CENTRE OF EXPERTISE FOR WATERS

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

Appendices

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APPENDIX

Appendix I. Quick Scoping Review methodology

This Quick Scoping Review (QSA) aimed to compile and describe available evidence on the impact of low emission slurry spreading (LESS) approaches for delivering an improved water environment (focussing on nitrate, phosphate, faecal indicator organisms, pathogenic microorganisms and veterinary medicine products as components of water pollution), to establish a general consensus on the strengths and weaknesses of this intervention for water quality, to identify potential gaps in current knowledge and understand the implications for policy and farmers.

I.1. Formulating the question

Primary question

This study aimed to address the following question:

What impact does the application of LESS approaches have on leaching of nitrate, phosphate, Faecal Indicator Organisms (FIO), pathogens and Veterinary Medicine Product (VMP)?

Secondary questions

- What factors determine pollutant losses to water following application of LESS approaches?
- What are the capital costs of different LESS approaches?

This is an impact question designed specifically to assess the effectiveness of LESS approaches as a policy driven intervention method, on the selected components of water pollution. This question can be broken down into its Population-Intervention-Comparison-Outcome (PICO) components:

This question can be broken down into its PICO components:

Primary outcomes measured were:

Nitrate, phosphate, and bacterial pathogens as components of water pollution.

Secondary outcomes were:

- Factors influencing impacts on water quality components
- Cost of the intervention

PICO element and definition	PICO element within this QSR -Primary Question	PICO element within this QSR -Secondary Question
Population – the subject to which the intervention is applied	Water pollutants (nitrate, ammonia, phosphates, FIO, pathogens, and VMT	
Intervention – the policy or related intervention/ exposure such as management regime	Application of LESS approaches Dribble bar, band application, trailing shoe, trailing hose, shallow injection, deep injection	
Comparator – control example of no intervention or alternative	Broadcast application, Or Absence of slurry application	
Outcome	Impact on water quality	• The factors influencing the impact on water quality • Cost of the intervention

I.2 The QSR Methodology

The method used in the development of the QSR was based on the guidance for the production of Quick Scoping Reviews and Rapid Evidence Assessments produced by Collins et al. 2014.

Searches

The search strategy was designed to identify both scholarly and grey literature and deliver an unbiased sample of the evidence base. An initial scoping search was performed to test for specificity and sensitivity using the online database Web of Knowledge. The results of the scoping search were used to inform the final search strategy.

Wildcards (*) were used, where accepted by a database/search engine, to pick up multiple word endings. For example, 'nitr*' would pick up nitrogen, nitrate, and nitrous oxide; 'leach' would pick leachate and leaching. Keywords were made more restrictive by the addition of a qualifier, or multiple qualifiers e.g. (slurry AND spreading AND "trailing shoe" AND nitr** AND leach* AND water quality). The combination of qualifiers and keywords varied for each outcome studied based on the results of the scoping search. The exact keyword and qualifier combinations used are listed in Table 1.

The following online sources were searched to identify relevant literature:

- ISI Web of Knowledge
- Google Scholar
- Google

Organisational websites:

- Defra online databases
- Environment Agency
- Natural Environment Research Council Open Research Archive
- Centre for Ecology and Hydrology
- Scottish Environment Protection Agency

All searches were conducted in the English language. The results of each search term on each database were imported into a separate EndNote X9 library file. Once the searching process was complete, all the database libraries were incorporated into one library, and the number of references captured was recorded. Using the automatic function in the EndNote software any duplicates were removed. All searches were completed by 15 November 2021.

A record of each search was made to enable a re-run of the search if necessary.

- Search string
- Number of hits
- Notes.

Study inclusion criteria

All retrieved studies were assessed for relevance using inclusion criteria developed in collaboration with the Project Steering Group (PSG). The studies that were considered for inclusion in this QSR met the following criteria.

i. **Relevant subject(s)**

    o Studies that explored LESS approaches using terms such as: dribble bar, band application, trailingshow, trailing hose, shallow/deep injection and slurry acidification.

    o Studies that investigated at least one of the following aspects of water quality as an effect of application of any of the LESS approaches: nitrate, ammonium, phosphate, FIO, bacterial pathogens, or any chemical characterised as Veterinary Medicine Product (VMP).

    o The PSG agreed that the study should focus on countries with similar farming systems to the Scotland such as EU countries and similar climate.

ii. Language

- o Studies published in English.

iii. Date

- o No date restrictions were applied but all searches were completed by 15 November 2021 therefore no evidence published post-2021 is included.

iv. Types of comparator included

- o Studies that compared effects on water comparing precision slurry spreading technologies to each other and/or with broadcast (splash plate) slurry application or no slurry spreading.
- o Studies that compared effects on water quality before and after or for a long-term period after slurry acidification.

v. Types of outcome

- o Differences in water quality following application of LESS approaches measured as change in levels of nitrate, ammonium, phosphate, and bacterial counts or VMP in leachate or surface or subsurface runoff in field or laboratory experiments.
- o Studies that mentioned the soil and land use context to different water quality effects of LESS approaches.
- o Differences in capital costs of LESS approaches.

vi. Types of study

- o Any experimental or correlative research study that collected primary data to investigate the impacts on water quality of LESS approaches.
- o Secondary data from systematic literature reviews when impacts of LESS approaches in primary evidence was inconclusive.
- o Any study reporting capital costs of LESS approaches.

Evidence screening and refinement

The articles collected were screened in two steps. The first step was to apply the study inclusion criteria in each article using only the title/abstract/highlights or headline/first paragraph and conclusion. If there was any uncertainty or where there was insufficient information to make an informed decision regarding a studies inclusion, then relevance to the next stage of the review process (full text assessment) was assumed. The refined list of search results went forward for use in the QSR and the number of references excluded was recorded. The inclusion criteria were applied by the author of this report to all potential articles, except where there was any uncertainty, where a consensus agreement with the PSG was sought, as for example in the case of "slurry acidification" which was not included in the original inclusion criteria, but a considerable number of studies explored its feasibility and impacts on water quality.

Data extraction strategy

Studies that passed the inclusion criteria were imported into an Endnote X database. Each article was coded and categorised using a combination of generic (e.g., country/s of study, publication date, length of study etc.) and topic specific (e.g., LESS approach and pollutant studied) keywords. Data regarding the study characteristics, quality of experimental design and results were recorded. The database was used to describe the extent of the research in the field and identify knowledge gaps. It is searchable by title/Author/abstract/year of publication.

Data synthesis and presentation

Summary tables of study characteristics, study quality and results have been presented, accompanied by a narrative synthesis. Where either quantitative or qualitative information on the effectiveness of varying LESS approaches to reduce losses of slurry pollutants to water was available for the studies assessed, the intervention was given a value for its effectiveness according to the system in Table 3.

Appendix II.1 Legislative framework

Legislation on slurry spreading

Slurry spreading on agricultural land is regulated under the General Binding Rules (GBR) activity 18 under CAR to limit odour and water pollution via leaching and runoff. For example, slurries must be applied at quantities that meet the needs of the crop and at the right time to ensure that the risk of losses via leaching and/or runoff during wet weather is minimised. Further, slurries must not be applied in land that:

- is within 10 m of any river, burn, ditch, wetland, loch, transitional water, or coastal water.
- is within 50 m of any spring that supplies water for human consumption or any well or borehole that is not capped to prevent water ingress.
- has an average soil depth of less than 40cm and overlies gravel or fissured rock, except where the
- application is for forestry operations.
- is frozen (except where the fertiliser is farmyard manure), waterlogged, or covered with snow; or
- is sloping, unless it is ensured that any run-off of fertiliser is intercepted (by means of a sufficient buffer zone or otherwise) to prevent it from entering any river, burn, ditch, wetland, loch, transitional water or coastal water towards which the land slopes.

