CREW CENTRE OF EXPERTISE FOR WATERS

Moving to more sustainable methods of slurry application: implications for water quality of waterbodies and water protected areas

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Executive Summary

Question

What are the effects of low emission slurry spreading (LESS) approaches on water quality?

Background

Ammonia emissions from field-applied slurry can have detrimental impacts on biodiversity and public health, and reduce slurry fertiliser value. The Scottish Government has announced The Water Environment (Controlled Activities) (Scotland) (Amendment) Regulations ("CAR") 2021 (SSI 2021/412) in relation to slurry application as part of strategies to mitigate ammonia and greenhouse gas (GhG) emissions from agriculture. The Amendment includes the phasing out of broadcast spreading of slurry by splash plates and the transition to precision spreading equipment by January 2027. Precision equipment enables accurate application by a band spreader (e.g., trailing hose and trailing shoe), or by direct injection into the soil, reducing ammonia emissions via volatilisation from field-applied slurry. Slurry acidification prior to application also reduces ammonia volatilisation. Precision equipment and acidification are low-emission slurry spreading (LESS) approaches.

Research method

This report is a quick scoping review (QSR) of the peer-reviewed and grey literature to provide an evidence-based comparison of different LESS approaches in terms of farming practice, ammonia and nitrous oxide emissions and risk of water pollution from slurry spreading to inform farmer-focused guidance on LESS. The work is focused on slurry-borne contaminants that are relevant to the water quality objectives under the river basin management plans (RBMP) set by the Scottish Environment Protection Agency (SEPA), such as nitrate, phosphorus and faecal indicator organisms (FIO). The reference slurry application technique for this comparison is defined as untreated (non-acidified) slurry spread over ("broadcast") the whole soil surface by splash plate. Where the term "surface application, it refers to application of slurry on the soil surface by broadcasting (splash plate), trailing hose or trailing shoe.

Key findings

- The implementation of LESS approaches can play a critical role in reducing ammonia emissions from field-applied slurry, with the greatest abatement efficiencies reported for slurry injection (up to 99%) and surface application of acidified slurry (up to 85%). However, their role in reducing losses of slurry-borne contaminants to water is not well understood.
- The effect of LESS approaches such as trailing shoe and acidification on runoff and leaching of slurry-borne contaminants is poorly studied compared to the effects of injection or the effects of LESS on ammonia and nitrous oxide emissions. Many studies examined LESS effects in the laboratory and in the context of different factors, therefore it is difficult to draw comparisons and conclusions based on available evidence.
- Slurry injection has agronomic and environmental benefits, including: (i) drastic reduction in odour and nuisance; (ii) minimal crop contamination risk (in open-slot injection) and potential for application before seeding or during growing season, reducing the need for further chemical fertiliser (in closed-slot-injection); and (iii) reduced losses of slurry-borne contaminants in runoff.
- Slurry injection has considerable practical and environmental limitations, such as: (i) high risk of damaging roots of growing plants, being suitable only for bare arable land, on fields with wide-row crops and on even ground, (ii) high fuel demand, low working rate and high capital cost; and (iii) increased potential for pollution swapping via nitrous oxide emissions, nitrate and phosphorus leaching and FIO survival, varying with soil moisture and soil retention capacity for different slurry borne contaminants and soil types.
- Band Spreading (trailing hose) and trailing shoe application of non-acidified slurry may provide a cost-effective alternative to injection that reduces the potential of pollution swapping. However, their effects on the loss of nitrogen, phosphorus and FIO in runoff and leaching have been poorly studied.
- Application of acidified slurry has additional benefits for air quality, i.e., no odour and low risk of nitrous oxide emissions, and agronomic practice, e.g., it is associated with better slurry fertiliser value and higher crop yield compared to non-acidified slurry.
- The main problem associated with slurry acidification is the higher potential for nitrogen, phosphorus and FIO leaching and survival in the soil.
- A clearer understanding of the effect of injection and application of acidified slurry on pollution swapping can support context specific guidance to farmers.

Key considerations for guidance to farmers

This QSR showed that the key factors influencing the impact of LESS approaches on losses of slurry-borne pollutants to water are: precipitation, soil moisture, soil permeability and drainage, and presence of vegetation, be it crop, grass or vegetated buffer strips. The role of these factors has already been captured in the current regulatory framework, stipulating specific obligations for farmers under GBR18 and The Action Programme for Nitrate Vulnerable Zones (Scotland) Regulations 2008. The already existing guidance is still valid to protect water quality. However, the choice of LESS approach should be determined by environmental designations (e.g. bathing waters, shellfish waters and NATURA sites). It should also account for the most vulnerable environmental component (e.g. soil, atmosphere, or waterbodies) of the agro-ecosystem. Guidance to farmers should also consider a compromise between feasibility, cost, and environmental and agronomic objectives.

Recommendations for further research

The review revealed considerable research and evidence gaps. There is a need to:

- Design and conduct field experiments to understand the effect of different techniques on nitrate leaching, and phosphorus losses in runoff and leaching.
- Conduct studies to understand trade-offs between different pathways of losses for slurry-borne contaminants such as phosphorus and FIO using different LESS and conditions.
- Conduct field experiments to understand the agronomic and water quality trade-offs of acidified and separated slurry.
- Explore the factors which enable the uptake of LESS by Scotland's farmers.
- Conduct a nation-specific cost-benefit analysis of the transition to LESS accounting for the integrated benefits to air quality, GhG emissions, water quality, biodiversity, public health, crop yield and the farming business in the context of availability of digestate and slurry.

1.0 Introduction

The Scottish Government has announced The Water Environment (Controlled Activities) (Scotland) (Amendment) Regulations ("CAR") 2021 (SSI 2021/412) in relation to slurry application as part of strategies to mitigate ammonia and greenhouse gas (GhG) emissions from agriculture (CAR 2021). The Amendment includes the phasing out of broadcast spreading of slurry by splash plates and the transition to precision spreading equipment by January 2027. It is widely recognised that slurry application by precision equipment and slurry acidification are low-emission slurry spreading (LESS) approaches, but it is less clearly understood how LESS should be used for also reducing losses of slurry-borne contaminants to water. The aim of this report is to review evidence on the effects of LESS approaches on water quality in the context of their benefits and costs related to ammonia emission abatement from field-applied slurry.

This report is a quick scoping review (QSR) of the peer-reviewed and grey literature. The QSR will provide an evidence-based comparison on the effects of different LESS approaches on farming practice, ammonia and nitrous oxide emissions and risk of water pollution from slurry spreading, and discuss gaps in the evidence-base to inform farmer-focused guidance on LESS. The work is focused on slurry-borne contaminants that are relevant to the water quality objectives under the river basin management plans (RBMP) set by the Scottish Environment Protection Agency (SEPA), such as nitrate, total phosphorus (TP), soluble reactive phosphorus (SRP) and faecal indicator organisms (FIO). The reference slurry application technique for this comparison is defined as untreated (non-acidified) slurry spread over the soil surface ("broadcast") by a tanker equipped with a discharge nozzle and usually onto an inclined plate designed to increase lateral spread (aka splash-plate) and not targeting application conditions such as incorporation to minimise ammonia loss or selected timing. Precision equipment refers to technology enabling accurate application by a dribble bar or band spreader (e.g., trailing hose and trailing shoe), or by direct injection into the soil. Where the term "surface application, it refers to application of slurry on the soil surface by broadcasting (splash plate), trailing hose or trailing shoe.

The remainder of this chapter briefly provides further background on the impacts of emissions and losses to water from field-applied slurry.

The report also includes the following chapters:

- Chapter 2 compares the technical and agronomic characteristics of different LESS.
- Chapter 3 compares gaseous emissions by different LESS.
- Chapter 4 compares losses of nutrients and FIO to waterbodies.
- Chapter 5 presents readily available evidence on different proxies of the cost of implementing LESS.
- Chapter 6 discusses the implications of pollution swapping and knowledge gaps and provides recommendations for further action.

Further details on the QSR methodology, including limitations and caveats, can be found in APPENDIX I. The impacts of ammonia on the environment, public health and biodiversity are summarised in APPENDIX II.1. The legislative framework on slurry application is given in APPENDIX II.2. The Scottish context on emissions from field-applied slurry are outlined in APPENDIX II.3. The hydrological and biogeochemical processes related to diffuse pollution are given in APPENDIX III. Evidence on gaseous emissions from field-applied slurry is detailed in APPENDIX IV. Evidence on the effects of LESS on losses of nitrogen, phosphorus and FIO to water are detailed in APPENDIX V.

