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REVIEW

A review of regulations and guidelines related to winter manure application

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Abstract Winter manure application elevates nutrient losses and impairment of water quality as compared to manure applications in other seasons. In conjunction with reviewing global distribution of animal densities, we reviewed worldwide mandatory regulations and voluntary guidelines on efforts to reduce off-site nutrient losses associated with winter manure applications. Most of the developed countries implement regulations or guidelines to restrict winter manure application, which range from a regulative ban to guidelines based upon weather and field management conditions. In contrast, developing countries lack such official directives, despite an increasing animal production industry and concern over water quality. An analysis of five case studies reveals that directives are derived from a common rationale to reduce off-site manure nutrient losses, but they are also affected by local socio-economic and biophysical considerations. Successful programs combine site-specific management strategies along with expansion of manure storage to offer farmers greater flexibility in winter manure management.

Keywords Animal production · Eutrophication · Manure management regulations · Nutrient management · Winter manure application

INTRODUCTION

In recent decades, increased demand for meat, dairy, and eggs has promoted a proliferation of animal agriculture in many areas of the world (Kearney 2010). This has challenged manure management to simultaneously satisfy environmental and food production objectives. Indeed, animal manure management has become a central component of worldwide efforts to mitigate agricultural impacts on the environment, especially water and air quality (Erisman et al. 2008; Kleinman et al. 2015; Li et al. 2015; Sharpley et al. 2015; McDowell et al. 2016). Among the issues related to animal manure management, land application of manure in winter is a priority topic that is also often polarizing, as the practical aspects of manure management confront environmental aspirations.

There is no doubt that land application of manure to frozen or cold and wet ground has potential to exacerbate nutrient loss in runoff. The absence, or poor growth of crops (limiting uptake of manure nutrients and water), winter weather, and winter soil conditions generally exacerbate off-site losses of manure-derived pollutants (Milne 1976; Fleming and Fraser 2000; Srinivasan et al. 2006; Lewis and Makarewicz 2009). However, winter application of manure is a practical reality, such as when manure storage is unavailable or manure storage facilities must be emptied. As a result, educated opinions vary widely over how to best manage manure in the winter. Opinions range from those advocating a complete prohibition of winter application to protect environmental quality, to those advocating limited application restrictions due to cost of manure storage infrastructure or other practical constraints (e.g., unavailability of field or labor in spring).

Concerns over land application of manure in winter date back to the late 1930s, when Midgley and Dunklee (1945) observed large amounts of nitrogen (N) runoff losses following dairy manure applied to frozen ground. Others also report elevated risks of both N and phosphorus (P) loss under winter conditions (Klausner et al. 1976; Young and

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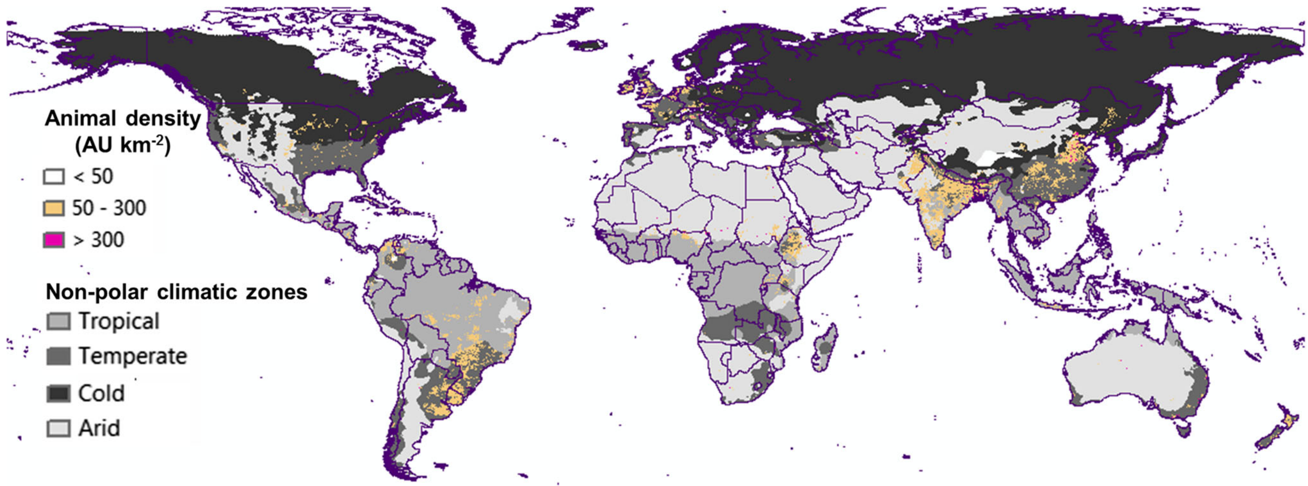

Fig. 1 Global density distribution of animal units (AU km^{-2}) overlain on a grayscale climatic zones map adapted from Peel et al. (2007). The global density distribution combines livestock and poultry counts from Robinson et al. (2014) after normalizing by typical animal weights (Kellogg et al. 2000; Hall 2015): 1 cow/steer/bull ≈ 0.75 AU, 1 pig ≈ 0.12 AU, 1 goat/sheep ≈ 0.1 AU, 1 chicken/duck ≈ 0.003 AU. A high-resolution map in .mxd format can be found in Supplementary Material S1

Mutchler 1976; Phillips et al. 1981; Komiskey et al. 2011), but some studies have observed no impact of winter manure application on nutrient losses (e.g., Young and Holt 1977; Ginting et al. 1998). These conflicting results reflect the complexity of environmental (e.g., weather, soil, and hydrology) and management-related (e.g., application timing, form, method, and rate) factors that interactively determine nutrient losses (Fleming and Fraser 2000; Srinivasan et al. 2006). For example, Steenhuis et al. (1981) found that N loss via runoff following winter manure application could range from trace amounts to up to 50% of the manure N applied, depending on the extent to which snowmelt water infiltrated into the soil profile.