The recent amendments (CAR 2021) incorporate The Control of Pollution (Silage, Slurry and Agricultural Fuel Oil) (Scotland) Regulations 2003 ("SSAFO") into CAR, introduce new GBR activities and amend existing GBR 18 on the "Storage and application of fertiliser". The overarching aim of these amendments is to provide further protection of the water environment from agricultural activities and reduce ammonia and climate change contributing emissions from the storage and application of slurry.

A key amendment to GBR 18 is the introduction of "precision equipment" to animal slurry and liquid digestate spreading (CAR 2021):

> *"If slurry is—*
> *(a) applied by contractors,*
> *(b) applied on farms with more than 100 milking cows or 200 beef cattle livestock units, or*
> *(c) applied on pig units with more than 800 fattening pigs or 800 sows*
>
> *then the slurry must be applied using precision equipment from 1 January 2023. Otherwise, slurry must be applied using precision equipment from 1 January 2027. In situations where slurry does not need to be applied using precision equipment until 1 January 2027, slurry must not be applied by means of a raised splash plate or rain gun after 1 January 2023.In calculating the number of beef cattle livestock units on the farm for the purposes of this rule an animal of 2 years and older is 1 unit, and an animal under 2 years old is 0.5 of a unit. In all cases, liquid digestate must be applied using precision equipment from 1 January 2023."*

Additional measures apply for the application of organic manure (including livestock manure and sewage sludge) in designated Nitrogen Vulnerable Zones (NVZ) under The Action Programme for Nitrate Vulnerable Zones (Scotland) Regulations 2008. These measures control the timing, frequency, quantities, and organic manure with high available nitrogen content (e.g., cattle and pig slurry, poultry manure and liquid digested sewage sludge). It is important to note that the use of high trajectory raised splash plates for spreading slurry is prohibited within NVZs and nitrogen fertilisers and organic manure must be accurately applied.

Several international environmental policies al policies aim at decreasing NH_3 emissions from livestock farming systems, including the UNECE Convention on Long-range Transboundary Air Pollution (UNECE, 1999) and the National Emission Ceilings directive in the European Union (European Commission, 2001).

II.2. Impacts of field applied slurry on air and water quality in Scotland

II.2.1 Slurry production and use in Scotland

A feasibility study of slurry storage on Scottish farms by Wiltshire (2018) on behalf of the Scottish Government estimated that 6.35 million tons (Mt) of slurry are produced annually. Slurry production is dominated by cattle and dairy farming systems (i.e., 5.56 Mt), followed by pig (0.73 Mt) and sheep (0.06 Mt). Slurry production varies by region, with higher production in south-west Scotland, East Lothian, Aberdeenshire, and Orkney. Slurry is applied, usually following storage, on arable crop, field horticulture, grassland, and forage crops. The study reported that 12 Mt of manure (including solid manure) was broadcast using splash plates, 5 Mt of slurry was applied via a band spreader and 600,000 tonnes of slurry was injected. Of those holdings using a band spreader, the majority used a trailing hose, and the majority of injection was shallow/open slot. However, the percentage of holdings that produce slurry, and subsequently apply this slurry to land, is unknown.

The feasibility study of slurry storage on Scottish farms by Wiltshire (2018) also assessed business receptiveness of LESS. For example, precision equipment is unlikely to be adopted voluntarily due to unclear financial benefit, additional costs, reduced work rate and perceived limitations of use on stony ground. Further, slurry acidification is not market-ready in Scotland and voluntary uptake is unlikely due to negligible perceived benefits, potential additional costs, and concerns in the agriculture industry about safety associated with the use of a concentrated acid (usually sulphuric acid) and the potential for increased emission of hydrogen sulphide. These observations and conclusions are in line with the results of studies exploring farmers' perspectives in Scotland, which reported that the cost of precision farming was viewed as inhibitory (Barnes et al., 2009; Feliciano et al. 2014).

II.2.2 Gaseous emissions from slurry spreading in Scotland

Agriculture is the dominant contributor to Scotland's emissions of ammonia (Jones et al., 2021) and nitrous oxide (Scottish Government 2021). Emissions from manure and slurry spreading were estimated to account for 31% of the 31kt of ammonia emitted in 2019. Before 2010, emissions from agriculture were primarily driven by decreases in livestock numbers (except for poultry) and declines in the use of nitrogen-based fertilisers. After 2010, however, the decline began to be offset by increased application of urea-based and organic fertilisers such as digestate to agricultural soils causing fluctuating emissions totals since 2008, with no significant trends across these years.

A recent field study in Scotland by Bell et al. (2016) estimated and compared ammonia and nitrous oxide emissions and emission factors (EF) between broadcast and band (trailing hose) application of cattle slurry on winter wheat in two contrasting seasons (i.e., Autumn and Spring). The lack of any significant differences in ammonia and nitrous emissions between broadcast and trailing hose application demonstrated that the method of slurry application had no effect on emissions in contrast to other studies that measured 30–70% lower ammonia emissions from trailing hose than broadcast application (e.g., Webb et al., 2010)**.** The use of low dry matter slurry in the experiments and the lack or low crop canopy may be responsible for the lack of difference in emissions.

The same Scottish study by Bell et al. (2016) showed an overlap in the range of values of emission factors (EF) for ammonia and nitrous oxide following broadcast and band (trailing hose) application of cattle slurry in two contrasting seasons (i.e., Autumn and Spring). The study indicated that environmental variables such as temperature and rainfall, soil type, and soil conditions may have a greater impact on these emissions than spreading technique. Further research is needed to understand the results reported by Bell et al. (2016).

II.2.3 Diffuse pollution pressures on Scotland's waterbodies

As of 2021, water quality is in good or better condition in 87% of the water environment for Scotland Districts (SEPA 2021) and 45% of the surface waterbodies in the Solway Tweed are in good or better ecological condition (EA and SEPA 2021). Diffuse pollution from agriculture remains one of the most significant pressures on Scotland's waterbodies. The regulatory framework contains provisions for protecting and improving the water environments from agricultural activity including slurry spreading. For example, the Activity 18 of CAR General Binding Rules (GBR18) and the Action Programme for

Nitrate Vulnerable Zones (NVZ) control the timing of organic fertiliser spreading to reduce the risk of nutrient pollution (see Appendix II).It is important to note that the use of high trajectory raised splash plates for spreading slurry is prohibited within NVZs and nitrogen fertilisers and organic manure must be accurately applied.

Appendix III. Biogeochemical processes driving losses of field-applied slurry components to the environment

III.1 Transformations related to gaseous emissions

Slurry nitrogen may be lost from the soil to the atmosphere in several different ways, including ammonia volatilisation when manure and slurry are spread on the soil surface, and nitrate denitrification and subsequent nitrous oxide emissions.

III.1.1 Ammonia volatilisation

Volatilised NH_3 is a potent atmospheric pollutant with a wide variety of environmental impacts. This gas is released from the ammonium (the reduced form of ammonia) produced when nitrogen-containing substances in the organic matter in the slurry are broken down. Ammonium is the form transported in the atmosphere and used by plants as a source of nitrogen. Ammonia can also be released during combustion, and is synthesised, using fossil fuels, for artificial nitrogen fertilisers.

The primary forms of nitrogen found in nitrogen fertilizers are ammonium (NH_4), nitrate (NO_3), and urea ($CO(NH_2)^2$) or combinations thereof. Plant availability and recovery of ammoniacal nitrogen or ammonium-forming fertilizers are reduced by nitrogen losses via leaching and runoff, denitrification, and ammonia (NH_3) volatilisation.

