors leading to MMS adoption. One potential way to accomplish this would be to add additional questions to national-level agricultural census surveys, which could capture a broader suite of factors that may be influencing farmer decision making.

### 4.2. Need for comparative studies

The need for comparative studies is another clear gap in the literature. Only three out of the 36 studies we found conducted research across multiple regions, with one additional study conducting a historical analysis across two regions. Comparative studies would add significant insight into understanding whether certain factors were related to MMS adoption across regions with different environments, farm structures and policies. Indeed studies identified this heterogeneity as a critical research gap that should be addressed in the future (Wirth et al 2013). Glenk et al note that further investigation of existing farm-specific barriers would be useful to investigate from a policy perspective (Glenk et al 2014). Regional variations could have major impacts on a variety of MMS, including how bovine diet variation across regions could influence manure nutrient content and applicable BMPs (Sheppard et al 2011). Some studies even suggested that there was heterogeneity within a given state, indicating that multiple scales of data may be necessary to collect for comparative purposes (Powell et al 2007). Others identified that future research could also focus on stakeholders in regions with contrasting agricultural and socio-political contexts to explore other drivers of or influences on MMS (Hou et al 2016). Future research could prioritize comparative studies at regional and national levels where the same questions are deployed to facilitate comparative analysis.
analysis and enable understanding about potential drivers of farmer MMS across many regions.

4.3. Additional technical needs
Multiple studies also suggested that there was need for additional technical feasibility research to better assess potential MMS adoption. This includes data and information about the characteristics of farms that apply manure at varying rates (Powell et al 2007), as well as equipment and infrastructure development that could enable farmers to haul manure longer distances, which could prevent over application in fields closest to storage facilities. The development of farmer-friendly software that could assist farmers in field by field data collection and record keeping could also assist in adoption of better MMS (Tao et al 2014), although emerging precision agriculture technologies are already making significant strides in this area and dairy farmer adoption of these technologies is growing (Carolyn 2014, Borchers and Bewley 2018).

Importantly, these technical needs may increasingly be related to understanding the existing policies and regulations that could be driving farm-specific behaviors, which could vary significantly by region. Indeed, our review highlights a theme of identifying the impact of heterogeneity; the literature consistently suggests that farm-specific factors—including variable geographic, environmental and cultural contexts and policy landscapes—might drive on-farm behaviors related to MMS—supporting this finding, a recent review of policies and regulations for winter manure spreading highlights significant difference across regions. Even in the United States, a complex suite of voluntary, mandatory and recommended best practices exist, which could influence the adoption of MMS on farms in various ways (Liu et al 2018). A greater understanding of the technical needs required by dairy farmers to comply with existing local, regional and national policies may also be necessary to fully explore the potential drivers of on-farm decision making beyond individual characteristics.

4.4. Summary
Despite the proliferation of research on agronomic and environmental aspects of MMS in recent years, there remains a dearth of social science research to specifically examine the drivers of dairy farmer behavior. Within the literature that does exist on this subject matter, there is a notable lack of geographic scope, and many of the key high-income, milk-producing countries or regions are not represented in the literature identified for this review. Similarly, there is a lack of time series data. None of the literature we identified analyzed farmer decision making across time.

We also note a lack of comparative studies examining farmer decision making across multiple locations. Such research will be necessary to identify whether certain factors are correlated with similar MMS outcomes in diverse contexts. This, in turn, will be crucial in determining and implementing appropriate best manure management practices at multiple geographic scales. Finally, we note a need for research exploring the technical needs of farmers to comply with existing and proposed policies and regulations related to manure management.

5. Overall conclusions
Understanding the factors involved in farmer decisions about MMS requires knowledge from multiple types of sciences—animal, agronomic, economic and social. This comprehensive literature review finds that despite a large body of research focused on the biophysical and environmental aspects of manure management, there are only a limited number of studies exploring the social and behavioral aspects influencing farmer decision making as it relates to MMS. Given the importance of MMS for overall financial and environmental outcomes at the farm, this lack of research is both surprising and concerning.

