climate change
Scotland's centre of expertise connecting climate change research and policy

Evidence review of the efficacy of nitrification and urease inhibitors

Dave Freeman, Jeremy Wiltshire, Becky Jenkins
Ricardo Energy & Environment
May 2020
DOI: http://dx.doi.org/10.7488/era/449

1 Executive summary

1.1 Background

Scotland's Climate Change Plan makes a policy commitment to reduce greenhouse gas (GHG) emissions from nitrogen fertiliser through improved understanding, efficient application and better soil condition[1].

Nitrification and urease inhibitors have been identified as potential tools in the mitigation of emissions (specifically nitrous oxide and ammonia) from the use of inorganic fertiliser. These inhibitors are particularly important for those who are modelling both GHG emissions and air quality. However, while some studies provide consistent messages concerning the evidence of their effectiveness and their impacts on the wider environment, others are contradictory.

This report reviews current knowledge and considers the potential for nitrogen and urease inhibitors to support emission reductions in Scotland, considering Scottish circumstances and conditions, such as soils, crops, rainfall and temperature.

1.2 Key findings

The evidence indicates that:

- There is generally a positive potential impact of inhibitors on GHG and Ammonia emissions under Scottish conditions, especially for nitrification inhibitors. Efficacy is impacted by factors such as pH, soil wetness and temperature.
- Both the literature and stakeholders suggested there were no significant concerns over the efficacy of inhibitors in Scotland. Both nitrification and urease inhibitors have been available in Scotland for many years. The low uptake relates to the niche market; inhibitors are primarily supplied for agronomic benefit with relatively marginal economic gains in most circumstances.
- While the efficacy of inhibitors has been confirmed by the review, there remain uncertainties over the magnitude of emissions reductions. There are also questions relating to the environmental risk, trade-offs with potential emission/pollution switching, industry knowledge and practical implementation.
- The persistence of the effects for both nitrification and urease inhibitors are likely to be impacted by a warmer climate. There are no specific studies relevant to Scottish conditions but,

---

[1] Climate Change Plan: third report on proposals and policies 2018-2032, p198

based on the evidence and projected climate changes, any impact is likely to be minimal. Emissions from unabated fertilisers are expected to increase as climate change progresses. Under these conditions, the role of inhibitors as a tool in mitigating nitrous oxide and ammonia emissions becomes increasingly important.

The evidence for environmental risks includes:

- There is little evidence exploring the impacts of N inhibitors on soil health and on impacts to non-target and nitrifying organisms.
- Use of nitrification inhibitors can lead to increases in ammonia emissions. However, alongside this, there are benefits for other environmental indicators (particularly GHG emissions and nitrate leaching). The potential increase in ammonia emissions can be mitigated by use of nitrification and urease inhibitors together.
- Some research highlights the risk of DCD (dicyandiamide - a nitrification inhibitor) leaching into surface and ground waters, particularly if application is poorly timed around rainfall. Leaching of DCD can have adverse effects on aquatic systems by blocking nitrification processes.
- There are concerns regarding animal consumption (directly or via traces found on grass/hay) as DCD has been found in dairy products in New Zealand. This led to DCD being banned in New Zealand.
- Increased risk of ammonia release from use of nitrification inhibitors will have adverse impacts on ecosystem biodiversity through deposition and increased N loading to sensitive sites.

The main practical/commercial considerations are:

- Both nitrification and urease inhibitors are available and effective in Scotland. They are not widely used due to poor cost effectiveness under conventional economic analysis at farm gate (i.e. not considering externalities of environmental or societal costs). Current use relates to minor crops or alternative systems for nutrient campaigns (e.g. single application early in the season with inhibitors effectively acting as slow release/controlled availability mechanisms).
- In the agriculture industry, there remains significant misunderstanding over the roles and practical application of inhibited fertilisers. Efficacy has been confirmed, but there is little investment in understanding the economic and agronomic benefits of inhibitors or to encourage new technologies and guidance on their use.
- Investment in nitrification inhibitors will not be driven by market pull. Stakeholders feel N inhibitors are not currently attractive prospects for increased investment.
- Urease inhibitors are more commercially viable (compared with nitrification inhibitors) and have potential economic benefits due to the potentially high emissions of ammonia losing significant N content. Interest and awareness of urease inhibitors is greater, both in the farming and advisory/supply networks.
- Price sensitivity: farmers in the UK are very sensitive to fertiliser price and will seek the most cost effective source of N. A perception of little or no economic value in inhibited fertilisers will discourage adoption.
- Increased cost of urease treated urea can lead to product substitution by ammonium nitrate; there is a perception in the industry that this can lead to increased leaching of nitrate and increased N_2O emissions.

