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

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TOPICAL REVIEW • OPEN ACCESS

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## TOPICAL REVIEW

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

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**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 causal 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

**Table 1.** Overview of studies by country and state and their world dairy production ranking and production.

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		
	Florida	2*		
	New York	2		
	Pacific Northwest	1		
	Pennsylvania	1		
	Iowa and Missouri	1		
	California	1		
	Connecticut	1		
	Texas and Florida	1		
United Kingdom	England	3	10 (United Kingdom)	15 256 000
	Scotland	1		
	England and Wales	1		
Canada	Ontario	2	19	8100 000
	Montreal	1		
	National	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

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

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

**Table 2.** Total number of articles included in the literature review detailed by focus, region, method and number of farmers.

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 <i>et al</i> 2014a	Partnerships for manure exchange- social aspects	Denmark	Survey	644	Dairy and pig
Asai <i>et al</i> 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 <i>et al</i> 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 <i>et al</i> 2015	Nutrient management practices	Ireland	Survey	271	Dairy, beef and sheep
Cabrera <i>et al</i> 2006	Climate forecasting to mitigate nutrient pollution	Florida	Interviews and focus groups	64	Dairy
Case <i>et al</i> 2017	Organic fertilizer usage	Denmark	Survey	452	Dairy, beef, poultry, pigs and arable
Dou <i>et al</i> 2001	Nutrient management practices	Pennsylvania	Survey	994	Dairy
Filson <i>et al</i> 2003	Manure management impact on quality of life	Ontario	Survey	194	Dairy
Gebrezgabher <i>et al</i> 2015	Manure separation technology	Netherlands	Survey	111	Dairy
Gedikoglu <i>et al</i> 2011	Nutrient management adoption	Iowa, Missouri	Survey	1127	Dairy, beef, pig, poultry and arable
Glenk <i>et al</i> 2014	GHG mitigation	Scotland	Survey	235	Dairy
Hou <i>et al</i> 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 <i>et al</i> 2011	Dairy housing, manure management	California	Survey	107	Dairy
Oenema <i>et al</i> 2011	Nutrient use efficiency	Netherlands	Pilot farms	16	Dairy
Ondersteijn <i>et al</i> 2006	Perceived environmental uncertainty	Netherlands	Survey	103	Dairy, mixed livestock and arable
Paudel <i>et al</i> 2008	Best management practices	Louisiana	Survey	49	Dairy
Poe <i>et al</i> 2001	Voluntary water quality practices	New York	Survey	470	Dairy
Powell <i>et al</i> 2005	Manure collection and distribution	Wisconsin	Survey	54	Dairy
Powell <i>et al</i> 2007	Nutrient management behavior	Wisconsin	Interviews and mapping	33	Dairy
Rahelizatovo and Gillespie 2004a	Best management practices	Louisiana	Survey	124	Dairy
Rahelizatovo and Gillespie 2004b	Best management practices	Louisiana	Survey	124	Dairy
Sheppard <i>et al</i> 2011	Nitrogen and manure management	Canada	Survey	523	Dairy
Smith <i>et al</i> 2001	Cattle manure management practices	England	Survey	986	Dairy and beef
Southgate <i>et al</i> 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 <i>et al</i> 2010	Adoption of anaerobic digestion	New York	Survey	418	Dairy
Tao <i>et al</i> 2014	Manure application	Connecticut	Pilot farms	4	Dairy
Thurrow and Holt 1997	Dairy regulations	Texas and Florida	Historical analysis	N/A	Dairy
Tranter <i>et al</i> 2011	Adoption of anaerobic digestion	England	Survey	384	Dairy, beef and pig
Welsh <i>et al</i> 2010	Adoption of anaerobic digestion	New York	Survey	418	Dairy
Wirth <i>et al</i> 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

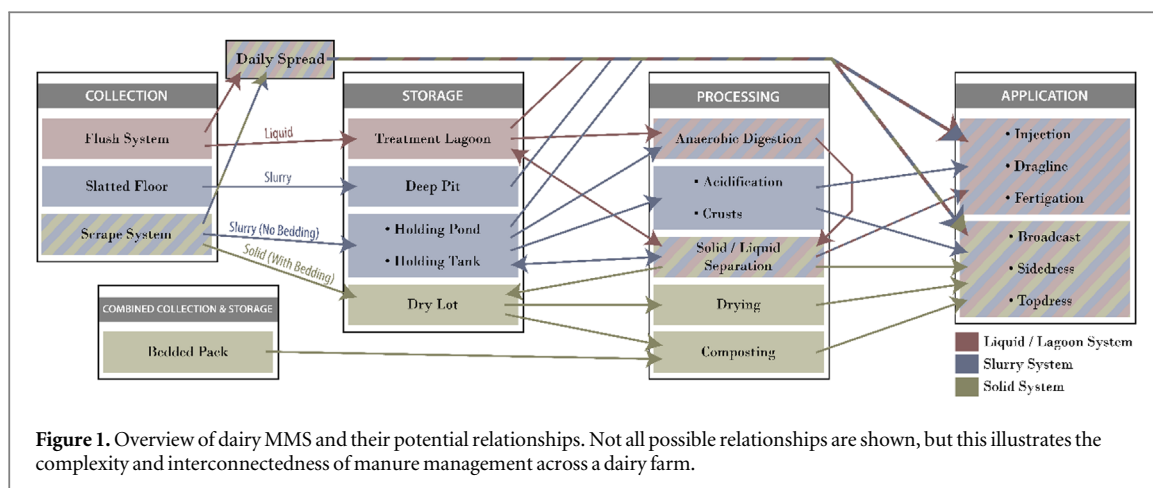
(Filson *et al* 2003, Sheppard *et al* 2011, Aguirre-Villegas and Larson 2017). The literature indicates that scrape and flush systems are the most common means of collecting slurry and liquid manures (Dou *et al* 2001, Meyer *et al* 2011, Aguirre-Villegas and Larson 2017). Bedded pack and gutter cleaners 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, Strazzer *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 (Strazzer *et al* 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 digester; 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 dairy 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 Statzu 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 Statzu 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 (Strazzer and Statzu 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 (Strazzer and Statzu 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<sup>4</sup>, neither of which were represented in our review. While the Netherlands, England, Denmark, Italy, and Ireland were all among the top ten producers of cow's 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.

<sup>4</sup> Note that this data excludes the Russian Federation from consideration as part of Europe in this analysis.

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 correlative 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 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.

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