This work highlights that multiple factors ranging from farm infrastructure to farmer attitudes and the policy and institutional environments in which farms operate can all influence decision making related to MMS. We highlight several potential future research gaps that can help inform efforts to assist farmers to meet their management goals. In particular, it is critical to expand our knowledge of dairy farmer decision making in MMS through more comprehensive and comparative studies across time. We hope that this work can foster a greater number of social sciences studies, particularly over time and across multiple regions, to better understand the heterogeneity of farm systems. The insights gained from this systematic review also help outreach practitioners of various public and private agencies to evaluate extension programs for their dairy farmer relevance, enable them to develop trusting relationships and synergies with dairy farmers that opens up two-way engagement for knowledge transfer, and help dairy farmers to overcome several of their concerns and risk perceptions about making assertive decisions to maximize the socio-economic benefits of on-farm manure management.

Acknowledgments
This work was funded by the Innovation Center for US Dairy, Rosemont, IL. We thank Serge Wiltshire for his work on figure 1.
References

Aguirre-Villegas H A and Larson R A 2017 Evaluating greenhouse gas emissions from dairy manure management practices using survey data and lifecycle tools J. Clean. Prod. 143 169–79

Anderson R C and Weersink A 2014 A real options approach for the investment decisions of a farm-based anaerobic digester Can. J. Agric. Econ. Can. J. agroeconomie 62 69–87

Asai M, Langer V and Frederiksen P 2014a Responding to environmental regulations through collaborative arrangements: Social aspects of manure partnerships in Denmark Livest. Sci. 167 378–80

Asai M, Langer V, Frederiksen P and Jacobsen B H 2014b Livestock farmer perceptions of successful collaborative arrangements for manure exchange: a study in Denmark Agric. Syst. 128 55–65

Barrington S F and Piche M 1992 Research priorities for the storage of solid dairy manures in Quebec Can. Agric. Eng. 34 393–9

Baumgart-Getz A, Prokopy L S and Floress K 2012 Why farmers adopt best management practice in the United States: a meta-analysis of the adoption literature J. Environ. Manage. 96 17–25

Bishop C P, Shamway C R and Wandschneider P R 2010 Agent heterogeneity in adoption of anaerobic digestion technology: integrating economic, diffusion, and behavioral innovation theories Land Econ. 86 585–608

Borchers M R and Bewley J M 2009 Farm structural change of a different kind: alternative dairy farms in Wisconsin—Graziers, organic and Amish Renew. Agric. Food Syst. 24 25–37

Buckley C, Howley P and Jordan P 2015 The role of differing farming motivations on the adoption of nutrient management practices Int. J. Agric. Manage. 4 152–62

Cabreria V E, Breuer N E and Hildebrand P E 2006 North Florida dairy farmer perceptions toward the use of seasonal climate forecast technology Clim. Change 78 479–91

Carlisle L 2016 Factors influencing farmer adoption of soil health practices in the United States: a narrative review Agroecol. Sustain. Food Syst. 40 583–613

Carroll C, DeWalt J and Joles J 2015 The role of fertilizer recommendations on adoption of nutrient management practices J. Dairy Sci. 98 4118–205

Case S D C, Oelofse M, Hou Y, Oenema O and Jensen L S 2017 Nutrient management on farms and impact on water quality: A systematic review Environ. Res. Lett. 12 04016

Dou Z, Galligan D T, Ramberg C F, Meadows C and Ferguson J D 2001 A survey of dairy farming in Pennsylvania: nutrient management practices and implications J. Dairy Sci. 84 966–73

FAO 2017 Whole Fresh Cow Milk, Livestock Primary FAO Stat Online (http://faostat3.fao.org/lstat/en/ @data/QL)

Filson G C, Pfeiffer W C, Painie C and Taylor J R 2003 The relationship between grand river dairy farmers’ quality of life and economic, social and environmental aspects of their farming systems J. Sustain. Agric. 151 84–95