Contents

1 Executive summary 1
1.1 Background 1
1.2 Key findings 1
2 Nitrogen Inhibitors and how they work 1
3 Context: Scotland's agriculture, soils and climate 2
3.1 Farming in Scotland 2
3.2 Climate 3
4 Nitrification and urease inhibitors: current state of knowledge 3
4.1 Analyses of strengths, weaknesses, opportunities and threats (SWOT) for the use of nitrification and urease inhibitors 4
4.2 PESTEL Analysis 5
4.3 Efficacy 10
4.4 Risks 14
4.5 Co-benefits 16
4.6 Uses of nitrogen inhibitors with livestock and their manures 16
5 Applicability to Scotland 16
5.1 Location-specific studies 16
5.2 Applicability of evidence to Scotland 19
5.3 Applicability of inhibitors in Scotland 19
6 Conclusions 20
7 References 22
Appendix 1: Reactions affected by inhibitors 27
Appendix 2: Efficacy of nitrogen inhibitors 28
Appendix 3: Climate change projections 32
Appendix 4: Co-benefits 38
Appendix 5: Uses of nitrogen inhibitors with livestock and their manures 39
Appendix 6: Land Capability for Agriculture classifications 40
Appendix 7: Scottish-focused research papers 43

2 Nitrogen Inhibitors and how they work

The inhibitors covered in this evidence review fall into two main types: nitrification inhibitors and urease inhibitors. In this report we refer to these collectively, as nitrogen (N) inhibitors. Nitrogen inhibitors are used with fertiliser nitrogen (inorganic fertilisers) and can also be used with livestock manures (and other organic materials that are spread to land) or applied directly to soil (e.g. at the time of livestock manure applications). The focus of this report is the use of N inhibitors with inorganic fertilisers.

Nitrification inhibitors reduce emission of nitrous oxide (N_2O) from soil and decrease leaching of soil nitrate (NO_3^-).

Urease inhibitors are used to decrease emission of ammonia (NH_3) following hydrolysis of urea in or on the soil.

Both nitrification inhibitors and urease inhibitors slow down losses of reactive nitrogen compounds to the environment, giving crops more time for nutrient uptake. See 'Appendix 1: Reactions affected by inhibitors' for more details of the chemical process by which this is achieved.

Some of the N inhibitors that are frequently mentioned in the evidence are listed in Table 1 as examples of chemicals with nitrification inhibitor or urease inhibitor activity.

Dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (known as DMPP) are the most common commercially available nitrification inhibitors (Rees et al., 2013).

In addition to the N inhibitors listed in Table 1, there are other chemicals that have been used commercially and/or experimentally, and there is potential for many more. Cardenas et al. (2019) in reviewing natural N inhibitors identified chemicals with nitrification inhibitor activity in root exudates of grasses, particularly tropical grasses in the genus *Brachiaria*, rice (*Oryza sativa*) and in the genus *Sorghum*. There is the prospect of breeding to include nitrification inhibition into crop species, especially cereals. For urease inhibition, natural compounds with activity have also been identified, including from *Aloe vera*, and garlic (*Allium sativum*). Research is needed to establish the efficacy of these and other plant extracts and, for effective candidates, to commercialise them either as products or in plant breeding programmes.

Slow release fertilisers, although not designed specifically for nitrification or urease inhibition, have some effect on these processes. Polymer-coated fertilisers use partially permeable coatings to slow the release of nitrogen (Li et al., 2018), and this has the effect of lowering the peak soil concentrations of active nitrogen compounds such as ammonium (NH_4^+) and nitrate (NO_3^-), which are needed for the reactions leading to ammonia and nitrous oxide emission. A meta review (Li et al., 2018) has shown large decreases in losses of ammonia and nitrous oxide for polymer-coated fertilisers. Indicative decreases of 74% were reported for emissions of ammonia and nitrous oxide in grassland systems. However, there is large variation in these emission decreases, and differences related to climate and soil type. Efficacy was poorer in dryland systems than in other cropping systems, and more effective in coarse-textured soils and soils with low organic matter content, than in other soils.