1.1 Background

Slurry from housed livestock excreta, farmyard mixtures and anaerobic digestion (AD) is increasingly used as a recyclable fertiliser resource for farmers. Its application, when matching crop demand and administered at the right place and time, can provide readily available nitrogen (i.e., ammoniacal nitrogen) and phosphate, and improve soil organic matter (OM) content. Slurry application has thus the potential to replace part of chemical fertilisers and thus reduce their production, which is highly energy consuming (Svanbäck et al., 2019), and based on fossil fuels (e.g., ammonium fertilizers) or non-renewable ore deposits (e.g., phosphate rock) (Sigurnjak et al., 2016).

However, it is difficult to meet crop demand and control impacts on the environment when the slurry is broadcast onto the soil surface because of the loss of TAN via ammonia volatilisation to ammonia gas (Bittman et al., 2014). Broadcast application by splash plate, either high or low trajectory, is the conventional method for the application of manure or slurry. However, it increases the risk of total ammoniacal nitrogen (TAN) transformation to gaseous ammonia during air exposure via a process known as volatilisation (APPENDIX II.1). Broadcast application is thus associated with emissions of ammonia in the range of 40%-60%, or more under drier conditions, of the total ammoniacal nitrogen (TAN) added with slurry (Bittman et al., 2014). Ammonia lost to the air is nitrogen lost for plant growth. The amount of TAN that is not volatilised can meet crop demand in nitrogen, improve yield and reduce the use and cost of chemical nitrogen fertiliser (Bittman et al., 2014). Thus, mitigating ammonia emissions has important benefits for farmers.

Ammonia is a potent atmospheric pollutant with a wide variety of biodiversity, environmental and human health impacts; therefore, ammonia volatilisation is an environmental burden. Ammonia combines with nitrate and sulphate in acid cloud droplets to form very fine particulate matter (PM2.5 and PM10) in the atmosphere (Gu et al., 2021), which are of concern for human health. Globally, approximately 39% of PM2.5 is derived from ammonia and results in a £320bn cost to health services (Gu et al., 2021). The PM2.5 can stay in the air over several days and travel long distances, before deposition on urban, terrestrial, and aquatic systems. The deposition of these particles onto the ground can cause soil acidification and loss of plant species diversity (e.g., Guthrie et al., 2018).

Impacts of ammonia on biodiversity and ecosystem function occur directly through dry deposition as NH_3 and by wet deposition following conversion to particulate ammonium (NH_4) in the atmosphere. The impacts of ammonia on biodiversity and ecosystem function occur through four main mechanisms: eutrophication, acidification, direct toxicity, and indirect effects (Stevens et al., 2004). Airborne nitrogen deposition is one of the leading causes of global decline in biodiversity alongside changing land use and climate change (Payne et al., 2017).

Slurry TAN as well as airborne ammonia deposition can increase the concentration of easily decomposed (mineralizable) nitrogen by microbes in the soil (APPENDIX II.2). This in turn increases the potential for chemical reactions such as nitrification (i.e., production soluble nitrate) and denitrification below the soil surface, which leads to production of nitrous oxide (Velthof et al., 2003; IPCC, 2006), a potent greenhouse gas (GhG). Other forms of nitrogen that can be emitted directly or indirectly to the air following slurry spreading are di-nitrogen and nitrogen oxide, which are not further examined in this report.

Slurry contains varying amounts of microorganisms, heavy metals, veterinary medicine products (VMP), trace elements and "forever chemicals"[1], depending on origin and pre-application processing (Liu et al., 2021; Kemper et al., 2008; Lukehurst et al. 2010; Fangueiro et al., 2015; Kay et al., 2004). Broadcast application leaves slurry-borne contaminants vulnerable to transport from agricultural land to adjacent waterbodies via surface runoff (Nicholson et al., 2017; Peyton et al., 2016; Nolan et al., 2020), or infiltration (leaching) (e.g., Børgesen and Olesen, 2011see also APPENDIX III.

1 Per- and polyfluorinated alkyl substances are also known as "*forever chemicals*": they are a large chemical family of over 9,000 highly persistent chemicals.

In addition to increasing air and water pollution risk, the loss of phosphorus and TAN from the soil following broadcasting further reduces the fertiliser value of slurry (Sørensen and Amato, 2002; Bittman et al., 2014). Effective agricultural practice must minimise loss of nutrients to air and water simultaneously and establish a nutrient balance at the farm level. In the case of nitrogen, slurry management aims at decreasing nitrogen surplus, which is related to adding chemical nitrogen fertiliser to compensate for ammonia emissions (Bittman et al., 2014), and increasing use efficiency, which is related to meeting nitrogen crop demand before soil conditions allow loss via leaching.

LESS approaches refer to slurry application with precision equipment and application of acidified slurry. Precision equipment enables accurate application of slurry by a dribble bar or band spreader (e.g., trailing hose and trailing shoe), or by direct injection into the soil. This technology can reduce ammonia emissions compared to broadcast application because it reduces ammonia slurry exposure to air. On the other hand, slurry acidification, i.e., lowering its pH, favours retention of TAN in the slurry, also having the potential to abate ammonia emissions following broadcast or band application by trailing hose, as compared to untreated slurry application (Fangueiro et al., 2018).

The question arises whether LESS can also reduce nitrous oxide emissions and losses of slurry-borne contaminants to water while increasing crop yield and at what cost.

2.0 Low emission slurry spreading (LESS): technical and agronomic characteristics

2.1 LESS description

This section provides a description of the technical characteristics of the equipment used for broadcast application with splash plate, precision equipment and slurry acidification. Broadcast spreaders with splash plate (SP) and precision equipment can be fitted onto a vacuum or pumped tanker or used with an umbilical supply system (Misselbrook et al., 2005). The description is given below in Box 1.

Box 1. Description of LESS approaches

Trailing hose (TH) also known as band application or dribble bar application: Precision technology consisting of a slurry tank, distributor and hoses mounted on a boom with equal distance (20–30 cm) The most common work width is 12m. The hoses distribute slurry close to the ground in narrow bands, slurry being fed to the hoses in advanced systems via a rotary distribution manifold which controls the flow of slurry evenly to each hose outlet. Slurry can be discharged at ground level to grass or arable land, with application between the rows of a growing arable crop possible.

Trailing shoe (TS) applicator, also known as trailing feet or narrow band application: Precision technology similar in configuration to the band spreader, with the hoses depositing slurry via a metal 'shoe' device designed to ride along the soil surface, parting the crop so that slurry is applied directly to the soil surface and below the crop canopy. Some types of trailing shoes are designed to cut a shallow slit in the soil to aid infiltration.

Slurry injection (SI): Precision technologies that place the slurry beneath the soil surface either via open slot, open slot injection (down to 50 mm), shallow closed injection (down to 5-10cm) or via deep tines (down to >150 mm). There are four types:

- Open slot injectors (O-SI): these cut with knives or discs 2-6cm slots into the soil, where the slurry is directed through rubber nozzles, leaving the slots open. The distance between slots is usually 20-40cm and the working width of the spreader is around 6m.
- Shallow (or close slot) injectors (S-SI): these cut narrow slots (typically 4–10 centimetres (cm) deep and 25–30 cm apart) in the soil that are filled with slurry or liquid manure. They are most commonly used on grassland. The slurry is ingested through rubber nozzles into the slots cut by discs and then the slots are closed with pressure wheels or rolls. The slurry falls into the slot by gravity
- Deep injectors (also known as arable injectors) (D-SI): these apply slurry to a depth of 10–30 cm in the soil using injector tines spaced about 50 cm or even 75 cm apart. The tines are often fitted with lateral wings to aid dispersion in the soil and to achieve high application rates. They are most suited for use on arable land because of the risk of mechanical damage to grass swards. The working width of the spreader is in the range of 3 to 8m. Slurry must be loosened.
- Direct ground injection: jets of slurry are forced into the soil under pressure, mixing with the soil in discrete pockets placed 5-13cm into the soil.

Slurry acidification (SA): Untreated slurry pH: 7.8-8.2. Target pH in acidified slurry : 5.0 -6.0.This can be achieved by slurry amendment with natural or chemical additives , with strong acids such as sulphuric acid being used most commonly. However, hydrochloric acid and nitric acid are also used. The target pH ranges from 4.5 to 6.8 and the choice of a specific pH depends on several factors, such as type of slurry, the acid/salt used, and the step of the slurry management chain at which the acidification is performed. A pH of 5.5 is the selected target for commercial ~~in-house~~ acidification. When adding acid to slurry at any stage of the farm operation, it is necessary to do this safely to avoid any risk to workers, animals and the environment. Lowering the slurry pH will impact multiple chemical and microbial processes in the slurry, changing its composition, an effect that does not occur with LESS technology.