Ammonia volatilisation occurs as NH_4 is converted to NH_3 gas at the soil surface and transported to the atmosphere. Ammonia volatilisation is controlled by two equilibriums, that is, the association–dissociation equilibrium between ammonium (NH_4) and ammonia (NH_3) in the slurry and the equilibrium of ammonia between the liquid and gas phase in immediate contact with the slurry applied to the soil surface.

III. 1.2 Nitrous oxide: Nitrification and denitrification

Nitrous oxide (N_2O) is an important greenhouse gas and contributes to depletion of the ozone layer. Fertilised soils are the major source of N_2O (Oenema et al., 2005). In soils, N_2O is produced during nitrification and denitrification processes, before the crop is able to utilise the available ammoniacal nitrogen. For this reason, it is important to add slurry to meet crop demand. The deposited NH_3 is also a source of indirect N_2O emission, as it may be transformed into N_2O via nitrification and denitrification (IPCC, 2006).

The application of slurry to soil increases the content of NH_4, and of easily mineralisable (N) and carbon (C) in the topsoil. This in turn may increase nitrification and subsequently denitrification locally, which may also increase emission of N_2O. The organic C compounds in slurry provide readily available substrate for denitrifying bacteria (Dendooven et al., 1998).

Nitrification

$NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$

Active microbes:

Nitrosomonas, Nitrobacter

Denitrification

$NO_3^- \rightarrow NO_2^- \rightarrow N_2O \rightarrow N_2$

Active microbes:

Pseudomonas, Achromobacter, Micrococcus

https://marylandbiochemical.com/products/bioremove-5900/nitrification-and-denitrification/

A delay of ammonium N nitrification was observed in soils amended with acidified slurries, relative to non-acidified ones (Fangueiro et al., 2010). This delay lasted for about 20 days, for both pig and cattle slurry. Furthermore, for more than 60 days, the TAN concentration in soil amended with acidified slurry remained significantly higher than in soil amended with the raw materials. The reasons for this are not clear and might involve a combination of nitrification delay, reduction/ inhibition of nitrogen immobilisation, and stimulation of organic N mineralisation (Fangueiro et al., 2009).

III.2 Processes related to losses to water

A. The processes influencing the delivery (also known as mobilization) of slurry components to water include:

- sorption-desorption cycles of slurry nutrients, FIO and VMPs;
- nutrient mineralisation;
- crop uptake of nutrients;
- leaching (i.e. loss of non-adsorbed pollutants from the soil matrix to groundwater or receiving streams through subsurface hydrologic pathways);
- FIO die-off;
- denitrification;
- soil erosion delivering adsorbed nutrients; and
- freeze–thaw cycles.

B. Slurry components can be in dissolved and particulate form in the slurry but following field application they can be delivered in dissolved, particulate, or gaseous form to the environment. These forms by delivery pathway and slurry pollutant are described below (Lintern et al., 2018; Rittenburg et al., 2015; Akoumianaki 2021):

- Nitrogen forms
  1. Ammonium can be volatised and emitted to air as ammonia (see APPENDIX III.1.1)
  2. Ammonium (usually adsorbed in soil particles until taken by crop) can be found in overland flow, preferential flow, soil matrix flow and streamflow;
  3. Nitrogen in the unsaturated zone, i.e., above the water table, can be transported in subsurface flow pathways (vertical or lateral) through fast preferential flow as nitrite/nitrate (dissolved), or through slow soil matrix flow paths as organic nitrogen sorbed to the soil matrix, where there is opportunity for biogeochemical transformation to nitrous oxide;
  4. Dissolved nitrate in baseflow and streamflow;
  5. Organic N can be found overland flow, in preferential flow, and soil matrix flow, where it can be transformed via denitrification to nitrous oxide (see APPENDIX III.1.2).

- Phosphorus forms
  1. Particulate P (adsorbed) is entrained in surface runoff;
  2. Particulate P (adsorbed) adheres on soil matrix;
  3. Dissolved P (non-adsorbed or weakly adsorbed) in surface runoff and preferential flow (vertical or lateral) into the soil solution;
  4. P adsorbed to very fine colloidal soil particles can travel significant distances, laterally or vertically, and reach groundwater waterbodies;
  5. Particulate P can be taken out of the delivery flow pathway (e.g., runoff and streamflow) by filtration from vegetation, sedimentation and infiltration during slow surface runoff, or sedimentation and deposition during slow streamflow followed by resuspension during high- flow regime;
  6. Under hypoxic (or even anoxic) conditions, P is released from the sediment resulting in the possibility that upwelling groundwater could contribute significantly to baseflow concentrations of P.

- Soil particles
  1. Soil particles contaminated with slurry are generally transported by overland flow into receiving surface waters;
  2. Finer soil particles can sometimes be transported by subsurface flows, depending on slope and vegetation;
  3. Sediment can be taken out of the delivery flow pathway by filtration from vegetation, sedimentation; and
  4. infiltration during slow surface runoff or sedimentation and deposition during slow streamflow.

- FIO forms
  1. In freely drained soils, E. coli O157:H7 can travel below the top layers of soil for more than 2 months after slurry initial application and can reach the water table of shallow groundwater (Avery et al., 2004).

C. Slurry-borne contaminants can be mobilised via the following processes (Lintern et al., 2018; Rittenburg et al., 2015; Bunemann, 2015):

- Phosphorus (P) transformations:
  1. Crop uptake of soluble reactive inorganic P (SRP);
  2. Organic phosphorus mineralisation through microbial decay;
  3. Particulate phosphorus adsorption on clay minerals in soil particles (thereafter undergoing similar mobilisation processes to soil);
  4. Phosphorus precipitation (immobilisation) as non-bioavailable phosphate soil minerals with aluminium, iron, manganese, or calcium;
  5. Microbial phosphorus immobilisation into microbial biomass;
  6. Phosphorus re-mineralised through microbial transformation of microbially-bound phosphorus to SRP;
  7. Phosphorus leaching into soil solution as SRP when sorption potential is low.

- N transformations:
  1. Microbial uptake of ammonium (immobilisation);
  2. Crop uptake of ammonium and nitrate;
  3. Leaching of excess N in soil into infiltrating water as dissolved nitrate;
  4. Nitrification: microbial transformation of ammonium to crop-available nitrites and nitrate under aerobic conditions; It is generally accepted that the average time for maximal nitrification to be reached ranges from 7 to 14 days (Addiscott, 1983 cited in Fangueiro et al., 2014) and, in our study, the peaks in the amendment treatments occurred on days 10 and 17 (for acidified amendments only).
  5. Ammonification: microbial transformation of nitrate to crop-available ammonium under aerobic conditions;
  6. Denitrification: microbial transformation of water-soluble nitrate into nitrous oxide and dinitrogen into the atmosphere under anaerobic conditions;
  7. Ammonia volatilisation: release of water-soluble ammonium into the atmosphere as ammonia (see APPENDIX III.1.1);
  8. Adsorption of ammonium on clay particles, thereafter, undergoing similar mobilisation processes to soil particles (i.e., transport downhill in surface runoff).

- FIO:
  1. Die-off or growth depending on responses of different types of bacteria to oxygen and nutrient levels, and exposure to solar radiation and salinity;
  2. Leaching is possible, especially in freely drained soils;
  3. Adsorbed FIO undergo similar mobilisation processes to soil particles (i.e., transport downhill in surface runoff).