Table 1: Examples of inhibitors.

Common names	Chemical name	Activity
DCD, DIDIN[1, 2]	dicyandiamide	Nitrification inhibitor
DMPP, ENTEC[1, 2]	3,4-dimethylpyrazole phosphate	Nitrification inhibitor
DMPSA[1]	2-(3,4-dimethyl-1H-pyrazol-1-yl) succinic acid isomeric mixture	Nitrification inhibitor
Nitrapyrin, N-Serve[3, 2]	2-chloro-6-(trichloromethyl)-pyridine	Nitrification inhibitor
NBPT, NBPT, nBTPT, or Agrotain® [1, 3, 4]	N-(n-butyl) thiophosphoric triamide	Urease inhibitor
PPD/PPDA[5]	phenyl phosphorodiamidate	Urease inhibitor
NPPT[5]	N-(2-Nitrophenyl) phosphoric triamide	Urease inhibitor

[1] Cardenas et al., 2019; [2] Watson et al., 2009; [3] MarketWatch, 2019; [4] Cowan et al., 2019; [5] MarketWatch, 2020

Products are being developed which utilise blends of urease inhibitors (NBPT and NPPT) which can provide advantages to the abatement of ammonia emissions. These products act on different processes within the soils and can offer greater potential emission abatement. In the stakeholder discussions these products were identified as relatively new to market but being sold commercially within the UK and may offset some of the limitations of single inhibitors used in isolation.

3 Context: Scotland’s agriculture, soils and climate

3.1 Farming in Scotland

In Scotland. 5.56 million hectares of land is utilised for agricultural production (73% of land area[2]). The type of production is limited by the land capacity. Figure 2: Land Capability for Agriculture in Scotland shows the distribution of land classifications across Scotland with the classifications; a further discussion of production types is presented in Appendix 6: Land Capability for Agriculture classifications.

[2] https://www2.gov.scot/Topics/Statistics/Browse/Agriculture-Fisheries/agritopics/Grassland

Approximately 1.9 million hectares (33%) of land receive a dressing of inorganic nitrogen fertiliser[3] and thus could be in scope to receive nitrogen and urease inhibitors. These areas are the improved grassland (supporting intensive beef, dairy and sheep) and the cropped area (dominated by barley and wheat production). Areas of rough grazing do not generally receive any applications of fertiliser.

Applications of fertiliser begins in the spring months as grass and crop growth begins, with no significant applications before March (Table 2). Over 90% of all fertiliser nitrogen is applied between March and June.

For croplands, the majority (70%) of nitrogen (as a nutrient) is applied as a straight fertiliser (single nutrient source); ammonium nitrate is the main source, with urea and urea ammonium nitrate being other significant sources. For grassland, the majority of inorganic nitrogen is applied as part of a compound fertiliser (mixture of nutrient types e.g. NPK). Emissions of nitrous oxide from urea fertilisers can be lower than from ammonium nitrate, but their use can lead to significant emissions of ammonia. These characteristics of fertiliser use are relevant to this study because the presence of other nutrient sources can have significant impacts upon the efficacy and durability of nitrogen inhibitors.[4]

Table 2: Timings of nitrogen fertiliser application in Scotland

Nutrient application	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Nitrogen (proportion of total)	0	1	11	43	27	10	6	2	0	0	0	0

3.2 Climate

The efficacy of nitrogen and urease inhibitors is impacted by factors such as pH, soil wetness and temperature. Therefore, it important to understand the effectiveness of these in the context of the current Scottish climate which is characterised as a temperate, mild climate, with cool summers and mild winters with rainfall spread throughout the year. But also, the likely impact of climate change on rainfall and temperature. To do so, this project uses the UK Climate Projections 2009 (UKCP09) medium emissions scenario, predictions for Scotland. The forward climate predictions from UKCP09 were provided for the 2020s, 2050s and 2080s to derive the changes in rainfall and temperature. Full details of the UKCP09 and the selected climate change scenarios are presented in Appendix 3: Climate change projections.