Source: Precision equipment (Misselbrook et al., 2005; Bittman et al., 2014; Morken & Sakshaug, 1998; Tamm et al., 2016); Slurry acidification (Fangueiro et al., 2015; Rotz 2004).

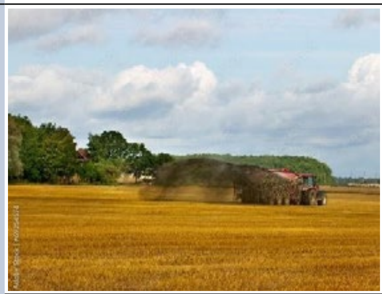
2.2 Practical considerations of LESS approaches

2.2.1 Slurry application equipment

This section reviews practical considerations for the use of precision equipment. The advantages and disadvantages of the LESS approaches are also presented comparatively in Table 1. Issues related to gaseous emissions and losses of slurry-borne contaminants to water are reviewed in Section 3 and 4, respectively.

Broadcast spreading -splash plate (SP). The key advantage is simplicity, low cost compared to precision equipment, and ease-of-use. However, there are many disadvantages such as high odour and nuisance, uneven spreading, and problems in application to growing plants, especially grasslands (Kaasik 2012). For example, it is not possible to prepare a high quality silage (hay) from plants polluted with manure or slurry, and the intake of such herbage is reduced in grazing or as a green fodder but it may depend on the growth stage of the grass . The typical range of dry matter content of the slurry can be

Table 1. Comparative presentation of practical and technical characteristics of slurry spreading methods. Comparison is based on qualitative and not quantitative differences between methods. Sources: Bittman et al., 2014; Tamm et al., 2015; NATURAL ENGLAND 2018; Kaasik 2012; Rhode et al., 2005.

	Broadcast application with splash plate (SP)	Band application -Trailing hose (TH)	Trailing shoe (TS)	Closed Shallow injector (SI)
Relative ease of use	✓ ✓ ✓	✓ ✓	✓	✓
Relative uniformity across spread width	✓	✓ ✓ ✓	✓ ✓ ✓	✓ ✓ ✓
Relative crop contamination risk	✓ ✓ ✓	✓	✓	
Relative risk of grass sward damage	✓ ✓		✓	✓ ✓
Relative odour	✓ ✓ ✓	✓ ✓	✓	No odour
Typical range of dry matter (DM)	Up to 12% (viscous slurry)	<9%	<6%	<6%
Requires separation or chopping	No	Yes (if DM>6%)	Yes	Yes
Relative work rate	✓ ✓ ✓	✓ ✓	✓ ✓	✓
Relative precision application	✓	✓ ✓	✓ ✓	✓ ✓ ✓
Relative suitability where field slopes>15%	✓ ✓	✓	No	No
Relative sensitivity to stones	✓	✓ ✓	✓ ✓ ✓	✓ ✓ ✓
Relative runoff risk	✓ ✓ ✓	✓ ✓	✓	✓
Visual				
		https://www.nutrientmanagement.org/managing-livestock-manures-3-p1--spreading-system/	https://www.farmersjournal.ie/listen-big-changes-for-fertiliser-and-slurry-spreading-472772	http://baen.tamu.edu/wp-content/uploads/sites/24/2017/01/EBN-007.-Advanced-Application-Techniques.-Making-the-Most-of-Your-Manure-Responsibility.pdf

up to 12% and does not require separation or chopping (Chambers et al., n.d.).

Band or trailing hose (TH) spreaders. The technique is applicable to grass and arable land (growing crops); application between the rows of a growing arable crop is feasible. Band spreaders have lower odour and nuisance risk but are less suitable for fertilising grasslands intended for silage production or grazing than trailing shoe spreaders or injectors, as contamination of grass by slurry may occur. Because of the large working width, the technique is not suitable for small, irregularly shaped fields or steeply sloping land (slopes >15%) but is less sensitive to stony ground than other LESS equipment and because of the large width maybe compatible with tramlines (Kaasik 2012; NATURAL ENGLAND 2018). An additional agronomic benefit is that they distribute slurry more consistently and uniformly than broadcast application of slurry (Bittman et al., 2014). The typical range of dry matter content of the slurry is up to 9% and when above 6%, it requires separation of solid material or chopping (Chambers et al., n.d.).

Trailing shoe (TS) spreaders (also reported as narrow band spreaders). The technique is applicable to grass and arable land (growing crops) but is not suitable for small, irregularly shaped, stony fields or steeply sloping land (slopes >15%) because of its large working width and when growing solid seeded crops (Kaasik 2012; NATURAL ENGLAND 2018). But it may be possible to use during winter and for row crops. This technique distributes the slurry more accurately near the base of the plant where it is needed as fertiliser, and also substantially reduces the amount of slurry deposited onto the plant surface, preventing plant contamination (Bittman et al., 2014). An additional agronomic benefit is that they distribute slurry more consistently and uniformly than broadcast application of slurry, with a more precise placement that can reduce the risk of slurry run-off and loss of useful slurry components from the soil and the crop (Bittman et al., 2014). The typical range of dry matter content of the slurry can be up to 6% and requires separation of solid material or chopping (Chambers et al., n.d.).

Open slot injectors. This type of injectors are mainly used for fertilising pasture and grassland (growing plants). The technique can reduce odour and nuisance risk but has several disadvantages. The application rate must be adjusted so that excessive amounts of slurry do not spill out of the open slots onto the soil surface and the plants (Kaasik 2012). Increasing application rate above 15-20 m3 of slurry per ha increases the risk of slurry overflowing from the slots and staying on the soil. The technique is not applicable to very stony soil or very shallow or compacted soils, where it is impossible to achieve uniform penetration of the discs to the required working depth (NATURAL ENGLAND 2018). For example, it is unsuitable in shallow and high-clay soils when very dry (>25% organic matter content). Injectors have a larger need of tractive power and at the same time have a smaller working width (Tamm et al., 2015).

Closed slot injectors. Closed slot injectors are the most environmentally friendly slurry spreading devices with minimal odour and nuisance (Bittman et al., 2014). Slurry injection can be undertaken directly prior to seeding or alternatively, during the growing season; however, crop productivity may decrease because of mechanical damage to underground parts of herbage grasses (NATURAL ENGLAND 2018). The use of deep injection is restricted mainly by the soil conditions. It is not applicable on soils with high clay and stone content (Kaasik 2012). The injectors require a large tractor and higher fuel consumption (Tamm et al., 2015). Rhode et al. (2005) reported that the working depth of injectors increases significantly with increasing soil water content, e.g., during wet weather, but the volume of slurry application is restricted by slot volume. It is unsuitable for slopes higher than 15% and stony/compacted soils (NATURAL ENGLAND 2018). Deep injection has a high risk of damaging roots of growing plants, therefore suitable only for bare arable land or on fields with wide-row crops (Kassik 2012). The typical range of dry matter content of the slurry can be up to 6% and requires separation of solid material or chopping (Chambers et al., n.d.).

2.2.2 Slurry acidification

Slurry can be acidified at different stages of the manure/slurry management chain: In-house, in-storage and in-field. Slurry acidification is used mainly in Denmark where 20% of all animal slurry was acidified in 2016 (Joubin 2018). A review of practical considerations at each stage can be found in Fangueiro et al. (2015). The impacts of slurry acidification have also been studied within the Interreg project, Baltic Slurry Acidification[2].

Application of acidified slurry may influence soil pH, the fertiliser value of the acidified slurry as well as the nitrogen, phosphorus or carbon dynamics, which might differ from patterns already known for non-acidified slurry (Wenzel and Petersen 2009). Acids such as sulphuric acid used for slurry acidification are dangerous and their handling must adhere to safety procedures, therefore application or storage of acidified slurry on farm requires careful planning.

This section focuses on practical considerations related to spreading of acidified slurry and subsequent effects on soil pH, slurry fertiliser value and crop yield. The advantages and disadvantages of slurry acidification and precision equipment are compared in Table 1.

2 https://projects.interreg-baltic.eu/projects/baltic-slurry-acidi-34.html

Effects on soil pH

The desirable soil pH is in the range of 6 to 7 (see Box 2). A soil is acidified when soil pH is below 5.5 (pH<5.5). It must be noted that soil acidification can be caused naturally (see APPENDIX III.2) but the most important causes of soil acidification on agricultural land are the application of ammonium-based fertilisers (including slurry) and urea, elemental sulphur fertilisers, and the growth of legumes (Goulding 2016). Acidification causes the loss of base cations via leaching, an increase in aluminium saturation and a decline in crop yields. Severe acidification can cause non-reversible clay mineral dissolution and a reduction in cation exchange capacity, accompanied by structural deterioration.