Across the globe, directives related to winter application of manure vary with climatic conditions, physiographic settings, and different production systems. Understanding this variability provides lessons for both agricultural and environmental communities. We review winter manure application directives across the globe using available information and expert knowledge. In addition, we investigate five case studies to explore causes of this variability and provide insight into the complexity of winter manure application issues. To accommodate the global scope of this review, we use the term "winter" in this paper to refer inclusively to the coldest astronomical season within the region of each case study as well as any other time when the region's ground is frozen or snow-covered. The global distribution of livestock and poultry is presented to emphasize the importance of regulating winter application of manure in areas, where frozen or snow-covered ground limits the time manure can be applied to a growing crop or prior to a crop.

GLOBAL LIVESTOCK AND POULTRY PRODUCTION

Today, animal agriculture (i.e., production of cattle, swine, goat, sheep, and poultry) plays a key role in global food and environmental security. Animal agriculture accounts for the world's largest use of land resources, and 80% of all agricultural land is used either for grazing or for producing feeds (http://www.fao.org/animal-production/en/). It is estimated that a total of 1.4×10^9 cattle, 9.8×10^8 swine, 1.9×10^9 sheep and goats, and 2.0×10^{10} poultry are currently raised worldwide (Robinson et al. 2014).

Globally, the density of livestock and poultry (animal units per square kilometer (AU km^{-2}); 1 AU = 450 kg animal body weight) is distributed unevenly, with greater densities (> 50 AU km^{-2}) concentrated in a few, major agricultural producing countries (Fig. 1). These include many developed countries with well-established animal producing systems (e.g., U.S. and European countries), plus major economy-expanding countries (e.g., Brazil, China, and India) that are experiencing dietary shifts towards more animal-source foods (Kearney 2010). Within a country or region, specialization of agricultural production systems has increased the quantities of concentrated animal production areas that are geographically disconnected from major crop production areas (Kellogg et al. 2000; Jarvie et al. 2015). By generating large amounts of manure that are difficult to transport to cropped areas of nutrient demand (Kleinman et al. 2015), concentrated animal production creates high risks of off-site nutrient loss via runoff, leaching, and emissions, especially when manures are repeatedly applied to soils above levels needed