[3] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/854404/fertiliseruse-report2018-20dec19.pdf

[4] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/854404/fertiliseruse-report2018-20dec19.pdf

4 Nitrification and urease inhibitors: current state of knowledge

Nitrification and urease inhibitors have been widely used across the world (particularly in the US, Europe, New Zealand and Australia) and promoted in the mitigation of gaseous emissions of nitrous oxide and ammonia. Efficacy of both types of inhibitors have been well evidenced, however there are a range of factors that need to be considered in the context of Scotland. The sections below set out the key considerations and state of understanding.

4.1 Analyses of strengths, weaknesses, opportunities and threats (SWOT) for the use of nitrification and urease inhibitors.

Table 3: Nitrification and urease inhibitors: strengths, weaknesses, opportunities and threats (SWOT)

Strengths	Weaknesses
• *Strong evidence that inhibitors reduce emissions if used correctly (matched to fertiliser and soil type).* • *Some evidence of higher yields associated with use (Bell, et al., 2015a).* • *Reduce leaching of nitrous oxide and ammonia into nearby water sources (Lam, et al, 2017).* • *Use of inhibitors can lead to reduced split N applications, so reduces management costs soil compaction and use of fossil fuels (Ni, et al., 2014).* • *Evidence shows nitrification inhibitors, such as DMPP, are efficient and have a low inhibitory effect onplant and soil biota (Qiao-Gang, et al., 2014).*	• *Abalos et al (2014) found in some instances, applying nitrification inhibitors to neutral or alkaline soils may lead to increased N losses.* • *If inhibitor is intercepted by plant canopy there a risk it will not reach the soil before nitrification and denitrification takes place (Bell, et al., 2015b).* • *NBPT degrades rapidly in high temperatures and acidic soils (Cantarella, et al., 2018).* • *NBPT is incompatible with phosphorus and sulphur and will degrade rapidly negating any inhibiting impact.* • *Decreased efficiency can be caused by sorption to the soil matrix (for example, clays and organic matter) and immobilisation by non-target microorganisms (Guardia, et al., 2018).* • *DCD and DMPP are not as efficient when applied during high temperatures (over 16 °C) (Chen, et al., 2008).*

Opportunities	Threats
• *Cantarella et al. 2018 predict the demand for urease inhibitor use will grow annually by 10-12% in the next 10 years. For example, as of 2020, Germany has introduced legislation that all urea fertiliser must either be incorporated into the soil or applied with urease inhibitors.* • *Improved formulation and understanding of nitrification and urease inhibitors will support improved nutrient use efficiency and should increase productivity.*	• *Potential withdrawal of products through concerns about food safety or environmental impact.*

4.2 PESTEL Analysis

Table 4: Nitrification and urease inhibitors: PESTEL Analysis

Type	Opportunities	Constraints	Potential mitigation measures
Political	• *Nitrification and urease inhibitors have been identified as mitigation strategies for both GHG and ammonia. Relatively high certainty of mitigation impacts. Usage could be easily measured for reporting on national targets*	• *Niche products with minimal market pull for uptake* • *Uncertainty over policy drivers varied between agriculture, climate change and air quality.*	• *Out of scope*

Type	Opportunities	Constraints	Potential mitigation measures
Economic	• *Evidence that use of inhibitors can increase nutrient use efficiency, mainly by reducing ammonia and nitrate loss.* • *Reduces cost impact of GHG and air quality impacts on wider economy*	• *Nitrification inhibitors do not generally provide any economic benefit to users; they have additional cost that is not recouped.*	• *R&D for improved understanding of economic benefit to users.*