However, the soils are buffered against acidification (Box 3). Once cation exchange becomes the main buffer, essential nutrient cations such as calcium, potassium and magnesium (Ca^{2+}, K^{+}, Mg^{2+} respectively) are leached, base saturation decreases together with nutrient availability, aluminium (Al^{3+}) saturation increases and crop yields begin to decrease. As a rule of thumb, a change in pH by 1 unit equals 1000 times more Al^{3+} in the soil, an effect that can lead to "root pruning"[2.]. Loide et al. (2019) showed that acidification reduced soil pH by 0.1 units when acidified slurry was applied at a high rate (45 m^3/ha) but no changes could be observed at a small slurry application rate (15 m^3/ha). Soil acidity can be ameliorated by applying lime or other acid-neutralising materials. Liming has no observable effects on soil and reduces nitrous oxide (N_2O) emissions, but this is more than offset by carbon dioxide (CO_2) emissions from the lime as it neutralises acidity (Goulding 2016).

Box 2. Soil pH in the UK.

The pH of agricultural soils is almost always measured in water, although 0.01m calcium chloride is sometimes used for research purposes (e.g., Blake et al., 1999) because it simulates the soil solution better than water. UK agricultural soils usually have a pH in water of between 5 (un-limed mineral soils) and 7.5 (chalky or limestone soils). Peats can have a pH of <4 and, if the mineral soils beneath them contain pyrite and are oxidised when the peat is removed, they can attain a pH of 2. Sodic (sodium saturated soils, e.g., from sea water ingress) can have a pH >8. Because crop plants vary in their tolerance to acidity and plant nutrients have different optimal pH ranges, target soil pH values in the UK are set at 6.5 (5.8 in peaty soils) for cropped land and 6.0 (5.3 in peaty soils) for grassland. An analysis of soil pH in 180 samples from Scotland showed that across the dairy and beef and/or sheep enterprises 63% of the soils were below pH 5.8, 10% were above pH 6.0 and only 27% were within the target range of pH 5.8 to 6.0.

Source: Blake et al., 1999; K. W. T. Goulding 2016. Data from Scotland: Dolan et al., 2019.

Effect of acidified slurry on nitrification in the soil

Nitrification (i.e., microbial transformation of slurry TAN to nitrate) relies strongly on soil properties, namely its buffer capacity Fangueiro et al., 2015); see also APPENDIX III.2.B. Application of acidified slurry delays microbial processes including nitrification and could be used as a measure to minimise nitrate leaching by reducing the amount of TAN transformed to nitrate and leached to water. However, acidification increases the opportunity for desorption and vulnerability of soil nutrients to leaching. Therefore, it is necessary to ensure that the nutrient amounts applied with acidified slurry, in particular easily soluble nitrogen and sulphur, correspond to the needs of the plants.

Box 3. Soils are buffers

Soils are 'buffered' against acidification by a series of chemical processes.

- At 7<pH<8 by the dissolution of carbonates and other basic rocks, i.e., the 'carbonate/bicarbonate' buffer;
- At 5<pH<6 by the replacement of exchangeable base cations [calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}) and sodium (Na^{+})] by H^{+} and aluminium (Al^{3+}), i.e., the cation exchange (CEC) buffer.
- At pH=4 by the dissolution of Al-bearing and manganese minerals, in the presence of manganese-bearing minerals proliferate.
- At pH=3 by the dissolution of iron-bearing minerals.

As a result of this buffering, soil acidification results in periods of constant or slowly decreasing pH while one process buffers inputs, followed by a relatively rapid decrease in pH when that process is exhausted and the next takes over. At pH ranges below 4, significant, non-reversible changes to the soil begin such as clay mineral dissolution and a reduction in cation exchange capacity (CEC), accompanied by structural deterioration. This degree of weathering is reversible over geological timescales and is a serious and costly degradation of soil quality that if not corrected, can extend deep into the subsoil.

Source: Blake *et al*., 1994) Blake *et al*., 1999; K. W. T. Goulding 2016.

Effects of acidified slurry on its fertiliser value, nutrient crop uptake and crop yield

Slurry acidification may have a considerable but variable effect on mineral fertiliser equivalent (MFE). For example, Kai et al. (2008) reported a 43% increase of the MFE with application of acidified slurry, relative to raw slurry, on arable land (winter wheat and spring barley rotation). Sørensen and Eriksen (2009) reported an increase of the MFE in a range of 39-63% for cattle slurry and 74-100% with pig slurry, when acidified slurry was band applied.

A key advantage of using acidified slurry as a substitute for mineral fertiliser is that nitrogen fertilisation is easier to manage with acidified slurry, since its TAN content is more constant relative to non-acidified slurry due to minimal ammonia volatilisation (Kai et al., 2008). Slurry acidification also increases phosphorus (P) availability and prevents P sorption (immobilisation, see APPENDIX III.2) in soil particles by inducing the dissolution of some inorganic phosphates, leading to higher inorganic P concentrations in the soil (Roboredo et al., 2012). Petersen et al. (2013) also reported an increase of P availability in soils amended with acidified slurry, relative to non-acidified slurry. The increased availability of nutrients in soils fertilised with acidified slurry increases yields of winter wheat spring barley and maize (see review by Fangueiro et al., 2015), and ryegrass (Loide et al., 2020). However, depending on crop demand for sulphur, sulphate ions in the soil following application of slurry acidified with sulphuric acid facilitate dissociation of Ca and Mg cations and increase their availability for leaching from the soil (Loide et al., 2020). Therefore, acidified slurry is unsuitable for Ca-poor soils.

The advantages and disadvantages of acidified slurry are also accounted for in Table 1.

3.0 Effects of LESS on gaseous emissions from field-applied slurry

Emissions of ammonia and nitrous oxide following slurry application onto land are affected by many factors related to environmental conditions, slurry composition, slurry pH, and the slurry spreading technique. The two following sections summarise evidence on the effects of these factors on ammonia emissions and nitrous oxide to inform a discussion on the trade-offs between abatement of ammonia and nitrous oxide and protection of water quality (Section 6).

3.1 Factors influencing ammonia emissions

The use of LESS approaches is based on one or both of the following principles (Bittman et al., 2014):

i. Decreasing the surface area where ammonia volatilisation can take place compared with broadcast application. This can be achieved through surface band application by trailing hose and trailing shoe, and by shallow or deep slurry injection.

ii. Decreasing the source strength of the emitting surface, i.e., through lowering the pH (slurry acidification), or reducing ammoniacal nitrogen concentration of the manure by adding water to viscous slurries before application.

The factors influencing ammonia emissions from field-applied slurry are well established in the literature. However, there are qualitative and quantitative inconsistencies in the available studies. For example, field measurements usually have a limited number of replicates. Further, accounting for all possible factors to understand the effects of application technique on ammonia emission is possible via modelling but its robustness depends on data availability and quality (Huijsmans et al., 2018; Pedersen et al., 2021). The measurements made when comparing different ammonia application techniques, differ between studies. This increases variation in the size of the effect of these factors on ammonia emissions and potentially introduces bias in the available evidence.

Examples of variation and bias were evidenced in the international database ALFAM2, which contains measurements related to ammonia emissions from field-applied slurry for 1895 plots from 22 research institutes in 12 countries, including the UK (Haffner et al., 2018). The ALFAM2 database contains concrete examples of variation, such as the wide variation in soil bulk density and pH values from different plots and institutes, and bias, such as the avoidance of rain during field trials, which could limit the understanding of rain effects on ammonia emissions from field-applied slurry.

The evidence on the effect of weather conditions (i.e., air temperature and humidity, rain, and wind speed), soil properties, slurry properties, slurry pH and land use (crop type and crop growth stage) is detailed in Appendix IV and is outlined in Box 4.

Due to interactions between the factors in Box 4 and with application technique (see APPENDIX IV), it is challenging to determine the effects of each technique on ammonia emissions in isolation from other factors. For example, there is evidence that the effect of application technique on ammonia emissions is influenced by land use (Table 2). The range of emission values is wide because the relationship between application technique and land use depends on other factors such as air temperature and soil properties, and slurry dry matter content, which differed between the studies included in Table 2. In addition to these factors, the studies included in Table 2 used different times of slurry spreading, and spreading took place at different plant growth stages. Despite these discrepancies, it can be observed that reductions in ammonia emissions can be greater with the use of trailing shoe (TS), injection (SI) and slurry acidification (SA) than with trailing hose (TH), presumably because TS, SI, and SA reduce ammonia volatilisation and facilitate slurry infiltration into the soil (see APPENDIX IV). Based on Table 2 the most effective LESS approaches in terms of abatement of ammonia emissions compared to broadcasting are the close slot shallow or deep injection and broadcast application of acidified slurry.