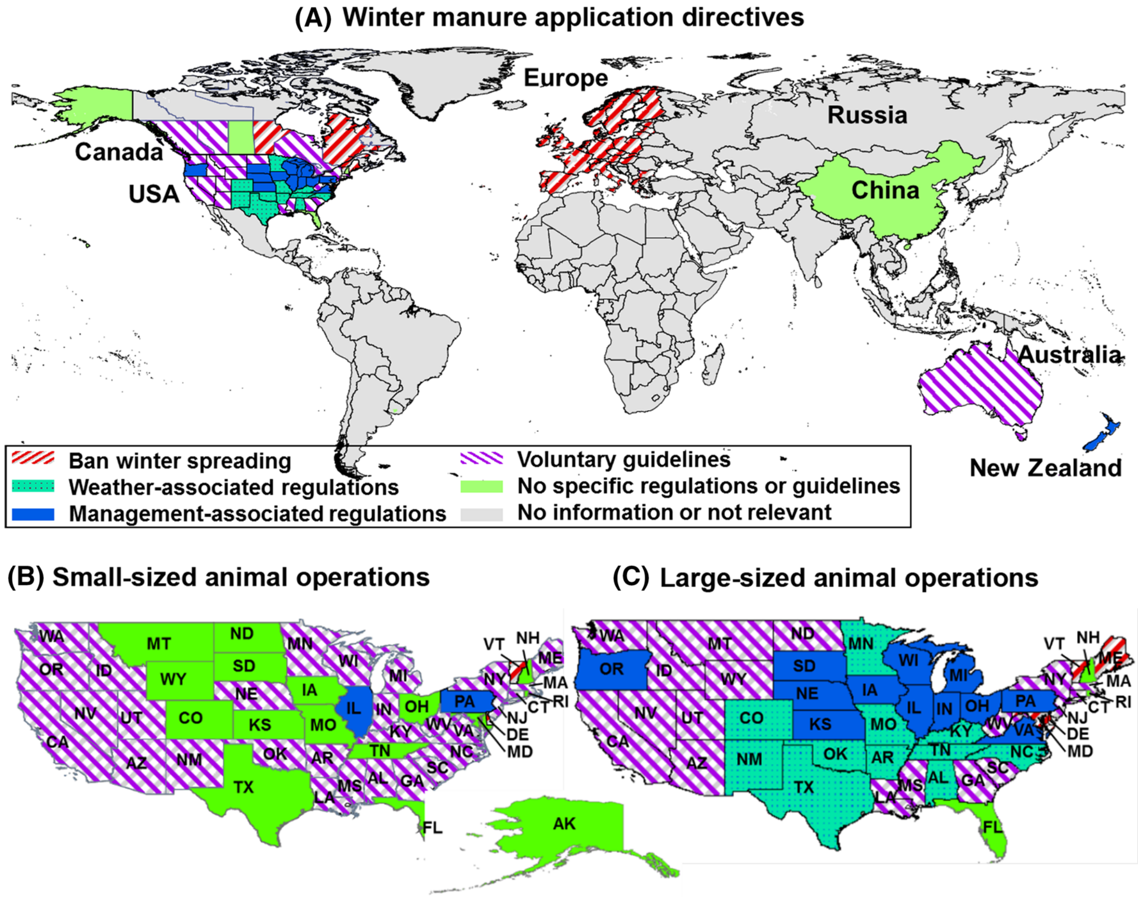

Fig. 2 Directives on winter manure application in the world. **a** A map of directives officially implemented at a national (such as European countries) or sub-national (such as U.S., Canada, and New Zealand) administrative level of a country. **b** U.S. directives for small-sized animal operations. **c** U.S. directives for large-sized animal operations such as those defined as Concentrated Animal Feeding Operations (CAFOs), or Animal Feeding Operations (AFOs). The metadata of the map were sourced from reviews by Webb et al. (2012), U.S. Environmental Protection Agency (2014) and Ullmann (2016) as well as directives found online: West Virginia Department of Environmental Protection (1998), Delaware Department of Agriculture (2003), Pennsylvania Code (2005), Pennsylvania Department of Environmental Protection (2011), Maryland Department of Agriculture (2012), State Council of the People's Republic of China Code 634 (2013), New York Natural Resources Conservation Service (2013), and Virginia Department of Conservation and Recreation (2014). This review included directives prior to 12/2014, and only regulations and guidelines supplemented with specific implementation strategies were counted. The strictest directives were mapped when there was more than one directive within a single administrative unit

for crop production (Beegle 2013). Notably, concentrated animal production (i.e., those > 300 AU km^{-2}) is often found in the temperate and cold climatic zones where winter conditions have important implications for land application of manure (Fig. 1).

GLOBAL VARIATIONS IN DIRECTIVES FOR WINTER APPLICATION OF MANURE

Across the globe, directives governing winter application of manure on agricultural land are diverse but are also clearly associated with the stage of agricultural development in a country. There is an absence of directives for winter application of manure, or an absence of information on such directives, for developing countries. In the developed world, the degree to which winter manure application directives are *voluntary guidelines* or *mandatory regulations* varies widely between countries and even within single countries, as do the nature of the restrictions they impose: from complete prohibition of land application of manure during winter months to conditional restrictions on when, where, how, and what manure is applied to no specific directives at all (Fig. 2a). For instance, most European countries prohibit land application of manure during winter months, with time lengths of prohibition varying by country. Other countries such as U.S., Canada, Australia, and New Zealand have promulgated a diverse array of directives imposing varying restrictions at a sub-national (state or provincial) level.

The presence of winter manure application directives is clearly tied to the implementation of environmental policies within a country. Overall, developed countries with strong agricultural research and extension programs are far in advance of developing countries in making and implementing environmentally driven directives that affect agricultural management. Driven by the concerns over nutrient impacts on water quality, developed countries began creating regulations for winter manure application about three decades ago (European Economic Community 1991). In contrast, the developing countries are still struggling with prioritizing environmental problems and identifying the right knowledge base for developing directives.

Directives for Winter Manure Application in Europe

In Europe, the European Nitrates Directive and Water Framework Directive regulate manure management. These two directives primarily aim to prevent nitrates and phosphorus from agricultural sources polluting ground and surface waters in nitrate vulnerable zones (European Economic Community 1991; European Commission 2000). In general, the Nitrates Directive requires ratifying countries to (1) identify threatened waters and designate nitrate vulnerable zones, (2) establish regulations requiring good agricultural practices and establishing action programs, and (3) monitor progress in water quality. The nitrate vulnerable zones may include the whole country or part of a country, and are, to a large extent, based on political decisions. For management of manure in nitrate vulnerable zones, adherence to "closed periods," which are the time periods during cold seasons when land application of manure is prohibited (Fig. 2a), is of high priority, and is closely linked to regulations requiring sufficient on-farm manure storage capacity. Other regulations limit the maximum allowable manure rate and maximum slope of fields receiving manure, or require specific application methods (e.g., immediate incorporation into soil), setback distances, and vegetative buffers between application sites and watercourses.

"Closed period" lengths vary considerably among European countries (Webb et al. 2012). The length of the closed period tends to increase from the southern European countries to the northern European countries, reflecting gradients of length and harshness of cold seasons. For example, the closed period is only 1 month in Hungary, in comparison to 6 months in Finland. However, the lengths of the closed period are not necessarily fixed by country. For example, lengths of the closed period differ for cultivated land and grassland in Germany, Norway, the Netherlands, and the United Kingdom.

Case study 1: Northern Europe (Prohibiting winter manure applications to reduce nutrient losses and improve nutrient use efficiencies)

The northern European countries of Denmark, Norway, Sweden, and Finland have probably the world's most restrictive regulations on agricultural nutrient management, due to long standing awareness of nutrient pollution concerns and well-established nutrient pollution mitigation programs for inland and coastal water environments. These countries have strong national visions regarding sustainability that permeate through agricultural policies (Kronsell 1997; Valpasvuo-Jaatinen et al. 1997). Indeed, manure management guidelines are frequently espoused on the basis of improved nutrient cycling, such as in targeting manure applications to growing seasons.

Since the 1990s, these countries have implemented strict regulatory caps for animal unit densities on farms with animals: e.g., 1.4 AU ha^{-1} on swine farms and 1.7 AU ha^{-1} on cattle farms in Denmark, 2.5 AU ha^{-1} in Norway, and 1.4 AU ha^{-1} in Sweden (based on P content of manure) (Andersen et al. 2014). Their relatively low animal densities (Fig. 1) greatly enlarge assimilative capacity for farm soils to receive manure as a fertilizer resource. In turn, they provide farmers with more manure management options than are available in regions where animal densities are much higher. Generally, restrictions placed upon farms in these countries are complemented by extensive, free advisory programs and economic incentives to improve manure nutrient use. For example, in 2001 Sweden started a national free advisory campaign called Focus on Nutrients, which offers field trips to the member farms and advice on measures to improve nutrient use efficiencies while reducing losses (http://www.greppa.nu/om-greppa/om-projektet/in-english.html). To date, the campaign has registered more than 9500 members, and P balances on participating farms have been reduced by 40% on dairy farms and 80% on swine farms (Malgeryd and Olofsson 2016).