Type	Opportunities	Constraints	Potential mitigation measures
Social	• *Improvements in air quality and mitigation of GHG emissions will have positive impacts on society. This is particularly true of ammonia where the wider environmental implications are well described. Improvements in the quality of designated sites through reduced N deposition will offer wider societal benefits.*	• *Perceived issues with NBPT and DCD have raised concerns in some areas (namely in the MSDS for treated and treated urea) and in milk in New Zealand. The evidence relating to these concerns is not clear. However, this creates uncertainty in both policy development and user acceptance.*	• *R&D into the wider risks and mitigations/safety relating to inhibitors.* • *Better understanding of users (farmers) and advisers through training and integration with advice and application methods.*
Technological (including agronomic)	• *Inhibitors have been developed and researched for a number of purposes – the use of inhibitors can assist with agronomic performance of N fertilisers.* • *Technologies (particularly in relation to formulation and effectiveness of urease inhibitors) continue to develop.* • *Knowledge and understanding of the effective use of inhibitors continues.*	• *Lack of perceived economic benefits for farmers have stalled investment in commercially available products (Stakeholder insight). The predominant nitrification and urease inhibitors are not new and have been available for a number of years. This is particularly the case with nitrification inhibitors.* • *Urease inhibitors are receiving more investment in light of growing drivers for reducing ammonia emissions and likely restrictions on unabated urea across Europe.*	• *Support for R&D to develop technologies and support greater understanding in the effective application of inhibited fertilisers in practical field use.* • *Promotion of the benefits of inhibited urea – agronomically, logistically (can help ease workload by reducing field operations) and environmentally.*

Type	Opportunities	Constraints	Potential mitigation measures
Environmental	• *Inhibitors can reduce losses of nitrous oxide, nitrate and ammonia. Their use can contribute to improvements in both water and air quality.* • *Changes to agricultural practices may also lead to improvements in soil conditions.* • *Reductions in the externalities associated with nitrogen losses should have additional benefits for both terrestrial and aquatic flora and fauna.*	• *Uncertainty over the wider environmental implications for increased loading on both nitrification and urease inhibitors. Little evidence on the direct impacts of inhibitors relates to assessments of biological activity within the soil, assessed via* CO_2 *measurement (Menédez, 2012).*	• *Need for R&D into the wider interactions with the soil biota and losses into water.* • *Varied opinion on the potential or actual risks on inhibitors to the environment and limited specific studies other than under REACH assessments.* • *Improved evidence should seek to clarify the implications of use against a relevant range of potential receptors.*

Type	Opportunities	Constraints	Potential mitigation measures
Legal/Regulatory	• *New EU fertiliser regulations[5] have specific provisions for putting inhibitors into the marketplace. While there is uncertainty over the adoption of these regulations in the UK, the presence of these regulations with near trading partners will have an influence on the availability of inhibited fertilising products. Regulation of N fertilisers has been proposed but is not currently enacted across the UK. Urease requirements are being promoted ahead of nitrification inhibitors due to NECD and Trans Boundary issues.* • *Their use has been promoted within the IPCC guidance in relation to nitrification inhibitors. Urease inhibitors have been widely promoted within voluntary codes and are now required for urea fertiliser in Germany.*	• *Lack of clarity in regulatory framework – no standards for defining properties or efficacy of products.*	• *Possible inclusion in voluntary quality standards.* • *Inclusion of provisions for inhibitor products within UK domestic fertiliser regulations.*

5 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2019:170:FULL&from=EN

4.3 Efficacy

The key finding of the review are summarised here; a more detailed analysis of the evidence and efficacy of nitrification and urease inhibitors is presented in Appendix 2: Efficacy

4.3.1 Nitrification inhibitors

The efficacy of nitrification inhibitors as a means of abating nitrous oxide emissions is highly variable. The efficacy for common nitrification and urease inhibitors is presented in Table 5 and Table 6. While the evidence suggests the efficacy of nitrification inhibitors is well established, the range of factors which influence their effectiveness should be noted and are presented in Table 7. Evidence identifies a risk of increased ammonia emissions when nitrification inhibitors are used, but additional work is needed to establish the risks under Scottish circumstances. The use of nitrification and urease inhibitors together has been shown to successfully mitigate this increased risk.

4.3.2 Urease inhibitors

Urease inhibitors are applied, principally, to mitigate emissions of ammonia, but can also reduce nitrous oxide, both directly and indirectly. The reductions in nitrous oxide emissions are presented in Table 6. The evidence for effects of urease inhibitors on nitrous oxide emissions is less strong than for effects of nitrification inhibitors, but the evidence for their effect on ammonia emissions is well established. The efficacy values given in Table 6 are further supported by other studies. In a recent review, Cantarella et al. (2018) state that the efficacy of NBPT to reduce ammonia loss is well documented, but there is a need for improvement to the shelf life of NBPT-treated urea, and the period for which it is active after application.