To sum up, the amount and rate of ammonia emissions following slurry spreading depends on a range of slurry composition (e.g., pH, TAN, dry matter), spreading (e.g., application rate, method and timing), soil (e.g., moisture content, texture) and environmental (e.g., temperature, wind speed, rainfall) factors.

Box 4. Environmental and slurry related factors influencing ammonia emissions

Ammonia emissions from slurry applied on field surface increase with:

- air temperature and wind speed
- soil humidity
- slurry dry matter concentration (%)
- compacted and impermeable soils
- slurry application rate
- TAN in applied slurry
- slurry pH

Source: Bussink et al. 1994; Misselbrook et al., 2005; Bittman et al., 2014; Haffner et al., 2018; Huijsmans et al., 2018; Fangueiro et al., 2015; Nicholson et al., 2013; See also APPENDIX IV.

Table 2. Indicative reductions in ammonia emissions with LESS technology compared to broadcast application (splash plate - SP) for grassland and arable land; sea also APPENDIX IV. *compared to SP. **compared to untreated slurry. The range is the range of the means reported in each paper considered.

Application method	Land use	Ammonia emission (TAN% applied)	Reference
Splash Plate (SP)	Grassland	28-52.5	Churchill et al., 2021
Arable		20.9-38.8	Churchill et al., 2021
Application method	**Land use**	**Ammonia reduction (TAN% applied) compared to SP**	**Reference**
Trailing hose	Grassland	0-74*	Smith et al., 2000; Webb et al., 2010; Hani et al., 2016
Trailing hose	Arable	0-75*	Smith et al., 2000; Misselbrook et al., 2004; Webb et al., 2010
Trailing shoe	Grassland	40-70*	Misselbrook et al., 2002; Webb et al., 2010
Trailing shoe	Arable	38-90*	Misselbrook et al., 2002; Webb et al., 2010;Hani et al., 2016
Open slot injection	Grassland	20-80*	Dell 2011
Closed slot injection	Grassland	50-97*	Smith et al., 2000; Misselbrook et al., 2002; Dell 2011
Closed slot injection	Arable	23-94*	Smith et al., 2000; Misselbrook et al., 2002
Deep injection	Arable	95-99*	Webb et al., 2010
Slurry acidification		40-80 with pig slurry (different acids)*	Kai et al., 2008; Fangueiro et al., 2015
Slurry acidification		15-85 with cattle slurry (different acids)**	Bussnik et al., 1994; Biocover A/S, 2012 (cited in Fangueiro et al., 2015); Nyord et al., 2013
Slurry acidification		65-88 (lactic acid, pH:5.7-4.2)**	Berg et al., 2006
Slurry acidification		29-71 (nitric acid, pH:5.7-4.2**	Berg et al., 2006

3.2 Factors influencing nitrous oxide emissions to air

Fertilised soils are a key source of nitrous oxide when soil microbes use the ammoniacal nitrogen added with slurry and transform it to nitrate (nitrification) and then to nitrous oxide and di-nitrogen (denitrification) before the crop is able to absorb it (APPENDIX III. 1.2). For this reason, it is important to add slurry at a time and amount to meet crop demand. There are large differences between studies reporting emissions of nitrous oxide from slurry fertilised soils. These differences are probably related to differences in soil aeration, nitrogen concentrations in the soil before slurry amendment, and soil depth, which determines the length of the diffusion path of nitrous oxide towards the atmosphere (Velthof et al., 2003). Soil aeration, which depends directly on soil water, is a key parameter for the nitrification and denitrification process (Sahrawat, 2008). Precipitation indirectly regulates these processes and the transformations between the different nitrogen forms; see also APPENDIX III.1.2.

The variability in the effects of soil processes on nitrous oxide production further complicates the study and understanding of the effect of LESS approaches on nitrous oxide emissions.

- Some studies indicate no clear or no effect of application technique on nitrous oxide emission or the rate of denitrification following slurry application to soil (Dendooven et al., 1998; Sommer et al., 1996; Velthof et al., 2003; Weslien et al., 1998).
- A UK study of nitrous oxide emission factors (EF=% Total Nitrogen-TN applied) estimated that reduction of bandspread slurry on arable land was associated with a reduction of nitrous oxide emissions by 20-23% in autumn with 122-100 kg TN ha^{-1} applied and an increase by 30-85% in spring compared to broadcasting with 90-98 kg TN ha^{-1} applied (Thorman et al., 2016). The same study reported nitrous oxide emissions for grassland: a reduction of nitrous oxide emissions by 14-45% in autumn with 24-71 kg TN ha^{-1} applied and an increase by 8-171% in spring compared to broadcasting with 67--77 kg TN ha^{-1} applied. This suggests a "pollution swapping" effect of bandspreading (trailing hose).
- There is also evidence that injection of slurry enhances nitrous oxide emission and denitrification compared to broadcast application. For example, Thomsen et al. (2010) found higher nitrous oxide emission from injected slurry than from surface-applied slurry in a relatively warm and dry year, but there were no differences in a relatively wet year. Velthof and Mosquera (2011) concluded that on both grassland and maize land shallow injection of slurry increased the average emission factor of nitrous oxide in comparison to surface application. This suggests a "pollution swapping" effect of close-slot injection.

Application of acidified slurry can also influence nitrous oxide emissions. Velthof and Oenema (1993) concluded that acidification of slurry with HNO_3 (nitric acid) led to higher nitrous oxide emissions, but they attributed this to the addition of nitrate via the acid rather than to a soil pH change. They also stressed the importance of the acidification time: when acidification was performed immediately before soil application, slurry pH (6 or 4.5) had no effect on nitrous oxide emissions, but when acidified one week prior to soil application, higher nitrous oxide emissions were observed from slurry acidified to pH 6 rather than pH 4.5. Fangueiro et al. (2010) observed lower nitrous oxide emissions from a sandy soil amended with acidified pig slurry compared to non-acidified slurry in the first 47 days of incubation but higher emissions after that period. The authors also reported that the start of the nitrous oxide emissions was delayed for the acidified slurry. This which was explained as result of the delay by acidification in the microbial processes leading to the production of nitrous oxide in the soil, i.e., the transformation of slurry ammonium to nitrate (nitrification) and consequently transformation of nitrate to nitrous oxide and di-nitrogen (denitrification).

To sum up, predictions that conserving slurry nitrogen by reducing ammonia losses by band spreading and injection would increase the soil mineral nitrogen pool and hence subsequent nitrous oxide emissions (Webb et al., 2010) are not always confirmed by field measurements. The "pollution swapping" effect of band spreading (trailing hose) and injection are season-and soil wetness-dependent (Thorman et al., 2016; Thomsen et al., 2010; Velthof and Mosquera 2011). Even in different years of the same study, band spreading and slurry injection could increase, decrease, or have no effect on nitrous oxide emissions compared to surface broadcasting. The implication of this finding is that the soil and environmental conditions giving rise to nitrous oxide production and emission (e.g.warm and wet soils) can be more important than application method in controlling nitrous oxide emissions (Chadwick et al., 2011).

4.0 Factors influencing impacts of LESS approaches on water quality

This section summarises evidence on the effect of LESS on runoff and leaching of nitrogen, phosphorus and FIO following slurry application. Most studies dealing with slurry spreading techniques have focussed on gaseous emissions and agronomic issues and much less importance has been given to losses of slurry-borne contaminants to water. Field-applied slurry by broadcasting is a source of diffuse water pollution via runoff and leaching to receiving waterbodies (e.g streams and groundwater) (Lintern et al., 2018; Hodgson et al., 2016). Adherence to regulations on the timing of slurry application (e.g., APPENDIX II for Scotland) has the potential to reduce the risk of losses to water. However, the relationship between implementation of the regulations for slurry spreading onto soil surface and water quality is inconsistent, with many review studies suggesting that there are long lag times between the installation of diffuse pollution control measures and improvements in water quality (Meals et al., 2010; Lintern et al., 2018; Akoumianaki 2021).

A varying combination of microbial, chemical, geological and hydrological processes influence the delivery (also known as mobilisation) of slurry-borne contaminants to water. The key factors determining the risk for water quality from slurry application regardless of application method is determined by the factors summarised below (this is detailed in APPENDIX III.2).