D. The delivery (loss) of slurry pollutants to water are influenced by environmental factors

- Temperature. Warming increases microbial activity, desorption of phosphorus from sediments, and decomposition and mineralisation of organic matter (Kaushal et al., 2014).
- Loss of ammoniacal nitrogen in runoff is more likely in the first couple of days after slurry application during heavy rainfall, while nitrate leaching can occur many years after application due to the mineralisation of organic N (Sørensen and Jensen, 2013).
- Leaching and runoff of depend on a variety of factors, such as soil type, precipitation, groundwater level, N application levels, the share of organic N in the slurry, and time of application.
- These circumstances are manure application to soil types with preferential flows, direct exposure of manure P to running water after application and repeated application of manure to the same area over many years, which can increase the risk of long-term P leaching (Sørensen and Jensen, 2013).
- Hooda et al. (1998) and Scholefield et al. (1993) have reported that NO_3-N leaching is higher after a dry and warm summer than after a wet and cool summer season, since in dry conditions nitrification may be high whereas denitrification and plant uptake of N can be lower than during cool and wet years.
- Rainfall can increase mobilisation of sediment-bound nutrients and FIO in surface and subsurface runoff and enhance infiltration in permeable soils (Kay et al., 2012).
- Predominance of soils susceptible to erosion increases soil loss in runoff and artificial drainage (Rickson, 2014). However, soil erosion varies temporally and regionally as it is determined by complex relationships between soil properties, runoff intensity, frequency of storm events and duration of periods between storm events, delivery pathways, antecedent (prior to rain) soil wetness, slope length and gradient, land use, soil conservation measures and vegetation (in arable land, grassland, and buffer strips) (Rickson 2014; Sheriff et al. (2016).
- Soil sorption capacity can be correlated positively with sediment-bound nutrient and FIO mobilisation, as nutrients adsorbed on clay and silt particles can be delivered to receiving waters primarily via overland flow (Lintern et al., 2018).
- For nutrients with high sorption potential by most soils and sediments (e.g., SRP and ammonium), as well as for FIO, (which also tend to cling on soil particles) sinks or storages from slurry fertilized fields to water are ubiquitous. As a result, there is: (i) continuous accumulation of these nutrients and FIO in the soil, and (ii) continuous re-mobilisation in runoff, streamflow, or through disturbance of the soil (e.g. erosion and livestock/machinery disturbance of the soil surface) (Rittenburg et al., 2015; Bunemann, 2015).
- Higher survival of *E. coli* and faecal coliforms have been observed at low pH (close to 6) than at high pH (close to 8) (Fangueiro et al., 2014).

Appendix IV. Factors influencing ammonia emissions from field-applied slurry

Ambient air - Weather

Weather conditions such as air temperature, solar radiation and wind speed that increase evaporation of water from the slurry following its application onto land or increase slurry infiltration into the soil (Bittman et al., 2014). Decreasing contact area with the ambient air by slurry application technique is in the order: surface spreading by splash plate, narrow-band application, and shallow injection (Huijsmans et al., 2001).

- Increases in air temperature and solar radiation, i.e., drier conditions, stimulate the formation of gaseous ammonia and decrease the solubility of ammonia in water, thus increasing the potential for ammonia volatilisation. Theoretical calculations of ammonia in the gas phase from a solution, show that a 1oC increase in temperature results in an approximately 13% increase in the gas-phase ammonia (Hafner et al., 2018;). However, Braschkat et al. (1997) and Misselbrook et al. (2005) found no effect of temperature on cumulative ammonia emissions, potentially due to crust formation of the slurry surface under high solar radiation which is expected to increase the surface resistance of ammonia transport to the atmosphere (Sommer et al., 2003).
- Wind speed also increases the diffusion of ammonia into the air. However, high wind speeds drying the upper layer of the soil prior to, or during application, may increase the potential of slurry infiltration into the soil, thus reducing contact with ambient air and the potential for ammonia volatilisation (Brunke et al., 1988).
- Rainfall and air humidity before, at the time of, and after application is a key determinant of ammonia emission from field-applied slurry. Beauchamp et al. (1982) found that ammonia emissions were suppressed by rainfall. Huijsmans et al. (2003 cited in Huijsmans et al., 2018) compared different application techniques and reported a decrease in ammonia volatilisation with increased air humidity but only in the case of narrow band spreading and no effect in the case of broadcast spreading or shallow injection. Misselbrook et al. (2002) reported low ammonia emissions from both surface broadcast and shallow injected slurry (to either 4 or 8cm) when very heavy rainfall followed application on grassland and arable land but also with no or minimal rain. Misselbrook et al. (2005) observed that rainfall following broadcast application reduced ammonia emissions from cattle slurry applied on grassland, potentially because the rainfall rinsed the slurry coating from grass leaves following broadcast application, reducing the surface area for emission and washing slurry Total ammoniacal nitrogen (TAN) into the soil.
- It is interesting to note that rainfall data were missing from nearly half the observations in the cattle and grass subset of the database containing measurements (footnote: developed to assess and model ammonia emissions based on measurements of emission, manure/slurry and soil properties, weather, application technique, and other variables) 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).
- TS decreases the manure surface area exposed to the air and increases infiltration into the soil (Natural England 2018).

Soil properties

- Soil type and humidity at the time of application have the potential to influence ammonia emissions from field applied slurry (Bittman et al., 2014) but are not as important as air temperature and wind speed (Huijsmans et al., 2018). Sommer and Jacobsen (1999) showed that ammonia emissions were lower by 30% from a dry soil (1% moisture w/w) than from wetter soils (8%, 12% and 19% moisture), and that this was because of increased TAN infiltration into the dry soil. In contrast, Smith et al. (2000b) reported emissions from cattle slurry applied to hard dry grassland to be greater than for applications to moist grassland or arable soils. This was probably due to the hydrophobic nature of the dry grassland soil, meaning that the slurry infiltration rate into the dry soil was slower than for the moist grassland and arable soils.
- Ammonia emissions decrease with increasing soil infiltration (Misselbrook et al., 2005). Pain et al. (1989) suggested that the more rapid infiltration of dilute slurries into soil may account for the lower NH_3 losses compared with thicker (high DM%) slurries.

- The effect of soil type on ammonia emissions from applied slurry depends on slurry application technique. For example, Pedersen et al. (2021) found that the NH_3 emissions from sandy loam is significantly higher than coarse sand and loamy sand for trailing hose and trailing shoe.

Crop type and height

- It is well established that ammonia emissions are higher from slurry applied to grassland than to arable land. (Footnote: Unlike arable crops, grassland is harvested several times per year, and slurry is applied to grassland throughout the growing season. However, the growth potential of grassland is greatest in the spring and the residual effects of manure applications can be utilized most effectively during the remainder of the growing season, so good agricultural practice would be to apply a large proportion of liquid slurry in the spring. Sommer et al., 2019).
- Crop canopy at the time of application has the potential to lower ammonia emissions (expressed as percentage of TAN applied with slurry) with trailing shoe application and shallow injection but not with splash plate (Huijsmans et al., 2018). Further, trailing hose application is more effective in reducing ammonia emissions when a crop canopy is present (Thorman et al., 2008).
- Misselbrook et al. (2002) reported no effect of application technique on ammonia emissions following slurry application on arable land. However, Weslien et al. (1998) reported large reductions in ammonia emissions with shallow injection to soil prior to cereal planting compared to broadcast application. Smith et al. (2000) estimated that reduction in ammonia emissions by shallow injection of almost 80% compared with surface broadcast on arable soils (assessments were generally on moist soils). Soil conditions such as soil temperature and soil compaction.
- A comparison of ammonia emissions between slurry application on grassland, arable, stubble, and fallow land showed greater losses for pig slurry from applications to stubble than to either fallow land or the growing crop, with cumulative losses of 28.5%, 15.0% and 15.8% of the TAN applied, respectively (Misselbrook et al., 2005).
- There is evidence of a reduction in emission as grass height increased. For example, Hafner et al. (2018) reported emission reduction in the range of 1.6%-2.5% per cm of height for trailing shoe and reductions up to 20% per cm of height for trailing hose.