Table 5: Examples of efficacy values and ranges (percentage decrease in nitrous oxide emissions) for different nitrification inhibitors.

<table>
<tr><th>Nitrification inhibitor</th><th>Efficacy (% decrease in nitrous oxide emissions)</th><th>Crop</th><th>Notes on conditions</th><th>Reference</th></tr>
<tr><td>DCD</td><td>42.3% ±2.2</td><td>Grassland: 48%
Cropland: 36%
Upland: 32%</td><td rowspan="2">Meta-analysis using 111 datasets from 39 studies.
There was little effect on efficacy of either soil texture or fertiliser type.</td><td rowspan="2">Gilsanz et al., 2016</td></tr>
<tr><td>DMPP</td><td>40.2% ±3.7</td><td>Grassland: 46%
Cropland: 38%
Upland: 35%</td></tr>
<tr><td>Nitrification inhibitors in general</td><td>40%</td><td>Not stated</td><td>Estimate based on review of three previous studies.
The estimate is for mineral fertiliser and slurry applications.</td><td>van den Broek et al., 2007</td></tr>
<tr><td>DCD</td><td>34%</td><td>Grassland</td><td>Work done in Scotland, urea + DCD</td><td>Bell et al., 2016</td></tr>
<tr><td>DCD, DMPP, N-Serve and pyrazole derivatives</td><td>8% to 57%</td><td>Not stated</td><td>Review of multiple studies, from multiple locations, and with multiple N sources</td><td>Lam et al., 2016</td></tr>
<tr><td>DCD</td><td>20% to 67%</td><td>Not stated</td><td>Review of multiple studies, from multiple locations, and with multiple N sources</td><td>MacLeod et al., 2015</td></tr>
<tr><td>Nitrification inhibitors in general</td><td>35%</td><td>Not stated</td><td>Review of multiple studies (140 data sets), from multiple locations, and with multiple N sources.</td><td>Ruser and Schulz, 2015</td></tr>
</table>

Table 6: Examples of efficacy values and ranges (percentage decrease in nitrous oxide emissions) for urease inhibitors.

Urease inhibitor	Efficacy (% decrease in nitrous oxide emissions)	Efficacy (% decrease in ammonia emissions)	Crop	Notes on conditions	Reference
nBTPT	0% to 47%	70%	Grass	Multiple sites and seasons. nitrous oxide mitigation efficacy greater where emissions were greater.	Smith et al., 2012
nBTPT	No data	53%	Not stated	A review of multiple studies, with differing climates and conditions	Cantarella et al, 2018
hydroquinone	5%	No data	Not stated	Meta-analysis, multiple studies	Modolo et al., 2018
nBTPT	48%	47%	Grass	Temperate climate, New Zealand	Singh et al., 2013
nBTPT	53%	90%	Grass for silage	Study site in Scotland (Easter Bush, Midlothian)	Cowan et al., 2019

4.3.3 Key parameters that influence effectiveness

Key parameters that influence effectiveness of nitrogen inhibitors for nitrous oxide and ammonia mitigation are summarised in Table 7. The review has identified the primary parameters, which have a direct impact upon the efficacy of inhibitors, as soil temperature, pH, soil type and soil moisture/precipitation. In Scotland it is unlikely that these will have a significant impact upon inhibitor efficacy, but their potential impact should be noted in relation to policy developments. It should also be noted these parameters can also affect the emissions of nitrous oxide and ammonia.