- **Type of contaminant.** This determines the contaminant's delivery path to water (runoff or leaching) and retention (immobilisation) in the soil at different degrees of water saturation and pH levels. For example, nitrate and soluble reactive phosphorus (SRP) are delivered via leaching or sub-surface runoff. Ammonium, sorbed (particulate) phosphorus, and FIO are predominantly delivered via runoff, if found on soil surface, or are retained in the soil matrix until soil conditions enable their transport, fast or slow, in subsurface runoff or leaching.
- **Precipitation regime/Weather.** This determines the intensity and frequency of rainfall, and influences soil drainage and soil oxygen concentration. For example, the greatest losses of slurry-borne contaminants occur when slurry is applied during rainy weather, with losses in runoff been greater from poorly, water saturated than freely drained soils, and from bare than vegetated fields. Leaching is enhanced in freely-drained soils.
- **Soil drainage.** This determines the dominant hydrological path for the delivery of slurry-borne and soil contaminants to water, such as runoff and leaching through vertical and horizontal soil macropores (fast pathways) or soil matrix (slow pathways). The relationship between leaching and soil drainage is inconsistent.
- **Soil oxygen concentration.** Continuous precipitation can result in poor drainage and excess soil water, which limits soil oxygen concentration. In drier soils nitrification may be high due to high aeration (oxygen) whereas denitrification and plant uptake of nitrogen can be lower than during cool and wet years, thus enhancing the potential for loss before crop uptake of nitrogen.
- **Soil texture and structure.** These determine soil's capacity to retain water and organic matter, in turn being the key determinants of soil aeration and regulating microbial transformations, e.g., nitrification and denitrification (see Precipitation regime) and soil drainage (see Soil drainage).
- **Soil pH.** This determines the dynamics of sorption/desorption of nutrients. A low soil pH (below 6) facilitates leaching of nutrients such as sulphur, calcium, and phosphorus from soil particles, as well as, potentially temporarily inhibiting microbial processes (see Section 2.2).
- **Slurry dry matter and nutrient content.** This determines degree of infiltration of slurry into the soil and its fertiliser value and therefore crop uptake, excess of nutrients in the soil and vulnerability of nutrients to microbial (e.g., nitrification) and biogeochemical transformations (de-sorption in low pH conditions). Acidified separated slurry is associated with a higher risk of leaching. However, it is well established that slurry should be added at a time and amount that meets crop nutrient demand to minimise loss of its fertiliser value and losses of slurry-borne contaminants.
- **Vegetation.** This includes factors such as crop growth stage, presence of stubble and implementation of diffuse pollution control measures such as vegetative filter strips downslope of fertilised fields. Vegetation delays runoff and helps to filter contaminants out of runoff, thus reducing risk of losses in runoff.
- **Slurry origin- Liquid separation.** Very few studies have explored the effect of different slurries in comparative experimental design, therefore a conclusion on its importance has not been reached. But if the digestate or slurry following liquid separation contains a soluble form of nitrogen such as nitrate then it can be associated with increased risk of leaching.

A model simulation of the distribution and transport of slurry-borne contaminants from the injection slot gives an integrated consideration of the combined effect of these factors (Amin et al., 2014). This simulation suggested that dissolved organic carbon retained in slurry can facilitate the transport of contaminants, with FIO and estrogens being vulnerable to leaching from the very first precipitation event after the slurry application, whereas nitrate started to leach as soon (more than a week) as it was transformed from TAN to nitrate (Amin et al., 2014). The simulation predicted that slurry-borne contaminants persisted for up to 4–6 months in the soil. These contaminants leached continually during this period at varying rates depending on their chemical behaviour (sorbed onto soil particles or soluble), the intensity and frequency of rainfall, and, in the case of FIO and estrogens, on their die-off and degradation, respectively.

It is also interesting to note that loss to water is one of the many possible fates for nutrients (if added in excess of crop demand, away from the root, or at inappropriate timing) and FIO in slurry fertilised soils. For example, dissolved nitrate and soluble reactive phosphorus (SRP) movement through the soil matrix can be slow and gradual and favour further biogeochemical transformations such as retention in the soil (see APPENDIX III.2). Under anaerobic conditions, nitrate-nitrogen can be lost to air via denitrification instead of leaching below the water table to contaminate groundwater (Vero et al, 2018). Soluble phosphorus (SRP) can be precipitated into clay minerals or adsorbed onto the soil matrix (Rittenburg et al., 2015) instead of leaching out of the soil. FIO can be adsorbed onto soil particles and be retained in the soil (Kay et al., 2012). Immobilised forms of nutrients (such as organic forms) and FIO can accumulate in the soil and be delivered into the water environment independent of slurry application at a much later time. This makes it difficult to study the effects of field-applied slurry on water quality and understand the effects of implementing LESS approaches on water quality, and requires long-term field measurements following slurry application.

The overall evidence reviewed in APPENDIX V on the effect of LESS approaches on the delivery potential of soil and slurry-borne contaminants to water can be summarised as follows:

- The effect of **band spreading (trailing hose) of non-acidified slurry on losses in runoff** is poorly studied. No significant differences have been reported for phosphorus (total phosphorus-TP and SRP) losses in runoff between band spreading and broadcasting or injection.
- The effect of **band spreading of non-acidified slurry on leaching** is also poorly studied. Available evidence shows no effect on nitrate leaching compared to broadcasting.
- The effect of **band spreading of acidified slurry on nitrate leaching** is poorly studied and has been compared only against injection. The available evidence shows that 42% of the nitrogen applied in sandy soils and 24% of the nitrogen applied in sandy loamy soils can be lost via leaching.
- The effect of **trailing shoe** on losses from fertilised soils to water has been poorly studied and only for phosphorus losses in runoff. The technique can reduce losses of SRP and TP in runoff compared to broadcasting and injection. However, grown crop is equally effective as trailing shoe in reducing phosphorus losses in runoff from field-applied slurry. Further, when slurry is applied onto wet soils, the trailing shoe can effectively reduce losses of phosphorus in runoff (by 41%) compared to broadcasting because wet soils enhance the potential for assimilation of slurry phosphorus into soil particles. This suggests the use of trailing-shoe during winter and early spring as a mitigation measure to minimise the risk of phosphorus loss in runoff during this period.
- The effect of **closed-slot injection on losses of nitrogen and phosphorus in runoff** has received little attention. Injection is effective in reducing losses of nitrate and TAN in runoff compared to broadcasting but the effect may be lower than that of a 10m vegetated buffer strip downstream from the slurry fertilised field in clay soils of grass ley.
- **Injection is effective in reducing losses of SRP and TP in runoff** compared to broadcasting but the composition of losses varies with soil moisture of the amended soils. For example, dry soils tend to lose phosphorus bound to soil particles near soil surface in runoff whereas wet soils tend to lose a high percentage of SRP, which is readily available and potentially poses a greater risk to surface waterbody status.
- **Injection into the soil is effective in reducing FIO in runoff** following slurry application compared to broadcast application. It can also reduce the risk of ‘incidental’ rapid losses of FIOs in runoff following heavy rainfall because the slurry is better protected from detachment mechanisms such as raindrop impact on the soil surface. However, FIO die-off is faster after broadcast application and runoff may still be FIO-contaminated following injection.
- The effect of **closed-slot injection on losses of nitrate via leaching** has been studied extensively. Injection may increase, reduce, or have no effect on

Table 3. Comparative summary of the effect of LESS approaches on lossess of slurry borne contaminants to water. Blank cells (grey) indicate lack of evidence. ↗: increased losses to water relative to broadcast spreading; ↘ : Reduced losses relative to broadcast spreading; ↔: no significant or variable effect on losses relative to broadcast spreading. References as in APPENDIX V.

Delivery path to water	Slurry borne contaminant	Trailing hose (TH)	Trailing shoe (TS)	Injection (SI)	Acidification (surface)	Separation + Acidification (surface)	Slurry Separation (surface)
Leaching	Nitrate	↔		↗	↔	↗	↗
Leaching	SRP						
Leaching	Total phosphorus			↗	↔	↗	↔
Leaching	Ammonium			↔	↗	↗	↗
Leaching	Organic Nitrogen			↔	↔	↗	↗
Leaching	FIO			↗	↗	↗	↗
Runoff	Total phosphorus	↔	↘				
Runoff	SRP	↔	↘				
Runoff	nitrate			↘			
Runoff	ammonium			↘			
Runoff	FIO			↘			

nitrate leaching compared to broadcast application, depending on rainfall, soil moisture, crop demand at the time application, and soil texture. For example, it has been suggested that rapid flow through soil macropores is obstructed by injection tines especially when used at high soil moisture conditions.

- The effect of **slurry acidification on losses of nitrate, phosphorus and FIO** has been mainly studied in the laboratory and is influenced by slurry separation. The potential of leaching increases for all slurry-borne contaminants following broadcast application of acidified separated slurry. **Band spreading of acidified slurry** may be an effective alternative option.

The findings of the QSR are summarised in Table 3.