The prohibition of winter manure application in Denmark, Norway, Sweden, and Finland is seen as a key environmental regulation aimed at improving water quality and overall nutrient use efficiency and is supported by programs that provide farms with adequate manure storage capacity as well as by other regulations and guidelines (Table 1). For these countries, closed periods are directed at the period from fall through early spring, when crop uptake of N and P is absent or negligible, and when most N leaching occurs (Ulén et al. 2010; Deelstra et al. 2011). Differences in the closed periods of Denmark, Norway, Sweden, and Finland follow the climatic gradients, for which the length of the closed periods (i.e., the degree of restrictions) increases from south to north (2.5 months in

Table 1 Manure management strategies to reduce nutrient losses and improve nutrient use efficiencies in Denmark, Norway, Sweden, and Finland

Manure management strategy	Denmark	Norway	Sweden	Finland
Closed period[a]	Nov 15–Feb 1	Nov 1–Feb 15	Nov 1–Feb 28	Oct 16–Apr 15
Manure storage capacity	6–9 months	8 months	6–10 months	12 months
Complementary regulations (all countries)	Maximum allowable manure application rates			
	Manure incorporation			
	Avoid sloping fields			
	Buffers and set-back distances above water courses			
	Avoid frozen soils			
	Implement cover crops			
	Crop-specific requirements			

[a] The closed period applies to nitrate vulnerable zones in Sweden (17% of the national land area), and all countries of Denmark, Norway, and Finland

Denmark, 3.5–4 months in Norway and Sweden, and the weather-adapted 5–6 months in Finland; Table 1). In addition to the ban of manure application during the closed periods, these countries also restrict manure applications in other periods. For example, Denmark restricts application of manure between mid-August and mid-November to actively growing crops and requires larger areas of fall cover crops on animal farms than on arable farms. Norway requires incorporation of manure within 18 h for applications through September and October. In Sweden, land application of manure in nitrate vulnerable zones from August 1 to October 31 is allowed only to growing crops or before sowing of winter rape and winter cereals. Outside nitrate vulnerable zones, land application of manure is allowed all year-round, but not on frozen, snow-covered, or water-saturated soils and manure has to be incorporated within 12 h.

Despite a general acceptance of closed period regulations in Denmark, Norway, Sweden, and Finland, the inflexibility of these regulations has been widely questioned by farmers and researchers. For example, it has been argued that the closed periods should be adapted to suit regional weather conditions. Alternatively, there are justifications for adjusting closed periods to different cropping systems. For northern European conditions, fall or winter application of manure slurry in cereal crop rotations has been observed to result in lower crop nutrient use efficiencies and greater N leaching than spring application (Oskarsen et al. 1996; Beckwith et al. 1998). However, recent studies found no evidence of greater N leaching for fall application of manure on grass/clover forage crops compared to spring application (Neumann et al. 2011; Aronsson et al. 2014). Sufficient storage capacity, together with extensive education of farmers, has resulted in most of the manure in this northern region of Europe being applied in spring and summer. Nevertheless, application of manure in spring is sometimes constrained by the labor availability of farmers, and, under wet conditions, heavy equipment traffic can damage soil structure. Therefore, it is regularly argued that greater flexibility in regulations (such as applying manure on frozen soil right before it melts, applying solid manure on sod in late fall) would help to protect soil quality without exacerbating off-site nutrient losses.

Directives for Winter Manure Application in North America

Canada and U.S. have a diverse set of directives affecting winter application of manure that vary among states/provinces (Fig. 2a). In Canada, regulations on land application of manure are determined by each province. The most restrictive regulations are found in Manitoba and Quebec, where land application of manure during winter months is banned (Fig. 2a). In contrast, other Canadian provinces adopt voluntary manure management guidelines or do not have specific directives on winter manure applications. From a biophysical perspective, the environmental risks associated with winter application of manure in Manitoba are similar to those in the other Prairie Provinces of Saskatchewan and Alberta; however, Manitoba's regulations are much more restrictive. This variation in directives for winter application of manure illustrates the large influence of socio-economic factors in the political process of developing manure management directives.

Case study 2: Manitoba, Canada (Prohibiting winter manure application to prevent manure nutrient losses in large snowmelt runoff on frozen soils)

Manitoba, Canada bans land application of manure between November 10 and April 10, unless a variance is declared due to unusually warm weather, with little risk of snowmelt runoff losses over frozen soils (Manitoba Environment Act 1998). Beginning in 1998, the ban originally applied only to large animal farms, but since 2013, the ban applies to all sizes of animal operations. Furthermore, in some more intensively farmed regions (e.g., the Red River Valley Special Management Area), manure applied during fall must be incorporated or injected into soil to minimize the risk of nutrient loss from fall-applied manure during snowmelt runoff. Manitoba's approach to discouraging winter application of manure also employs incentives. For example, at various times during the last 20 years over which the manure regulations have become increasingly restrictive, financial assistance was provided from several federal and provincial government programs to subsidize the expansion of manure storage facilities on Manitoba's animal farms.

Manitoba's strict regulations on land application of manures during winter months are due in part to the Canadian prairie region's climate, which is semi-arid or sub-humid, with cold winters that result in heavily frozen soils and a lengthy period for collection of snowfall, prior to a spring snowmelt period that lasts for only a few days. During snowmelt, most of the soil remains frozen, severely restricting infiltration. Therefore, snowmelt typically accounts for 80% of annual runoff in this region (Nicholaichuk 1967; Glozier et al. 2006). Spring snowmelt is also the period when the greatest amounts of nutrients are lost to runoff (Fig. 3; Green and Turner 2002; Glozier et al. 2006; Sheppard et al. 2006). Manure placed on top of frozen soils or snow during the winter is particularly vulnerable to loss during spring thaw in this region, because the manure does not interact with soil prior to snowmelt and can be directly transported to surface water. A variety of studies have confirmed greater N and P losses with winter application manure than with manure application during other periods (Green 1996; Maule and Elliott 2006).