Table 7: Parameters that influence effectiveness of nitrogen inhibitors

Parameter	Description, influence on effectiveness
Temperature	For DCD and DMPP, efficacy decreases as temperature rises (Guardia et al., 2019). Freeze-thaw cycles increase nitrous oxide emissions and the interaction with efficacy is highly uncertain (Ruser and Schulz, 2015).
Soil type	For DCD and DMPP, it has been shown that efficacy decreases as pH rises (Guardia et al., 2019). McGeough et al. (2016) provided evidence that the efficacy of DCD was governed by the interaction between temperature, soil clay content and soil organic matter.
Soil pH	For DCD and DMPP, efficacy decreases as pH rises (Guardia et al., 2019)
Soil moisture	Menéndez et al (2012), persistence of DMPP influence by soil moisture status. As soil moisture increases the DMPP molecule is less exposed to oxidation and so persists for longer. There is no direct impact upon the inhibiting effect.
Formulation	Some evidence was supplied by stakeholders that formulation of fertilisers has been improving the performance and shelf life of inhibitors. These comments relate to urease inhibitors where the persistence of the molecules in the environment is relatively short. There is no specific evidence of formulation implications or modifications for Scottish conditions. Nitrification inhibitors DCD and DMPP are relatively stable with no reported shelf life concerns. DMPP is not stable within liquid fertiliser formulations.
Form of available N applied to the soil	The fertiliser applied significantly influences the potential emission losses; nitrification inhibitors have been shown to be effective on all N forms but can be influenced by the fertiliser type and more inherent emission potential. Urease inhibitors are directly relevant to urea fertilisers and the mitigation of ammonia as discussed in earlier sections.

4.3.4 Efficacy in a changing climate

There is limited literature relating to the impact of climate change on nitrification inhibitor efficacy and we have been unable to identify any literature on the the impacts on urease inhibitors. We have therefore based our review on the primary parameters affecting efficacy and the likely climate change impacts upon these parameters. Temperature is identified in the review as the primary parameter that may influence efficacy. In Scottish conditions, with fertiliser application from February – June and the cool Scottish climate, it is unlikely that temperature will reduce nitrification inhibitor effectiveness significantly. The most likely warming scenarios across Scotland all project an increase in temperature to no higher than 17 ºC as a summer average, which is broadly within the effective temperature range of inhibitors.

For urease, the increased temperatures will likely reduce duration of emission abatement. While the inhibitors will still be effective, their persistence in the soil will be reduced to the 10-15 day window after application.

However, future warming and rainfall scenarios would indicate climate conditions similar to sites reported on within the literature and efficacy of urease inhibitors could be expected to remain. In temperate conditions with relatively high rainfall during the application period, there is not likely to be a significant impact on the efficacy of urease inhibitors.

These potential implications for warmer future climate impacts are unlikely to significantly reduce overall efficacy of both nitrification and urease inhibitors and could be mitigated by improved formulations, understanding of the use of inhibitors by farmers and advisers, and better use of technology and best practice in nutrient management (stakeholder insight).

4.4 Risks

Risks to air, water and biodiversity are summarised in Table 8. In the literature reviewed, there were more risks found for use of nitrification inhibitors than for urease inhibitors. This is an area for possible future review; stakeholders felt there was a lack of clear consensus, particularly in relation to soil health implications of all inhibitors and to operator health implications of urease inhibitors. There were no risks to air or water identified for urease inhibitors. Some other risks identified that do not fall into one of these subcategories are as follows:

- *It is uncertain how efficacy is affected by freeze-thaw cycles (Ruser and Schulz, 2015), but the timing of fertiliser applications in Scotland would put most inhibitor applications outside the expected period for significant and repeated freezing.*
- *There are commercial risks, with increased costs without certainty in benefits to nutrient uptake. These restrictions limit the likely interest in inhibitors without additional drivers beyond market controls.*
- *Uncertainty for co-benefits (not looked at in detail as this report focuses on nitrous oxide emission). There are conflicts between papers on efficacy for nitrate leaching mitigation. Industry advice is that nitrification inhibitors have a greater agronomic value in limiting losses through nitrate leaching. This is a generally accepted benefit of nitrification inhibitors but has not been reviewed in detail in this study.*
- *Entry of inhibitors into the food chain – uncertainty over transmission into food and any human health implications. Marsden et al. (2015) confirmed plant uptake into wheat; records of DCD presence in milk in NZ have been reported (Pal et al 2016). There is no evidence for food safety concerns (relating to DCD) but this is a perceived risk and needs more detailed review.*

Table 8: risks to air, water and biodiversity.