Table 3 also gives an account of the availability of evidence. As shown, the effect of different LESS on losses of nitrate to water has received more attention than other contaminants such as phosphorus and FIO.

5.0 Cost of LESS for farmers and society

This section reviews evidence on the cost of LESS related to savings from reducing ammonia losses and impacts on biodiversity (abatement efficiency) and equipment costs related to upgrading from splash plate to LESS.

The overall cost-benefit ratio of LESS depends on the ratio between equipment cost and abatement efficiency. Table 4 summarises the factors determining the cost:benefit ratio of LESS. The table also refers to co-benefits of a low cost-benefit ratio, such as protection of biodiversity and reduction of odour and nuisance, and increased palatability of herbage, uniformity of application and consistency of crop response to manure. Some of these benefits are difficult to quantify but are reported here to inform recommendations for further action. The table also accounts for factors that are indirectly related to cost for farmers, including farm size, slurry nutrient content (i.e., chemical fertiliser replacement value), chemical fertiliser prices, slurry availability and slurry transport cost.

Cost of impacts on biodiversity. A recent review of the evidence on the impact of ammonia on UK biodiversity found that bog and peatland habitats, as well as grasslands, heathlands, and forests, and the animal species depending on these systems, are vulnerable to ammonia deposition (Guthrie et al., 2018). For some widespread rain-fed ecosystems in upland UK, dry deposited ammonia has been shown to be much more damaging per unit nitrogen deposited than wet deposited nitrate and ammonium (Shepherd et al., 2011). However, much of the wider evidence on biodiversity impacts relates to all nitrogen pollution of both terrestrial and aquatic ecosystems, rather than just ammonia deposition on terrestrial habitats. Wet deposition of particulate ammonium in water systems causes eutrophication i.e., excess nutrient supply leading to algae proliferation and oxygen depletion or predominance of toxic algae. Conservative estimates for the costs of the impact of ammonia emissions on UK biodiversity are likely to be in the range £0.2–£4 per kg of ammonia emitted (Guthrie et al. 2018).

Table 4. Summary of the factors determining the cost:benefit ratio of LESS approaches. Source: Bittmann et al., 2014; Tamm et al., 2015.

Equipment costs	Ammonia abatement efficiency	Co-benefits	Indirect factors
• Purchase/ Return on investments • Tractor costs/ labour • Operation • Maintenance • Performance • Housing costs • Other: insurance, fuel, lubricant • Depreciation of investments costs of the applicator	• N in animal feed • Slurry additives • Slurry storage • Slurry acidification • Precision • Meeting crop needs • Reducing losses to water • Reducing mineral fertiliser use	• Biodiversity protection • Public health protection • Palatability of herbage • Uniformity of application-consistency of crop response • Nuisance reduction	• Economies of scale • Farm size • Sharing • Availability of contractors • Slurry N, P, K content • Fertiliser price, • Slurry availability • Transport cost • Slurry "thickness"

Public health cost. A recent study (Giannakis et al., 2019), estimated that the economic benefit from prevention of premature deaths over Europe amounts to 14,837 M€/ year. The analysis indicated that the costs of compliance by the agricultural sector with the commitments of the European air quality regulations are much lower than the economic benefit. The study suggested that the monetisation of the health benefits of ammonia emission abatement policies and the assessment of the implementation costs can help policy-makers devise effective air pollution control programmes. However, the study focused on abatement options related to slurry storage and urea fertiliser application. It is reported here to inform recommendations for further action.

Cost of TAN saved from reducing ammonia emissions. This mainly refers to a nitrogen management that aims to decrease nitrogen losses to air and water. Nitrogen management is based on the premise that decreasing the nitrogen surplus (N-surplus) and increasing N-use efficiency (NUE) contribute to the abatement of ammonia emissions (Bittman et al., 2014). This assumes that slurry is as valuable as the chemical fertiliser it can replace. Nitrogen management also aims to identify and prevent pollution swapping between different N compounds and environmental compartments. Establishing an N input-output balance at the farm level is a prerequisite for optimising N-management in an integral way. Table 5 presents ranges of costs related to slurry TAN content: the higher the TAN content, the lower the abatement cost. Mean costs are likely in the lower half of the range, especially when application is done by contractors, on large farms or with shared equipment.

Capital cost. A thorough review and cost-benefit analysis of the transition to LESS approaches could not be undertaken during this project due to logistic constraints. Evidence on the capital (i.e., machinery) cost is presented to inform a discussion on the feasibility of the transition to LESS. Evidence from Tamm et al. (2019) and the Scottish Government's sustainable agriculture capital grant scheme (SACGS 2021) is presented in Table 5, which compares this evidence with cost per TAN saved by reducing ammonia emissions. It must be noted that a thorough cost-benefit analysis in relation to mitigation of slurry-borne contaminants to water is outwith the scope of this QSR.

Table 5. Comparative presentation of literature-based evidence on the cost of ammonia abatement. It must be noted that a thorough cost-benefit analysis in relation to mitigation of slurry-borne contaminants to water is outwith the scope of this QSR. Sources:

Application technique	Cost (£) per kg TAN saved[1]	SACGS standard cost (£)[2]
Broadcast		
Trailing hose	-0.6 – 1.8	11,500
Trailing shoe	-0.6 – 1.8	18,165
Injection	-0.6 – 1.8	24,666.67
Acidification	-0.6 – 1.20	

1. All costing data from Bittman et al. (2014) converted to sterling and 2018 prices. Note that some interventions might result in benefits – e.g., through increased crop yields or lower fertiliser costs – once upfront costs are overcome (hence negative values within some ranges). Savings are relative to broadcast application.

2. SACGS 2021. These prices may need adjustment.

6.0 Implications

6.1 Pollution swapping

Clearly, when comparing broadcast slurry application to LESS approaches the main differences are related to ease of use, production of odour and nuisance, capital cost, and ammonia emissions. Broadcast application is easier and considerably less costly with regard to equipment compared to LESS approaches without contributing to nitrous oxide emissions to the atmosphere. However, it is associated with high ammonia emissions and a high risk of loss of slurry-borne contaminants to water in runoff and via leaching, if applied immediately before or during rain on bare land in areas with permeable soils and sloped terrain without vegetated filter strips.

Ammonia emissions negatively affect humans, ecosystems and biodiversity, and injection is the most effective approach to reducing ammonia emissions. Nevertheless, while after surface application (with splash plate, trailing hose or trailing shoe), volatilisation is the main nitrogen loss process, leaching becomes the prevalent process when the slurry is injected. On the other hand, application of untreated slurry by trailing hose or trailing shoe, and broadcast or band (trailing hose) application of acidified slurry seem to reduce both runoff and leaching of nitrate, phosphorus and potentially FIO. Regarding emissions from direct and indirect nitrous oxide production, surface application with splash plate, trailing hose or trailing shoe are the best application methods for reducing nitrous oxide, particularly if the soil is very permeable and well oxygenated as in sandy sediments. This nitrogen swapping makes the selection of the best slurry application method difficult.

6.2 Ammonia mitigation through pollution reduction synergies

Reducing the potential for pollution swapping requires implementation of LESS approaches in the context of "win-win" strategies (Bittman et al., 2014). This translates to implementing LESS approaches with a view to reducing odour, ammonia and nitrous oxide emissions, and crop contamination risk while increasing crop yield and benefits for farmers and the water environment.

A win-win ammonia abatement strategy should:

- Reduce odour
- Prevent nitrous oxide emissions
- Reduce crop contamination risk
- Increase nitrogen and phosphorus crop use efficiency and slurry fertiliser value, which reduces mineral fertiliser cost and replacement requirements
- Reduce the risk of excess application of nutrients and subsequent loss in runoff and leaching
- Increase agronomic flexibility for slurry application, such as enabling application on growing arable crop (e.g., cereals), windy or damp weather
- Increase harvest output and, thereby, financial benefits for farmers

The evidence reviewed in this QSR allows for an assessment of LESS approaches in the context of win-win ammonia abatement strategies. This assessment is summarised in Table 6.

As shown in Table 6 (see also Table 4), it is important to consider the extent of the interactions between abatement options and their impacts on the environment. Limiting assessment to a single pollutant, i.e., nitrogen, may lead to a biased guidance decision. For example, nitrate leaching may be associated by minimal loss of phosphorus or FIO. Given the extent of interactions between multiple pollutants, any one-dimensional policy initiatives might prove to be suboptimal. From a broader point of view, all LESS approaches are promising abatement options, reducing not only ammonia emissions but also nitrous oxide and odour and losses in runoff and, potentially, via leaching when averaged over broadcasting. Further research is needed to understand how to avoid leaching and action to raise awareness about suitable application methods.