Dou Z, Galligan D T, Ramberg C F, Meadows C And Ferguson J D 2001 A survey of dairy farming in Pennsylvania: nutrient management practices and implications J. Dairy Sci. 84 966–73

Glenk K, Eory V, Colombo S and Barnes A 2014 Adoption of greenhouse gas mitigation in agriculture: An analysis of dairy farmers’ perceptions and adoption behaviour Ecol. Econ. 108 49–58

Global Research Alliance 2014 Reducing greenhouse gas emissions from livestock: Best practice and emerging options. (http://globalesearchalliance.org/wp-content/uploads/2014/12/LRG-SAI-Livestock-Mitigation_web2.pdf)

Greenhalgh T, Robert G, Macfarlane F, Bate P, Kyriakidou O and Peacock R 2005 Storylines of research in diffusion of innovation: a meta-narrative approach to systematic review Soc. Sci. Med. 61 417–30

Holly M A et al 2018 Short communications: identifying challenges and opportunities for improved nutrient management through the USDA’s dairy agroecosystem working group J. Dairy Sci. 101 6632–41

Hou Y et al 2016 Stakeholder perceptions of manure treatment technologies in Denmark, Italy, the Netherlands and Spain J. Clean. Prod. 172 1620–30

Hsieh H-F and Shannon S E 2005 Three approaches to qualitative content analysis Qual. Health Res. 15 1277–88

Ingram J 2008 Are farmers in England equipped to meet the knowledge challenge of sustainable soil management? An analysis of farmer and advisor views J. Environ. Manage. 86 214–28

Liu J et al 2018 A review of regulations and guidelines related to winter manure application Ambio 47 657

Meyer D, Price P L, Rossow H A, Silva-Del-Rio N, Karle B M, Robinson P H, Depeters E J and Fadel J G 2011 Survey of dairy housing and manure management practices in California J. Dairy Sci. 94 4744–50

Montes F et al 2013 Special topics—mitigation of methane and nitrous oxide emissions from animal operations II: A review of nutrient management mitigation options J. Anim. Sci. 91 5070–94

Motew M et al 2018 The synergistic effect of manure supply and extreme precipitation on surface water quality Environ. Res. Lett. 13 44016

Niles T M T, Brown M and Dynes R 2016 Farmer’s intended and actual adoption of climate change mitigation and adaptation strategies Clim. Change 135 277–95

OECD and FAO 2017 OOECD-FAO Agricultural Outlook 2017–2026 (Paris) OECD and FAO (https://doi.org/10.1787/agr_outlook-2017-en)

Oenema J, Van Keulen H, Schils R L M and Aarts H F M 2011 Participatory farm management adaptations to reduce environmental impact on commercial pilot dairy farms in the Netherlands NIAS—Wageningen J. Life Sci. 58 39–48

Ondersteijn C J M, Giesen G W J and Huirne R B M 2006 Perceived environmental uncertainty in Dutch dairy farming: the effect of external farm context on strategic choice Agric. Syst. 88 205–26

Owen J and Silver W L 2015 Greenhouse gas emissions from dairy manure management: a review of field-based studies Glob. Chang. Biol. 21 580–605

Paudel K P, Gauthier W M, Westra J V and Hall L M 2008 Factors influencing and steps leading to the adoption of best management practices by luisiana dairy farmers J. Agric. Appl. Econ. 40 203–22

Pettersson M and Roberts H 2006 Systematic Reviews in the Social Sciences: a Practical Guide (Malden, MA: Blackwell Publishing)

Poe G L, Bills N L, Bellows B C, Crosscombe P, Koelsch R K, Kreher M J and Wright P F 2001 Will voluntary and educational programs meet environmental objectives? Evidence from a survey of New York dairy farms Appl. Econ. Perspect. Pol. 23 473–91

Powell JM, Jackson-Smith DB, McCrory DF, Saam H and Mariola M 2007 Nutrient management behavior on Wisconsin dairy farms Agron. J. 99 211–9