One of the distinctive features of Manitoba's ban on winter application of manure is some flexibility in the prohibition period (Manitoba Sustainable Development 2017). The main purpose of the ban is to prevent manure application on frozen or snow-covered land. Therefore, depending on weather conditions, the provincial government occasionally allows application of manure within the period between November 10th and April 10th, if

- soils are unfrozen and dry enough to enable manure application and
- soils are well drained to moderately well drained and are not expected to be saturated during spring thaw and
- the field is not prone to water erosion and
- the application practices that are employed will not negatively affect water quality (e.g., if the manure is applied by sub-surface injection or surface applied followed by incorporation).

The Province uses information such as soil moisture conditions, weather forecasts, etc. to authorize these variances on a regional or provincial basis, after consulting with various agricultural stakeholder groups in Manitoba. Animal producers can also request individual variances, which will be considered according to the same criteria as the regional or provincial variances.

In the U.S., states have differing directives for small-sized animal operations (Fig. 2b) and for large-sized animal operations such as those defined as Animal Feeding Operations (AFOs) and Concentrated Animal Feeding Operations (CAFOs; Fig. 2c). National guidelines are provided by the U.S. Department of Agriculture's Natural Resource Conservation Service (USDA-NRCS), Practice Standard 590 for Nutrient Management (NRCS Standard 590). This standard, which is intended to serve as national

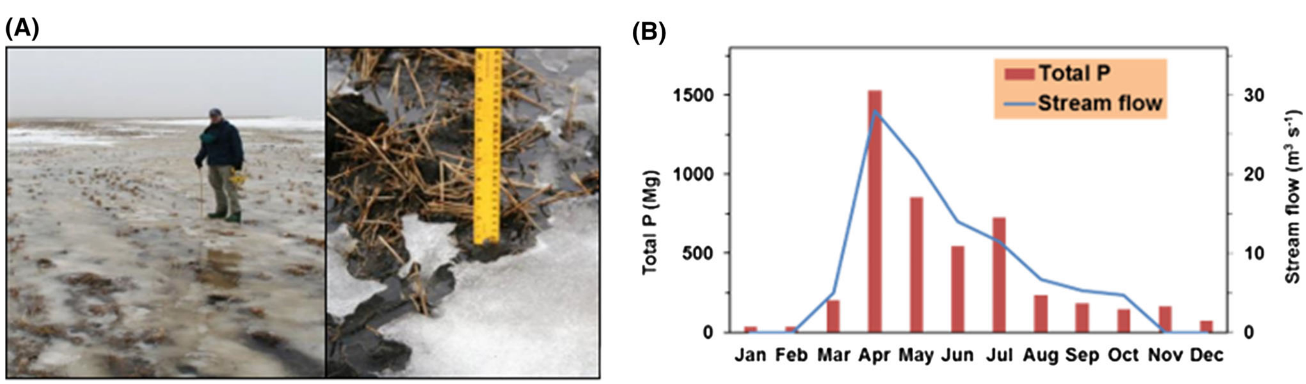

Fig. 3 Land application of manure in the Canadian prairie region is challenged by the large snowmelt runoff on frozen soils in spring. **A** Photos of snowmelt runoff on frozen soils in Manitoba (Photos by David Lobb). **B** Long-term (1994–2005) mean monthly stream flow and total P loading in the Red River at Selkirk, Manitoba (adapted from Lake Winnipeg Stewardship Board 2006)

guidance for state regulations and is implemented on farms receiving federal support for conservation and nutrient management, recommends no nutrient application under winter environmental conditions (i.e., snow-covered, water-saturated, or frozen land), and implementation of conservation practices when manure is applied to frozen soils with slopes greater than 9% (U.S. Department of Agriculture's Natural Resource Conservation Service 2003). Because the U.S. is characterized by strong protection of the rights of individual states to self-govern, state nutrient management directives generally supplant the NRCS Standard 590, but are expected to be no less restrictive than environmental protections offered by the national NRCS 590 Standard.

For U.S. states, the responsible environmental protection and/or agricultural agencies modifies and enforces the federal nutrient management standard to suit to its own conditions. As a result, the statewide directives fall into five categories (Fig. 2): (1) regulations that ban land application of manure during winter months (the closed period approach); (2) regulations that restrict land application of manure based upon weather-related conditions (e.g., banning application to snow-covered, water-saturated, or frozen soil); (3) regulations that restrict land application of manure based upon management conditions (e.g., by manure source, application method, ground cover, vulnerability of soils to nutrient loss); (4) provide recommended guidelines but not regulations; and (5) no specific regulations or guidelines.

In the U.S., a total of 26 states have stricter directives for large-sized animal operations than for small operations (Fig. 2b vs. 2c). For example, Maine and Maryland have adopted regulations that ban winter application of manure for large-sized animal operations, but they do not regulate winter manure application for smaller-sized animal operations. Several states such as Wisconsin, Kentucky, Michigan, and Alabama regulate weather-associated or management-associated restrictions for large-sized animal operations, but only have guidelines for small-sized animal operations.

Case study 3: Chesapeake Bay Watershed, U.S. (Water infiltration in soils allows more options for winter manure application)

The 166 000 km^2 Chesapeake Bay Watershed has been the focus of intensive efforts to address nutrient losses from farms due to the eutrophication of the Chesapeake Bay. The watershed is home to 3.9 million AUs generating 294 000 Mg of N and 78 000 Mg of P in manure per year (Fig. 4). It is estimated that animal manure contributes 20% of the total N and 30% of total P loadings to the Bay (Chesapeake Bay Program 2010). Strong pressure has been exerted on the Chesapeake Bay states (Delaware, Maryland, Virginia, Pennsylvania, West Virginia, and New York) to restrict winter application of manure, which is widely viewed as negatively impacting water quality. Since the implementation of watershed-wide regulations aimed at cleaning up the Chesapeake Bay in 2011, most states have implemented new directives that address winter application of manure. However, these directives vary widely from calendar-based regulatory prohibitions on land application of manure (Delaware and Maryland) to regulatory restrictions based upon field conditions and management factors