6.3 Knowledge gaps

The review showed that the effectiveness of LESS approaches to reduce impacts to the environment was much less studied for losses to water than for losses to air. The major knowledge gaps are related to:

- Phosphorus losses to water. Need for field studies to understand the effect of different LESS on phosphorus losses in runoff and leaching, ideally accounting for the effect of rain, soil properties, including soil moisture soil pH, crop type, crop growth stage and the implementation of control diffuse pollution measures downstream of slurry fertilised soils (e.g., vegetated buffer strips) so that an all-encompassing comparison of different options can be made.
- The implications of acidification and slurry separation for farmers and water quality.
- The effect of liquid digestate use on other slurry-borne contaminants such as VMPs.
- Cost-benefit analysis. Economic analysis of the transition to LESS that accounts for the integrated benefits to air quality, mitigation of GhG emissions odour and nuisance, water quality, agronomic considerations and public health in the Scottish context.

Table 6. Assessments of the additional direct and indirect benefits of LESS approaches. Blank cells indicate lack of evidence. ↗: increase relative to broadcast spreading; ↘: Reduction relative to broadcast spreading; ↔: no significant or variable effect relative to broadcast spreading. WQ: water quality.

Effect		Broadcast (SP)	Trailing hose (TH)	Trailing shoe (TS)	Injection (SI)	Acidification (surface)
Ammonia emissions		↔	↘	↘	↘	↘
Nitrous oxide emissions		↔			↗	↘
Odour		↔	↘	↘	↘	↘
Runoff N/P/FIO		↔	↔	↘	↘	↔
Leaching N/P/FIO		↔	↔		↗	↗
Crop contamination risk		↔	↘	↘	↘	
Nutrient use efficiency		↔	↗	↗	↗	↗
Risk of excess application		↔			↘	↘
Agronomic flexibility	Application on growing arable crop	↔		↗	↘	
	Windy or damp weather	↔	↗	↗	↗	
Cost per TAN saved		↔	↔	↔	↔	
Capital cost for farmer		↔	↗	↗↗	↗↗↗	?
Cost of biodiversity		↔	↘	↘	↘	↘
Strengths		FIO die off	Ammonia abatement Less strong odour GhG mitigation Low crop contamination Nutrient use Agronomic flexibility Biodiversity Lower cost than TS/SI	Phosphorus mitigation Less strong odour Ammonia abatement GhG mitigation Low crop contamination Nutrient use Agronomic flexibility Biodiversity Lower cost than SI	Ammonia abatement No odour Runoff losses mitigation Low crop contamination Nutrient use Agronomic flexibility Biodiversity	Ammonia abatement Less strong odour GhG mitigation Nutrient use Biodiversity
Weaknesses			Poor evidence on WQ effects	Poor evidence on WQ effects	High leaching risk Unclear effect on GhG High cost High fuel consumption Practical limitations	High leaching risk Unclear feasibility CO_2 emissions (liming) Few field studies

6.4 Key considerations for guidance to farmers

This QSR showed that the key factors influencing the impact of LESS approaches on losses of slurry-borne pollutants to water are: precipitation, soil moisture, soil permeability and drainage, and presence of vegetation, be it crop, grass or vegetated buffer strips. The role of these factors has already been captured in the current regulatory framework, stipulating specific obligations for farmers under GBR18 and The Action Programme for Nitrate Vulnerable Zones (Scotland) Regulations 2008 (see APPENDIX II). The already existing guidance is still valid to protect water quality. However, the choice of LESS approach as best practice should depend on environmental designations and account for the most vulnerable environmental component (soil/atmosphere/waterbodies) of the agro-ecosystem. Guidance to farmers should also consider a compromise between feasibility, cost, and environmental and agronomic objectives.

6.5 Recommendations for further research

The review revealed considerable research and evidence gaps. There is a need to:

- Design and conduct field experiments to understand the effect of different techniques on nitrate leaching, and phosphorus losses in runoff and leaching, ideally accounting for the effect of rain, soil properties, including soil moisture soil pH, crop type, crop growth stage and the implementation of control diffuse pollution measures downstream of slurry fertilised soils (e.g., vegetated buffer strips).
- Conduct integrated studies to understand trade-offs between different pathways of losses for slurry-borne contaminants such as phosphorus and FIO.
- Conduct field experiments to understand the agronomic and water quality trade-offs of acidified and separated slurry.
- Conduct feasibility studies to understand the factors enabling the uptake of LESS.
- Conduct a cost-benefit analysis of the transition to LESS that accounts for the integrated benefits to air quality, GhG emissions, water quality, odour and nuisance and crop yield in the Scottish context and availability of digestate and slurry.

7.0 Conclusion

Recent research on the effect of low-emission equipment for spreading slurry (acidified or non-acidified/ whole or separated), which are collectively reported here as LESS approaches, has provided a better understanding of the agronomic considerations and processes occurring in fields after spreading onto arable land and grassland.

Current findings suggest that:

- The implementation of LESS approaches can play a critical role in reducing ammonia emissions from field-applied slurry, with the greatest abatement efficiencies reported for slurry injection (up to 99%) and surface application of acidified slurry (up to 85%). However, their role in reducing losses of slurry-borne contaminants to water is not well understood.
- The effect of LESS approaches such as trailing shoe and acidification on runoff and leaching of slurry-borne contaminants is poorly studied compared to the effects of injection or the effects of LESS on ammonia and nitrous oxide emissions. Many studies examined LESS effects in the laboratory and in the context of different factors, therefore it is difficult to draw comparisons and conclusions based on available evidence.
- Slurry injection has agronomic and environmental benefits, including: (i) drastic reduction in odour and nuisance; (ii) minimal crop contamination risk (in open-slot injection) and potential for application before seeding or during growing season, reducing the need for further chemical fertiliser (in closed-slot-injection); and (iii) reduced losses of slurry-borne contaminants in runoff.
- Slurry injection has considerable practical and environmental limitations, such as: (i) high risk of damaging roots of growing plants, being suitable only for bare arable land, on fields with wide-row crops and on even ground, (ii) high fuel demand, low working rate and high capital cost; and (iii) increased potential for pollution swapping via nitrous oxide emissions, nitrate and phosphorus leaching and FIO survival, varying with soil moisture and soil retention capacity for different slurry borne contaminants and soil types.

- Band Spreading (trailing hose) and trailing shoe application of non-acidified slurry may provide a cost-effective alternative to injection that reduces the potential of pollution swapping. However, their effects on the loss of nitrogen, phosphorus and FIO in runoff and leaching have been poorly studied.
- Application of acidified slurry has additional benefits for air quality, i.e., no odour and low risk of nitrous oxide emissions, and agronomic practice, e.g., it is associated with better slurry fertiliser value and higher crop yield compared to non-acidified slurry.
- The main problem associated with slurry acidification is the higher potential for nitrogen, phosphorus and FIO leaching and survival in the soil.
- A clearer understanding of the effect of injection and application of acidified slurry on pollution swapping can support context specific guidance to farmers.

This QSR showed that the key factors influencing the impact of LESS approaches on losses of slurry-borne pollutants to water are: precipitation, soil moisture, soil permeability and drainage, and presence of vegetation, be it crop, grass or vegetated buffer strips. The role of these factors has already been captured in the current regulatory framework, stipulating specific obligations for farmers under GBR18 and The Action Programme for Nitrate Vulnerable Zones (Scotland) Regulations 2008. The already existing guidance is still valid to protect water quality. However, the choice of LESS approach should be determined by environmental designations (e.g. bathing waters, shellfish waters and NATURA sites). It should also account for the most vulnerable environmental component (e.g. soil, atmosphere, or waterbodies) of the agro-ecosystem. Guidance to farmers should also consider a compromise between feasibility, cost, and environmental and agronomic objectives.

The review revealed considerable research and evidence gaps. There is a need to:

- Conduct integrated studies to understand trade-offs between different pathways of losses for slurry-borne contaminants such as phosphorus and FIO.
- Design and conduct field experiments to understand the effect of different techniques on nitrate leaching, and phosphorus losses in runoff and leaching, ideally accounting for the effect of rain, soil properties, including soil moisture soil pH, crop type, crop growth stage and the implementation of control diffuse pollution measures downstream of slurry fertilised soils (e.g., vegetated buffer strips).
- Conduct field experiments to understand the agronomic and water quality trade-offs of acidified and separated slurry.
- Conduct feasibility studies to understand the factors enabling the uptake of LESS.
- Conduct a cost-benefit analysis of the transition to LESS that accounts for the integrated benefits to air quality, GhG emissions, water quality, odour and nuisance and crop yield in the Scottish context and availability of digestate and slurry.

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