Slurry properties

- The effect of soil type on the total emission may be explained by different infiltration capacities for slurry, being generally lowest for clay soils, moderate for peat soils and highest for sandy soils (Huijsmans et al., 2018).
- Slurry DM content is commonly, although not universally, reported as one of the most important factors affecting NH_3 volatilisation. For example, reducing the dry matter content of cattle slurry, either by separation or dilution, has been shown to be an effective means of reducing ammonia volatilisation following land application (Frost, 1994; Stevens et al., 1992; Frost et al., 1990). Smith et al. (2000b) estimated that an increase of ammonia emissions increasing by 6% of the TAN applied for each 1% increase in DM content, in the case of cattle slurry applications to grassland under moist soil conditions.
- A review of data from 19 experiments (108 observations) showed a significant effect of DM on NH_3 emission, with the emission being 50% lower on average for slurries with DM<=4g kg^{-1} compared to slurries with DM>4g kg^{-1} (Pedersen et al., 2021).
- Statistical analysis of the data in the ALFAM2 database showed that ammonia emissions following open slot injection increased by 13–25% per % increase in DM, which may be related to inefficient injection, or insufficient infiltration, due to high dry matter[1] (Hafner et al., 2019). (footnote: an increase in slurry dry matter is expected to increase emission by reducing soil infiltration and increasing the fraction of slurry at the soil surface or on crop or stubble surfaces.) In this context, Infiltration following trailing hose application should also be affected by dry matter.
- In some cases, higher dry matter could conceivably lead to a reduction in emissions, for example by helping to maintain trailing shoe bands or increasing mass transfer resistance through crust formation (Hafner et al., 2018).

1 Cattle slurry typically contains more fibrous material, which increases the viscosity and gives a greater water holding capacity and may impede soil infiltration to a greater extent than the more ‘gravelly’ natured solid material in pig slurry

- The effect for broadcast (3% per % increase in DM) is much smaller than observed responses compiled by Sommer (2013: Table 12). Slurry origin (e.g., cattle, pig, or poultry) and content, especially in terms of dry matter (DM) content (%) and TAN% (see application rate) can also influence ammonia emissions. Misselbrook et al. (2005) observed important differences in the strength of the relationships between ammonia emissions and dry matter (DM) content for the cattle and pig slurries, with ammonia emissions increasing with DM% when cattle slurry was applied to grassland and cereal stubble. This relationship was not consistent for pig slurry.
- Slurry TAN concentration (%) is also a key determinant of ammonia emissions. With all else equal, mass transfer theory predicts a 10-fold increase in ammonia emissions with a 10-fold change in TAN). This effect can be reversed by dilution of slurry, but with a less clear response from injection and trailing hose application techniques (Hafner et al., 2018). For example, Huijsmans et al. (2018) reported a negative effect for TAN content in case of shallow injection, which implies that the relative ammonia emission (i.e., EF as % of TAN applied) is lower with increasing TAN content. However, total absolute emission (as kg NH_3-N emitted per ha) may still increase with increasing TAN content. The increase of ammonia emissions from open slot injection of diluted slurry is probably related to the quantity of slurry remaining on or close to the surface.
- Soil hydraulic properties, pH, and the capacity for sorption of ammonium could affect ammonia emissions, and earlier studies have also shown large effects of soil properties on emissions (e.g., Sommer et al., 2006). Analysis of data in the ALFAM2 database showed that soil interactions with slurry and ammonia emissions are not related solely to soil texture categories but emission from sandy soils is consistently lower than emission from other soils, when data from the same institute are examined (Hafner et al., 2018).

Slurry pH

- Slurry pH is known to have a large effect on ammonia emissions (Bussink et al., 1994). Based on well-known principles of chemical equilibrium, an increase in pH from 7 to 8 results in a 10-fold increase in free NH_3, resulting in a 10-fold increase in emission rate, all else being equal. Acidification Bussink et al. (1994) measured reductions in 4d or 10d emission of 55%, 72%, and 85% by reducing pH from around 7.5 to 6.0, 5.0, and 4.5, respectively (some of these data are included in the ALFAM2 database).
- Slurry pH controls the chemical equilibrium between ammonium (NH_4) and ammonia (NH_3) (McCrory and Hobbs, 2001). Acidification reduces losses of nitrogen by shifting this equilibrium towards a higher proportion of ammonium nitrogen, which cannot be emitted in gaseous form. Therefore, acidification of slurry is used to reduce NH_3 emissions (Kai et al., 2008; Fangueiro et al., 2015).
- In liquid manure, ammonia (NH_3) and ammonium (NH_4) are in chemical equilibrium, where the balance of each is largely dependent on pH. As pH increases, a larger proportion of ammonium occurs as ammonia, which can be lost as a gas. Lowering the pH shifts the equilibrium towards ammonium, which is water soluble and does not evaporate, decreasing the risk of emissions. Around a pH of 4.5 there is almost no measurable free ammonia. Acidification of slurry can therefore be considered a viable technique for reducing ammonia emissions from manure during various points in the handling chain.
- Acidification may change the slurry dry matter content. However, the effect of slurry acidification on dry matter content is not consensual in the international literature, with some studies reporting an increase and others a decrease (see review by Fangueiro et al., 2015).
- Previous studies (Fangueiro et al., 2009; Daumer et al., 2010; Roboredo et al., 2012) observed almost complete dissolution of slurry compounds when lowering the pH. The acidified slurry thus has higher concentrations of dissolved inorganic compounds relative to untreated slurry with positive impacts on its fertilizer value, such as for phosphorus (Roboredo et al., 2012).
- The effect of slurry pH may be influenced by slurry DM content and crop type. For example, Misselbrook et al. (2005) found no significant effect of slurry acidification on total ammonia emissions following pig slurry application to cereal stubble. However, in that experiment, ammonia losses were very low at all slurry pH values (mean loss of 12% of applied TAN) and other factors such as DM content may have had a greater influence than slurry pH.
- Field application of acidified slurry decreases in ammonia emissions in the range of 40%-80% with pig slurry and 15-80% with cattle slurry can be achieved (see review by Fangueiro et al., 2015).
- The sulphuric acid has so far proved to be the most appropriate substance for acidification. When the pH is decreased

from a pH of typically around 7.5–5.5, the gaseous acid–base compound concentration of NH_3 decreases from 1.8% to 0.02% (Kai et al. 2008; Fangueiro et al. 2014).

Application rate

- Absolute NH_3 loss (kg N ha^{-1}) increased with increasing application rate but there was no clear trend for relative ammonia emissions (as TAN%).Increasing slurry application rate has previously been shown to decrease the proportion of TAN emitted as NH_3 (Frost, 1994), presumably because of a decreased surface area to volume ratio for higher application rates.
- The ALFAM2 database provided evidence of reductions in relative ammonia emissions with an increase in application rate for trailing hose application, i.e. about a 30% reduction in relative emission due to a doubling in application rate, but no clear effects of application rate for broadcast or trailing shoe in any of the models (Hafner et al., 2018). Smaller effects have been observed in experiments where application rate was varied (Frost, 1994).