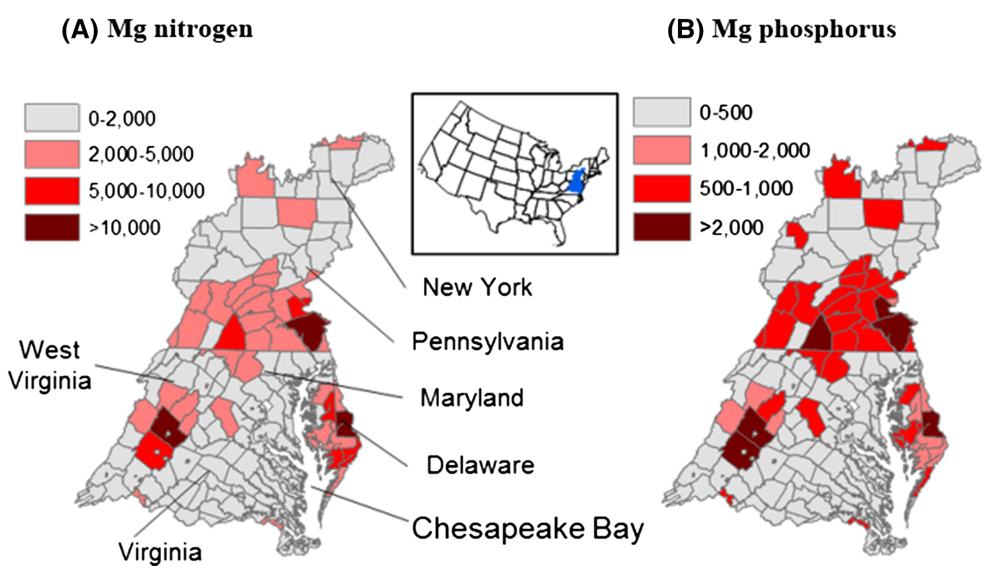

Fig. 4 Annual production of manure nutrients (Mg) in 2015 in counties of the Chesapeake Bay Watershed, U.S. **A** Nitrogen, **B** Phosphorus. Location of the watershed is identified in the inset map of the U.S. Watershed figures are updates of the versions provided by the U.S. Environmental Protection Agency (2010)

Table 2 Winter manure management policies for the states in the Chesapeak Bay Watershed, USA

	Delaware	Maryland	Virginia	Pennsylvania	West Virginia	New York
Policy type	Regulation	Regulation	Regulation	Regulation	Guideline	Guideline
Farm size concerned	All	> 50 AU	CAFOs	All	All	All
Category of regulation/guideline						
Winter conditions[a]					Yes	
Closed period	Yes	Yes				
Manure form			Yes			Yes
Manure rate			Yes	Yes		Yes
Manure placement			Yes			Yes
ESA setback[b]			Yes	Yes		Yes
Field slope			Yes	Yes		Yes
Ground cover			Yes	Yes		Yes

[a] Winter conditions, i.e., snow-covered, water-saturated, or frozen land

[b] ESA setback: Setback from environmentally sensitive areas, including streams, ponds, lakes, tops of stream banks, existing open sinkholes, drinking water sources, and above ground inlets to agricultural drainage systems where the surface water flows toward the inlet (Pennsylvania Department of Environmental Protection 2011)

(Virginia and Pennsylvania) and guidelines (West Virginia and New York; Table 2). Interestingly, regulations/guidelines are more restrictive in states in close proximity to the Bay, in spite of the milder winter conditions compared to the more distant, northern states of New York and Pennsylvania.

Differences in state directives are exemplified by the contrast between the winter manure application directives of Maryland and Pennsylvania. Maryland has historically implemented some of the most restrictive agricultural nutrient management policies in the U.S., and was the first state to pass regulations mandating P-based nutrient management planning. Regulations in Maryland have prohibited winter application of manure by major commercial operations since 2016 (Maryland Department of Agriculture 2012), with prohibition dates differing between eastern Maryland (Nov 2–Feb 28) and western Maryland (Nov 16–Feb 28). However, winter application of manure is still permitted under certain circumstances, such as for operations with less than 50 AUs, for dung deposited directly by animals, and for cash crop production in greenhouses. Notably, winter-like conditions (frozen soils and snow) are often reported in Maryland through the month of March (National Oceanic and Atmospheric Administration 2016). As a result, it is not uncommon to see land application of manure during the days following the ‘closed period’ even though winter conditions exist, raising the question as to whether concentrating application around certain dates in the spring may sometimes exacerbate environmental losses relative to land application of manure during the winter months.

In Pennsylvania, manure applications are not prohibited during the winter months, even though Pennsylvania abuts Maryland and there are many commonalities in farming operations, particularly with regard to small dairy farms in southern Pennsylvania and western Maryland. Instead, Pennsylvania has implemented site-specific regulatory restrictions on winter application of manure to limit the risk of off-site pollution, restrictions that apply equally to all sizes of farming operations (Pennsylvania Code 2005; Pennsylvania Department of Environmental Protection 2011). Specifically, winter manure application regulations include setbacks from environmentally sensitive areas, maximum allowable application rates, maximum field slopes, and minimum crop/residue cover percentages on the soil surface (Table 2). Such regulations recognize the practical realities of small farming operations, many of which lack significant manure storage (Dou et al. 2001).