Powell JM, McCrory DF, Jackson-Smith DB and Saam H 2005 Manure collection and distribution on Wisconsin dairy farms J. Environ. Qual. 34 2036–44
Progressive Dairyman 2016 2016 US Dairy Statistics (https://progressivepublish.com/downloads/2017/general/2016-pd-stats-lowres.pdf)
Prokopy L S S, Floress K, Klotthor-Weinkauf D and Baumgart-Getz A 2008 Determinants of agricultural best management practice adoption: evidence from the literature J. Soil Water Conserv. 63 300–11
Rahelizatovo N C and Gillespie J M 2004a Factors influencing the implementation of best management practices in the dairy industry J. Soil Water Conserv. 59 166–75
Rahelizatovo N C and Gillespie J M 2004b The adoption of best-management practices by Louisiana dairy producers J. Agric. Appl. Econ. 36 229–40
Robin W and Kathleen K 2005 The integrative review: updated methodology J. Adv. Nurs. 52 546–53
Sharpley A N, Daniel T, Gibson G, Bundy L, Cabrera M, Sims T, Stevens R, Lemenyon J, Kleiman P and Parry R 2006 Best management practices to minimize agricultural phosphorus impacts on water quality US Department of Agriculture, Agricultural Research ServiceARS–163 50 (www.ars.usda.gov/is/np/BestMgmtPractices/Best%20Management%20Practices.pdf)
Sheppard S, Bittman S, Swift M, Beaulieu M and Sheppard M 2011 Ecoregion and farm size differences in dairy feed and manure nitrogen management: a survey Can. J. Anim. Sci. 91 459–73
Smith K A, Brewer A J, Crabb J and Dauven A 2001 A survey of the production and use of animal manures in England and Wales. III. Cattle manures Soil Use Manage. 17 77–87
Southgate D, Sharp B M H, Lovejoy S B and Bouwes N W 1980 A case study of incentives for adoption of less-polluting manure handling techniques North Cent. J. Agric. Econ. 2 123–30
Sovacool B K, Noel L, Assen J and Kempton W 2018 The neglected social dimensions to a vehicle-to-grid (V2G) transition: a critical and systematic review Environ. Res. Lett. 13 13001
Strazzera E and Statznu V 2016 A choice experiment study on the farmers’ attitudes toward biogas and waste reuse in a nitrates vulnerable zone 2016 5th AIEAA Congress (Bologna, Italy: Italian Association of Agricultural and Applied Economics) (AIEAA)
Swindal M G, Gillespie G W and Welsh R J 2010 Community digester operations and dairy farmer perspectives Agric. Human Values 27 461–74
Tao H, Morris T F, Bravo-Ureta B E and Meinert R 2014 Factors affecting manure applications as directed by nutrient management plans at four connecticut dairy farms Agron. J. 106 1420–6
Thurow A P and Holt J 1997 Induced policy innovation: environmental compliance requirements for dairies in Texas and Florida J. Agric. Appl. Econ. 29 17–36
Tranfield D, Denyer D and Palmininer S 2003 Towards a methodology for developing evidence-informed management knowledge by means of systematic review Br. J. Manage. 14 207–22
Tranter R B, Swinbank A, Jones P J, Banks C J and Salter A M 2011 Assessing the potential for the uptake of on-farm anaerobic digestion for energy production in England Energy Policy 39 2424–30
United Nations Food and Agriculture Organization 2014 Livestock Primary: Production of Milk FAOSTAT (http://faostat.fao.org/)
Welsh R, Grimberg S, Gillespie G W and Swindal M 2010 Technoscience, anaerobic digester technology and the dairy industry: factors influencing north country new york dairy farmer views on alternative energy technology Renew. Agric. Food Syst. 25 170–80
Wirth S, Markard J, Truffer B and Rohracher H 2013 Informal institutions matter; professional culture and the development of biogas technology Environ. Innov. Soc. Transit. 8 20–41
World Bank 2019 (https://data.worldbank.org/income-level/high-income)