Appendix V. Factors influencing impacts of field-applied slurry on water quality

V.I Broadcast application

Slurry components can be delivered (mobilised) to water via the following hydrological pathways (Cameira et al., 2019; 2020, McConnell et al., 2013; Hodgson et al., 2016; Uusi-Kamppa and Heinonen-Tanski 2008):

- Runoff
- Leaching
- Preferential pathways (rapid infiltration)
- Soil matrix flow (slow Infiltration)

Runoff

- Runoff can be surface or subsurface, depending on the sites where slurry has been applied and the type of pollutant. In general, particulate forms of pollutants are largely transported by overland (surface) flow whilst dissolved forms are transported by both surface and subsurface (lateral and vertical) runoff (Rittenburg et al., 2015).
- Delivery of pollutants from slurry fertilised fields to receiving waters in overland runoff has a relatively short hydrologic travel time ranging from days to weeks (Jarvie et al., 2013).
- Particulate and dissolved pollutants entrained in overland flow could be partially deposited onto soil if runoff is slow or filtered out of flow due to the presence of vegetation (hydraulic reduction) (Rittenburg et al., 2015). This implies that the crop growth stage and the presence of vegetated buffer strips are important determinants of diffuse pollution from field applied slurry.
- Dissolved pollutants such as nitrate can be delivered to streams faster in loamy, relatively impermeable soils than in sandy soils due to increased infiltration in sandy soils (Hansen et al., 2019).
- The greatest losses of nutrients such as ammonium, TN and TP in runoff occur following rainfall and application on wet clay soils (e.g., Uusi-Kämppä and Mattila 2010; Uusi-Kämppä and Heinonen-Tanski 2008.)

The risk of mobilisation of particulate compounds in field-applied slurry (such as particulate phosphorus, ammonium and FIO) and transport into water via runoff increases when (Rittenburg et al., 2015; McConnell et al., 2013; Cameira et al., 2019; Uusi-Kampa and Heinonen Tan et al., 2019):

- the soil is poorly drained (but also in freely drained soils in areas with frequent and high rainfall) and the water table is shallow;
- (high rainfall) the predominant hydrological path is soil matrix (slow) infiltration, and, under soil saturated conditions, surface runoff; and
- (low rainfall) the predominant hydrological path is infiltration via lateral preferential flow and subsurface runoff.

This risk can be mitigated by avoiding fertiliser nutrient inputs in excess of crop demand and by implementing agricultural measures that intercept flow enabling deposition, enhance plant uptake of mobilised nutrients, enable soil matrix infiltration by delaying flow while also encouraging loss of excess nutrients via denitrification to di-nitrogen (Heathwaite 2010; Akoumianaki 2021; Jabloun et al., 2015).

Leaching

- Hooda et al. (1998) and Scholefield et al. (1993) have reported that NO_3-N leaching is higher after a dry and warm summer than after a wet and cool summer season, since in dry conditions nitrification may be high whereas denitrification and plant uptake of N can be lower than during cool and wet years.
- The site of slurry application (reference nitrate soil concentrations, differences in management), soil properties, preceding crop, crop rotation, crop cover during autumn and winter and climatic conditions are significant determinants to soil nitrate concentration and leaching for winter and spring cereals (Jabloun et al., 2015; Askegaard et al. 2005; 2011).
- Several studies have shown that rainfall increases the potential of nitrate leaching (e.g., Cameira et al., 2019)
- Higher temperature during winter and summer would increase NO_3-N concentration and leaching for winter cereals which could be attributed to an increase in soil mineralisation rates (Jabloun et al., 2015; Wick et al., 2012). With increased temperatures, soil organic matter turnover increases and this potentially increases available soil mineral N, thus amplifying the risk of N leaching (Børgesen and Olesen, 2011). Changes in air temperature will also involve changes in planting and harvesting times as well as in fertilization rates and strategies (Doltra et al., 2014), which will also affect nitrate leaching.
- The physical and chemical properties of the soils affect both the drainage and nitrification processes (Sahrawat, 2008), thus influencing the amount available for leaching.But the effect of soil characteristics on nitrate leaching is complex and contrasting results have been reported in previous studies. Other studies (O'Connor et al., 2016; Shepherd et al., 2010) indicated that a freely drained soil led to greater NO_3-leaching than a poor drained soil. Sorensen and Rubaek, (2012) found that the soil type had negligible effect on NO_3-leaching after solid manure application. Soil texture acts indirectly at source level by affecting the exposure of ammonia to microbial attack, since NH_4 can be fixed on clay soil minerals or be immobilised in microorganism's biomass.
- The effect of soil characteristics on nitrate leaching is complex and contrasting results have been reported in previous studies. Gaines and Gaines (1994) studied specifically the impact of soil texture on nitrate leaching and they concluded that the sandy soil led to significantly higher NO_3-leaching than sandy loam soils. Other studies (O'Connor et al., 2016; Shepherd et al., 2010) indicated that a free drained soil led to greater NO_3-leaching than a poorly drained soil. However, Sørensen and Rubaek, (2012) found that the soil type had negligible effect on NO_3-leaching after solid manure application. In fact, the long-term slurry application to soil might contribute to modifications of soil hydraulic properties and consequently impact the drainage.
- Research in the 1990s using livestock manures showed that NO_3-leaching losses can be greatly reduced by applying the materials in spring compared with autumn applications and this has led to the introduction of no-spreading periods for high available N materials being an integral part of legislation worldwide. Nicholson et al. (2013) reported surveys showing that significant percentages of biosolids (64%) and other non-farm organic materials (32%) are still applied to winter sown crops in August, September and October and hence may be prone to nitrate leaching losses.
- For sandy soils the slurry injection technique may lead to pollution swapping: despite reducing the N gas losses, it might increase NO_3-leaching (Cameiro et al., 2019).

- Phosphorus leaching in soil amended with animal slurry relies mainly on the soil properties (Glaesner et al., 2011 cited in Fangueiro et al., 2014) and indirectly on the manure application history (Koopmans et al., 2007). Indeed, Liu et al. (2012a cited in Fangueiro et al., 2014) compared P leaching from two soils, a loamy sand and a clay loam, following pig slurry application and observed significant effects of slurry application on P leaching only in the clay loam soil, whereas in the loamy sand soil the leaching was similar in amended and non-amended soils.

The risk of leaching of water-soluble slurry compounds (such as SRP and nitrate from nitrification of TAN) into water increases when (Rittenburg et al., 2015):

- the soil is freely drained
- the water table is low
- the predominant hydrological path is infiltration

This risk can be mitigated by avoiding fertiliser nutrient inputs in excess of crop demand and by implementing agricultural measures that reduce infiltration such as buffer strips (Akoumianaki 2021; Jabloun et al., 2015).

Infiltration into soil matrix

Dissolved pollutant infiltration along the soil matrix is influenced by processes such as "adsorption onto clay particles" potential. Artificial (tile) drainage can cause a preferential, lateral flow path, transporting weakly and non-absorbed pollutants in dissolved form and strongly adsorbed pollutants associated with fine soil colloids to waterbodies (Rittenburg et al., 2015). Sediment and particulate nutrients such as phosphorus (Sharpley et al., 2013), can accumulate rapidly between rainfall and flood events in the soil. However, measuring and quantifying the time component of these processes requires long term soil and water quality and catchment data (e.g. temperature, solar radiation, humidity, rainfall) data, which are rarely available.

V.2 Effects of LESS on losses of nitrogen to water

V.2.1 Band application

Leaching. Two UK studies reported cumulative NO_3 leaching losses from sandy loamy soils following autumn band spreading of food-based liquid digestate (from AD plants using mainly commercial and municipal food wastes as a feedstock) and pig slurry application on arable land (Wensum) in relation to broadcasting and spreading of farmyard manure (FYM) and compost (Nicholson et al., 2017; Thorman et al., 2020). The studies found that leaching from the slurry treatments was greater than from the pig FYM and compost treatments, with no significant differences between band spreading and broadcast liquid digestate treatments. Nitrate leaching losses from the digestate applications were 15% of the total N applied. Ammonium-N concentrations in the drainage waters were very low on all treatments (<0.05 mg/l) and cumulative leaching losses were <0.02 kg/ha (i.e., <0.01% of the total N applied). These results strongly suggest that, as for livestock slurry and other highly readily available N organic materials, farmers should be advised to apply food-based digestate in the spring where practically possible, or in autumn to an actively growing crop such as grass or oilseed rape which will take up available N from the soil so it will not be lost via overwinter NO_3 leaching.