Directives for Winter Manure Application in New Zealand and Australia

In New Zealand and Australia, dairy farms are largely based on grazing pasture and not confinement feeding. The use of confinement feeding is prevalent in beef production in Australia, but not New Zealand. The warm Australian winters mean that there are fewer risks from land application of manure from Australian confinement feeding operations compared to those in Europe or North America. In contrast to the solid manures or slurries generated in the Northern Hemisphere, Australian and New Zealand dairy sheds are washed with water; the liquid effluent (usually < 1% solids) is collected in ponds and then land applied. While the soil is seldom frozen, evapotranspiration in winter can be low and decreases farther to the south. Hence, emphasis is placed on applying effluent when the soil is not saturated thereby avoiding macropore flow and loss of effluent contaminants in artificial drainage or ponding and loss of contaminants via runoff.

Regulations and guidelines for the management of effluent over winter vary in Australia and New Zealand, as well as across regions within the two countries (McDowell et al. 2016). In Australia, dairy farming is typically mixed with other land uses that can dilute the water quality impact of effluent application. In response, Australian state and federal governments encourage self-regulation of the dairy industry, rather than developing regulations which limit nutrient losses (Gourley and Weaver 2012). An example of such approaches is the Dairy Self-Assessment Tool (DairySAT) (Dairy Australia 2015) used to demonstrate compliance with environmental standards, thus meeting buyer and investor demands. In New Zealand, the National Policy Statement for Freshwater Management (Ministry for the Environment 2014) dictates that regional authorities must maintain or improve water quality by setting catchment limits. However, the allocation of these limits to the farm boundary varies. Effluent management falls within the implementation of these limits if bad practice is deemed by the regional authority to be highly likely to contribute to poor water quality. This judgment is based on the density of dairy farms, likely topography and climate of the region: a summary of compliance requirements by each authority is available at—http://www.dairynz.co.nz/environment/effluent/effluent-compliance/.

Case study 4: New Zealand (Effluent management to reduce nutrient and fecal bacteria losses in water-saturated soils)

In New Zealand, the impact of manure effluent on nutrient and fecal indicator bacteria (*E. coli*) concentrations in streams and rivers is a clear indicator of bad practice in winter or early spring. For example, Houlbrooke et al. (2008) found N and P losses in artificial drainage to be 6–10-fold greater when applied to saturated soils in winter. McDowell et al. (2011) found approximately 50% of catchment-scale N, P and *E. coli* loadings were attributed to the application of effluent when soils were saturated in winter, in violation of local manure application directives.

Although the majority of New Zealand's 16 regional authorities prohibit the ponding and runoff of land-applied effluent year-round, regulation in certain areas also focuses on the timing and nutrient content of effluent (Fig. 5). For example, in Canterbury, where there is a large number of aquifers vulnerable to contamination, the volume of effluent is restricted to that delivering 150 kg N ha^{-1} y^{-1} or less (Jenkins 2013). Further south, in Otago and Southland where topography and climate requires artificial drainage, applications are discouraged or even prohibited by regulation when the soil is saturated (largely in winter and early

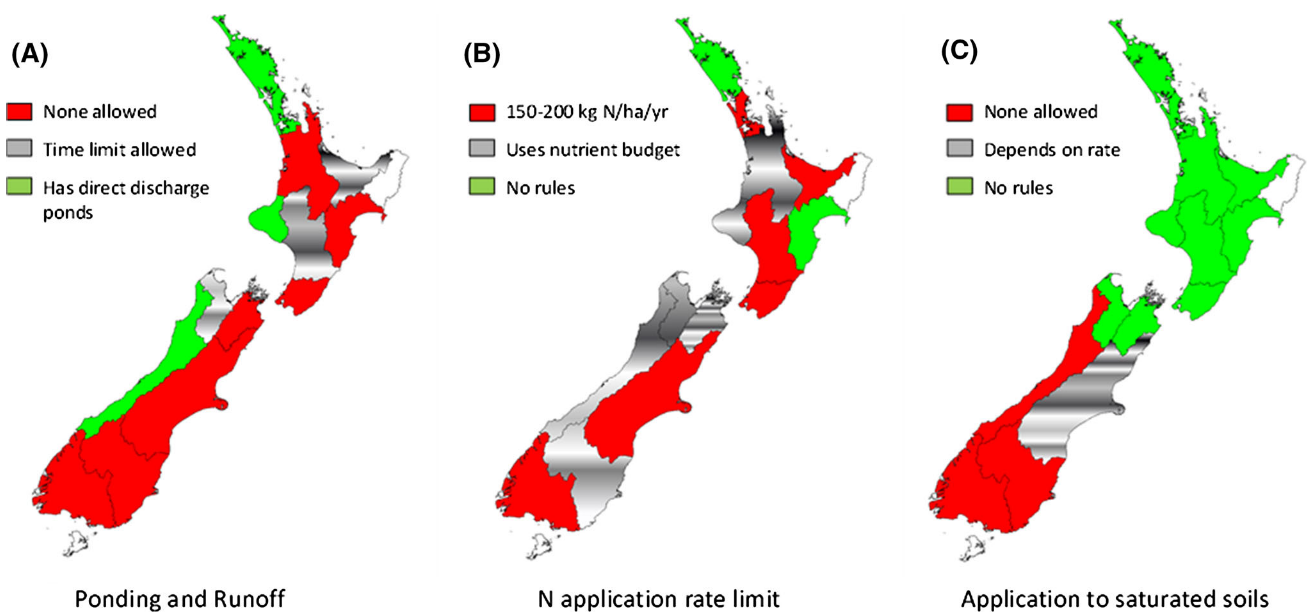

Fig. 5 Manure management in New Zealand focuses on restricting effluent application to soils to prevent ponding and runoff year-round (**A** "none" refers to no ponding or runoff at any time; "time limit" allows for some ponding and runoff; and "direct discharge" refers to discharges from effluent settling ponds directly to streams), restrict applications over the year to a N rate limit (**B** < 150–200 kg N ha^{-1} y^{-1} via direct measurement of the effluent or a nutrient budget), and prohibit applications to saturated soils in winter (**C** applications are either not allowed, allowed if below a certain rate, or unrestricted). Data taken from McDowell et al. (2017)

spring) and likely to cause effluent-drainage. Moreover, farmers are required to have effluent ponds that have sufficient storage of, for example 90 days, to allow them to apply when soil moisture deficits are greater (DairyNZ 2015).