V.2.2 Band application of acidified slurry

Experiments simulating the effect of band spreading (trailing hose) using acidified slurry (pH=5.5) on sandy and sandy loamy soil showed that the annual cumulative nitrate-N leaching in the year of band spreading was lower than that from injection and was in the range of 42% of the nitrogen applied in the sandy soils and 24% of the nitrogen applied in the sandy loamy soils (Cameira et al., 2019). The above difference was attributed to the higher soil organic matter content of the sandy loam soil (1.5% against 0.8% in sandy soil), which promotes aggregation of soil particles improving water retention, thus decreasing the nitrate leaching potential.

V.2.3 Slurry injection

Runoff

The benefits of slurry injection for water as a measure to prevent losses of nitrogen in runoff to surface waters vary by study. For example, Uusi-Kampa and Matilla (2010) found that injection of cattle slurry into clay soils of grass ley reduced the losses of total nitrogen, ammoniacal-nitrogen in runoff by 34% and 83%, respectively, compared with surface broadcasting over a 36-month period and a slope of 0.9-1.7%. These reductions are smaller than the reduction in TN load in runoff achieved by a 10m untreated buffer zone downstream of the field where cattle slurry was applied (Heathwait et al., 1998).

Leaching

When injecting the slurry at or below 10 cm depth, ammonium nitrification may occur out of the reach of roots during the early stage of plant development. Therefore, less nitrate is potentially recovered by plants and more nitrate is available for leaching. Additionally, more ammonium is available to be nitrified and potentially lost as nitrate, since much less volatilisation occurs as compared with broadcasting and band application. However, if the predominant hydrological paths in an area included preferential pathways and soil matrix movement, then there may be no difference between broadcasting and injection because injection may disrupt the structure of soil macropores resulting in a decrease of leaching. Overall, evidence that injection increases the risk of nitrate leaching is mixed.

Cameron et al. (1996) observed that NO_3-N leaching was consistently higher after subsurface injection of dairy pond sludge compared to surface application.

Uusi-Kampa and Matilla (2010) observed that soil mineral nitrogen was consistently higher in clay soil of grass ley when slurry was applied by injection compared to broadcasting and considered this finding as an indirect indication of higher risk of nitrate leaching with injection.

Cameira et al. (2019) reported a severe risk of pollution swapping with raw slurry injection on winter oats since it led to an increase of nitrate leaching relative to band application of raw or acidified slurry (more than 100% in the sandy soil and around 30% in the sandy loam soil for the rainiest year). The lower increase in sandy loam soils was explained as a result of a reduction of the nitrification process due to lower O2 availability associated with the higher water retention capacity of this soil. The study also showed that in sandy soils, close slot injection led to higher nitrate leaching than band application of acidified slurry (see V.2.3). Unlike the sandy soil, in the sandy loam soil there were no significant differences between injection and band application. This can be explained, on one hand, by the higher fixation of the NH_4 in the cationic exchange complex (CEC). On the other hand, a reduction of the nitrification process could be expected due to lower O_2 availability associated with the higher water retention capacity of this soil.

Kayser et al. (2015) also observed an increase of nitrate leaching with slurry injection relative to surface broadcast in productive grassland on organic–sandy soil.

Powell et al. (2011) compared the effects of broadcasting and closed-slot injection on nitrate leaching from cattle slurry applied to oats and winter rye in each spring in three consecutive years. They found that leaching following injection was lower than after broadcasting only in the first year but observed no difference in nitrate leaching in the two subsequent years.

Misselbrook et al. (1996a) observed no significant differences in nitrate leaching losses for cattle slurry applied to grassland by shallow injection or surface broadcast, while Misselbrook et al. (1996b) did observe an increase in NO_3 leaching losses from digested sewage sludge applied to grassland by injection when compared with surface application.

Turpin et al. (2007) determined that field-saturated hydraulic conductivity was, on average, lower at the bottom of furrows made by injection tines than undisturbed soil conditions at similar depths. In that study, flow through soil macropores is limited by injection tines especially when used in high soil moisture conditions.

Fangueiro et al. (2014) found that injection led to a worsening of nitrate leaching.

V.2.4 Slurry acidification

The effect of slurry acidification on nitrification relies strongly on soil properties, namelyits buffer capacity.

Application of acidified slurry delays microbial processes including nitrification and could be used as a measure to minimize nitrate leaching by reducing the amount of TAN transformed to nitrate (Fangueiro et al., 2016).

It has also been found that slurry acidification is associated with increased nitrogen use efficiency by increasing crop yield (e.g. by 57% in sandy soil and 40% in sandy loam soils compared to broadcasting of raw slurry) and lowering ammonia emissions (by approximately 97% in sandy and sandy loam soils) (Fangueiro et al., 2018).

In a similar vein, Loide et al. (2020) showed increases in rye grass and maize yields of 40% and 20%, respectively, compared to non-acidified slurry in-pot experiments amended with 15 and 45m³ ha⁻¹ of slurry application. However, a significant effect of acidified slurry on soil pH, but only when the large amount of acidified slurry (45 m³ ha⁻¹) was used, was a soil pH decrease by 0.1 units, which has been shown to facilitate dissociation of sulphate from soil particles. With sulphate anions, an equivalent amount of Ca and Mg cations is always leached from the soil, and therefore application of acidified slurry in Ca-poor soils in combination with the inhibitory effect of slurry acidification on nitrification and denitrification may increase the risk of nutrient leaching. This suggests that for environmental protection purposes, it is necessary to ensure that the nutrient amounts applied with slurry, particularly easily soluble nitrogen and sulphur, correspond to the needs of the plants.

Fangueiro et al. (2014) conducted a laboratory experiment over 24 days in controlled conditions, with undisturbed soil columns (sandy soil) in PVC pipes to compare the effects of four different treatments, (no slurry, injected whole slurry, surface application of whole and liquid-separated slurry, acidified whole and liquid-separated slurry) on nitrogen, phosphorus, and pathogen losses. The results showed that both broadcast application of acidified and liquid-separated slurry increased nitrate, phosphorus and FIO losses via leaching relative to all the other treatments throughout the experiment. Acidification reduced nitrate losses after an "irrigation" event relative to non-acidified treatments but increased nitrate losses relative to the "no slurry". Surface application of acidified cattle slurry increased the leaching risk for ammonium. Furthermore, FIO concentrations in broadcasting of acidified (before and after separation) slurry increased compared to injection or broadcast application of non-acidified slurry.Fangueiro et al., (2014) also found that separation increases the potential of leaching in sandy soils. The higher ammonium and labile carbon contents of the separated slurry relative to whole slurry support higher nitrification, followed by accumulation in soil and consequent leaching. The effect of acidification on N_{org} leaching is not clear, but the effect of solid–liquid separation was significant over the entire experiment with higher amounts of N_{org} lost from liquid slurry than from whole slurry. More than 70% of the total N applied could be lost by leaching in soils receiving ALF or LF. Therefore, application of slurry following separation should be restricted to the spring when the leaching potential is lower than in the autumn.

In conclusion, none of the strategies generally used to minimize ammonia emissions impact positively on leaching potential relative to the traditional surface application of CS. Furthermore, some treatments, such as separation, might significantly increase the risk of leaching. Acidification also led to lower soil pH.

V.3 Effect of LESS on losses of phosphorus to water

Trailing hose - Runoff

Johnson et al. (2011) studied trends in phosphorus (TP) losses in runoff (kg ha⁻¹) following broadcast spreading, band spreading and injection and found few differences in losses of soluble reactive phosphorus (SRP) between treatments, reflecting high variability in runoff depths.