While voluntary schemes can raise awareness of bad practice, the interpretation of guidelines can vary without direction tailored to each farm's unique topographic or climatic features. For instance, the dairy and clean streams accord in New Zealand, a self-regulation scheme, included good effluent practice amongst its many guidelines and had impressive rates of adoption (e.g., 90% within 3–5 years) (Ministry for Primary Industries 2013). However, auditing found the true rate of compliance to be more like 50–70%, depending upon the region (Sanson and Baxter 2011). Regulation of effluent application rates in Canterbury initially found similar levels of non-compliance (60%) (Burns 2015). However, with enforcement and industry-led education, the rates of non-compliance have decreased. A similar picture has emerged from regulation in regions further south (Ministry for Primary Industries 2013). Depending on the degree to which effluent comprises farm-scale contaminant losses, farm-scale improvements in effluent practice will take time to be measured as catchment-scale improvements in water quality. To date such improvements have largely been elusive, or restricted to a few small catchments, and hence will require further investigation of flow paths and management practices, including those in winter, if substantial water improvements are to be achieved.

Absence of Directives for Winter Manure Application in the Developing Countries

In contrast to the developed countries, where winter application of manure is well managed through mandatory regulations and/or voluntary guidelines, there is a common absence of such directives in the developing countries. This is despite the fact that many of the developing countries such as China, India, Brazil, and South Africa own large animal production industries. In this context, China provides a stark example of the state of manure management in countries with fast-growing animal agriculture, but generally limited directives related to land application of manure in any season.

Case study 5: China (No specific regulations or guidelines for winter manure application)

In China, animal numbers and resultant manure generation have increased more than seven-fold in the past 60 years (China Statistics Press 2010). Large-scale confinement feeding operations are replacing the traditional mixed small-holder farming systems across the country. As a result, manure-borne pollutants have become a great source of non-point pollution to water and air. In an analysis of nutrient flows in the food chain of China, Ma et al. (2010) estimated that only half of the manure produced in China's animal production systems was appropriately returned to cropland, while the remaining half was mishandled, to a large extent, due to lack of appropriate storage and handling facilities. In recent years, well publicized incidents of water eutrophication and air pollution have alerted the government to enact and enforce more stringent environmental directives. Nationally, however, manure management efforts are still far less than what is needed to combat pollution associated with animal production. For instance, recent national regulations on large-sized animal operations require, in very general terms, that animal farms be constructed with appropriate manure storage and handling facilities and that manure not pollute water, but there are no concrete directives for land application of manure to achieve these outcomes (State Council of the People's Republic of China Code 634, 2013). To solve the severe problem of eutrophication, more detailed directives are needed to guide better manure management, including directives that guide land application of manure in winter.

DISCUSSION AND CONCLUSIONS

Across the globe, directives on managing manure application in winter range from regulatory bans of all winter manure application to guidelines that provide recommendations for best management strategies. The directives are generally derived from the common rationale to reduce off-site manure nutrient losses, but they are also affected by factors such as local socio-economic and biophysical considerations. First, the directives have been largely influenced by overarching environmental policies. Driven by the Nitrates Directive, for instance, countries across Europe have uniformly adopted 'closed period' regulations. In contrast, U.S., Canada, Australia, and New Zealand defer to states/provinces/regions, resulting in a diverse range of regulations and guidelines. Moreover, the directives reflect regional winter conditions. For instance, in cold regions with frozen soils and low expectation of snowmelt infiltration like the northern European countries and parts of Canada, regulations tend to ban winter manure application. In the regions with relatively mild winters and possibilities of snowmelt infiltration like Chesapeake Bay Watershed, U.S., Australia, and New Zealand, directives usually provide more options for site-specific management. Furthermore, directives are affected by production systems and confinement as well as availability of subsidies for implementing the directives. For instance, a strong history of subsidies in combination with relatively low animal densities has supported the construction of manure storage facilities in the northern European countries, enabling selective timing of manure application. Finally, the "right to farm" attitude is prevalent in the U.S., often making it difficult to develop regulations and enforce manure application directives on U.S. farms.

Clearly, manure needs to be well managed to reduce off-site nutrient pollution. The 'closed period' approach has sometimes been questioned for its lack of flexibility. Some countries/regions such as Finland and Manitoba increase the flexibility of the closed period by considering weather conditions for fall/winter manure application. Still, more flexibility may be needed to account for variation in climate and cropping systems within a country. The other approaches related to winter manure application, such as weather-associated restrictions and management-associated restrictions, present their own concerns and have been challenged to demonstrate that they can reduce levels of nutrient losses comparable to spring application.

There are clearly important environmental and economic trade-offs with regard to land application of manure during winter months. Undoubtedly, regulated bans on land application of manure under winter conditions is an effective means of preventing nutrient losses. For major animal producing countries such as U.S. and China, however, complete prohibition of winter manure application is hardly possible in the short-term, because many farms currently have insufficient capacity to store manure produced throughout the winter. Opportunities exist to explore precision manure application during the winter, i.e., applying right source and right rate at right time and right place, to minimize losses of nutrients and other contaminants associated with winter conditions. In a modelling study, Liu et al. (2017) found that targeting manure applications to low-risk fields in winter and fall could reduce P runoff losses to levels below those resulting from spring application if low-risk fields were not targeted. This suggests that efforts for reducing manure nutrient losses associated with winter application should be complemented with strategies in other seasons as well. Moreover, that study found that different manure storage capacities had marginal effects on water quality at the outlet of a watershed with relatively low animal densities. Again, this raises the issues of environmental and economic trade-offs. As a general long-term goal, however, manure storage capacities should be increased over time such that the farmers will have more options for timing manure applications.

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