Trailing shoe and Injection-Runoff

The impact of LESS on phosphorus (P) losses in surface runoff has received little attention. An Irish study examined the effect of slurry spreading techniques, (no slurry), broadcasting, injection, and trailing shoe on phosphorus losses in runoff using 0.5m by 1.0m plots with grass swards at two different stages of growth, a stubble and a 4-week regrowth. Slurry was applied by hand (40m³ ha⁻¹) (McConnell et al., 2013). Rainfall simulations (40mm h⁻¹) were conducted at 2, 9, and 28d post–slurry application. When slurry was applied to the stubble, SRP concentrations in runoff at Day 2 were 47% and 37% lower from the injection and trailing shoe treatments compared to broadcasting. Similarly, at Day 2, TP concentrations in runoff following injection were 27% lower than after broadcasting. A plausible explanation of these findings is that broadcasting covered more than 80% of the surface area on the broadcasting plots whereas slurry covered less than 20%

and 10% of the surface area on the trailing shoe and injection treatment plots, respectively. This would have resulted in a greater rate of slurry–water mixing and an increased likelihood of the dissolution and solubilisation of slurry P occurring on the broadcasting plots, resulting in elevated SRP concentrations in runoff. In contrast, with the trailing shoe and injection techniques, a reduction in contact area, cumulative raindrop impact, and interaction time probably limited the potential for dissolution of P from slurry to runoff. However, application technique had no effect on P concentrations in runoff following slurry application to the regrowth treatment, partly because of crop uptake and reduction of mobilisation of surface soil after rainfall due to growing plants. Overall, the study McConnell et al. (2013) suggested that trailing shoe and injection techniques offer the potential to reduce SRP concentrations in runoff during the period immediately after slurry application on grass swards and stubble.

Trailing shoe-Runoff

McConnell et al. (2016) assessed the effectiveness of the trailing-shoe technique as a means of reducing P losses when slurry is applied during periods of high soil moisture levels (immediately after rainfall) and lower herbage covers. The study included three treatments (no slurry), broadcasting and trailing shoe). Dairy cow slurry was applied at a rate of 20m^3 / ha, while simulated runoff was generated 2, 9 and 16 days later and analysed for a range of P fractions. The study found that SRP concentrations in runoff at day 2 was 41% lower when slurry was applied using the trailing shoe technique, compared to broadcasting. This finding was explained as a result of better assimilation of slurry P into soil in wet soils. Up to 60% of P from dairy cow slurry can infiltrate into soil provided a slurry DM content of less than 15% (Vadas et al., 2007 cited in McConnell et al., 2016), with up to two-thirds of infiltration occurring during the first four days after slurry application (Vadas, 2006 cited in McConnell et al., 2016). Once infiltration takes place slurry P is subject to rapid sorption by soil colloids, thus reducing its availability to runoff water. Soil moisture conditions seem to enhance sorption of P onto soil colloids. The study concluded that phosphorus concentrations in runoff appeared to be primarily driven by soil moisture levels, and not by date of slurry application per se, thus highlighting the importance of considering soil conditions at the time of spreading when seeking to minimise nutrient losses from applied slurry. In addition to optimal timing of slurry application, the use of trailing shoe during winter and early spring should be considered as a mitigation measure to minimise the risk of nutrient loss during this period.

Slurry injection-Runoff and leaching

Runoff. The benefits of slurry injection for water as a measure for preventing losses of phosphorus in runoff to surface waters vary by study. For example, Uusi-Kampa and Heinonen Tanski (2008) found that injection of cattle slurry into clay soils of grassland reduced the total phosphorus and SRP load in runoff by 65% and 75% (annual mean), respectively to the same level as in the control (compared to mineral fertiliser broadcast onto the soil surface), although the amount of fertiliser P applied to control plots was only half of that added in slurry. When slurry was injected in dry soils, reductions of TP and SRP in runoff were associated with 53%-66% of TP being bound to mobilised soil particles. When slurry was injected into wet soils, over 50% of TP losses consisted of SRP. Turtola and Kemppainen (1998) found that total phosphorus and soluble reactive phosphorus (SRP) concentrations and losses in runoff did not increase after an autumn slurry application if ploughing was done immediately, whereas the losses were drastically increased after autumn and winter slurry application without ploughing. Cameron et al. (1996) reported that SRP leaching and its concentration in drainage water were uniformly negligible after surface application and subsurface injection of dairy pond sludge to pasture on fine sandy loam soil.

Fangueiro et al. (2014) found that injection led to a worsening of total P leaching.

Acidification

Acidification triggered the dissolution of slurry P when the pH was lowered increasing the potential of P leaching (Daumer et al., 2010, Fangueiro et al., 2009).

Fangueiro et al., (2014) observed that effects of previous fertiliser applications and subsequent retention of P in the soil (mainly clay and sandy loamy soils) may confound the effect of acidification, separation or injection on P leaching. They suggested that the broadcast application to a sandy soil of 50kg P ha^{-1} of acidified whole slurry or 15kg P ha^{-1} as separated (acidified or not) slurry should not be problematic in terms of P losses to water.

V.4 Effect of LESS on FIO losses to water

Slurry injection-Runoff

The benefits of slurry injection for water as a measure to prevent losses of FIO in runoff to surface waters are poorly studied. For example, Uusi-Kampa and Heinonen Tanski (2008) found that injection of cattle slurry into clay soils of grassland only partially protected water quality from losses of microbial load in runoff. Despite reductions of faecal coliforms and somatic coliphages by 60% and 95%, respectively, when injecting slurry relative to broadcasting, microbial loads in runoff were above the threshold for safe waters (i.e. 350 CFU $(100\ mL)^{-1}$and 110 PFU $(100\ mL)^{-1}$, respectively.

Hodgson et al., (2016) found that method and timing of the slurry applications have an effect on FIO survival, with longer survival when slurry is applied by shallow injection than by broadcast application, and when applied in October compared to July, or May. The study also reported that FIOs die off up to 4 times faster when slurry is applied by broadcast application than by shallow injection because exposure to solar UV radiation enhances die off. The study concluded that injection can prolong the persistence of FIOs in soil, potentially increasing the risk of their subsequent transfer to water.

Fangueiro etal. (2014) conducted a laboratory experiment over 24 days in controlled conditions, with undisturbed soil columns (sandy soil) in PVC pipes to compare the effects of four different treatments, (no slurry, injected whole slurry, surface application of whole and liquid-separated slurry, acidified whole and liquid-separated slurry) on FIO losses. The results showed that injection led to a worsening of FIO leaching compared to broadcast application of non-acidified slurry; however, the E. coli and total coliform concentrations in acidified whole and liquid-separated slurry were significantly higher than in injection or broadcast application of non-acidified slurry.

Both studies suggested that slurry injection into the soil is likely to 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, Avery et al. (2004) found that *E. coli* O157 from bovine slurry and bovine stomach contents added onto the surface of experimental soil cores were mainly contained within the top layer of soil resulting in overall greater survival in surface-spread cores compared to cores amended with shallow injection. This result also suggested that sub-surface injection of organic wastes into soil may reduce the risk of pathogen persistence in the environment.

Acidification-Separation

Fangueiro et al. (2014) showed that surface application of acidified separated and whole slurry increased FIO leaching compared to injection or broadcast application of separated and whole non-acidified slurry, potentially as a result of higher survival rates of FIO at lower pH. Further, they showed that that a higher amount of FIO leached from the soils amended with materials obtained by separation. FIO leaching is more likely to occur immediately after application, as FIO leaching can be delayed due to soil adsorption, which is expected to happen when whole slurry is applied. This is an additional indication that slurry application should be prevented when rainfall is expected, and therefore leaching of FIO is more likely. Surface application of liquid separated slurry (acidified and not) had a negative impact on the potential leaching of nitrogen, phosphorus and FIO and therefore should be recommended only in cases where the leaching potential is low, i.e., clay and loamy sediments.

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