Inhibitor	Air	Water	Biodiversity
Nitrification inhibitors	Depending on soil properties, nitrification inhibitors risk increased ammonia emissions due to extended availability of NH_4^+ (Wang et al, 2020; Misselbrook et al, 2014). See also Zaman and Blennerhassett (2010) for evidence of increased ammonia emissions (by 41% and 18% in autumn and spring respectively) when DCD was applied with urine. When ammonia is emitted to air, indirect nitrous oxide emission can follow (Lam et al., 2017). Use of nitrification inhibitors can increase ammonia but wider benefits on other environmental considerations need to be considered – use of nitrification inhibitors and urease inhibitors together can offset these limitations (Ni, 2014)	Some research highlights the risk of DCD leaching into surface and ground waters, particularly if application is poorly timed around rainfall (Bell et al., 2015a; Bell et al., 2015b). Studies have found DCD has little impact on reducing nitrate leaching.	Potential leaching of DCD can have adverse effects on aquatic systems by blocking nitrification processes (Bell et al., 2015a). Concerns over application through animal consumption (directly or via traces found on grass/hay) as traces have been found in dairy products in New Zealand (Cantarella et al., 2018; Qiao et al., 2015). Studies found DCD application resulted in over 150% increase in soil CH_4 (Dong et al., 2018). Applying DCD does not always have a positive impact on yield; some studies have found it deteriorates plant growth (Chen et al., 2008). Increased risk of ammonia release will have adverse impacts on ecosystem biodiversity (Lam et al., 2017). Uncertainty on impacts to non-target and nitrifying organisms in soils (Ruser and Schulz, 2015).

Inhibitor	Air	Water	Biodiversity
Urease inhibitors	No risks to air were identified that are additional to risks associated with fertiliser use.	No risks to water were identified that are additional to risks associated with fertiliser use.	Temporary impacts on internal N metabolism found in plants due to absorption of NBPT through plant roots (Cantarella et al, 2018; Mathialagan et al, 2017). Temporary yellowing of leaf tips caused by urea toxicity soon after application of NBPT due to changes in metabolic pathways. This has not been found to have impacts on growth (Cantarella et al, 2018).

4.5 Co-benefits

A number of additional benefits may be realised through the utilisation of nitrogen inhibitors; the main benefits are described in Appendix 4: Co-benefits and are summarised below:

- *Reduction of nitrate leaching into water is a co-benefit in the context of this study*
- *Mitigation of ammonia emissions (in the context of GHGs)*
- *Increased yields and economic performance*
- *Decreased nitrogen inputs*
- *Fertiliser application practice - applications may be made earlier, and in a single application (reducing the number of field operations, and decreasing risks of soil compaction)*

4.6 Uses of nitrogen inhibitors with livestock and their manures

Through the review of literature, we have identified the use of nitrification and urease inhibitors within livestock systems. Although not a primary element of this review, the inhibitors have been extensively researched for application direct to pasture, within manures, and directly to livestock via rations and water. They can be effective in mitigating emissions from direct deposits and applications of manures and slurries. More detail is provided within Appendix 5: Uses of nitrogen inhibitors with livestock and their manures.

5 Applicability to Scotland

5.1 Location-specific studies

We found eight papers that were specific to Scotland, with an even split between SW and SE Scotland. The majority are based on one single nitrification inhibitor, with only two discussing urease inhibition. All the studies reported high rainfall. In the absence of an inhibitor, high rainfall shortly after fertiliser application leads to peaks in nitrous oxide emissions and, in the case of Scotland, this would mean there is a greater need for inhibitors. Generally lower temperatures were present at the Scottish study sites when compared with the majority of the research identified, these relatively cooler temperatures benefit DCD efficacy. Details of our analysis can be found in Appendix 7: Scottish-focused research papers.

Table 9: Field studies in Scotland.

Source	Location	Soil type	Crop type	Inhibitor used	Notes
Bell et al., 2016	Dumfries (South-West)	Free-draining sandy to sandy-loam	Grassland	DCD + AN	Reduced nitrous oxide emissions
Bell et al., 2015a	East Lothian (South-East)	Sandy clay loam	Spring barley	DCD + AN DCD + urea	Reduced nitrous oxide emissions
Bell et al., 2015b	Dumfries (South-West)	Free-draining sandy to sandy-loam	Grassland	DCD + dung and urine	No significant reductions to emissions
Cardenas et al., 2019	Dumfries (South-West)	Sandy loam	Grassland	DCD + AN DCD + urea	Reduced nitrous oxide emissions
Chadwick et al., 2018	Dumfries (South-West)		Grassland	DCD + dung and urine	Reduced nitrous oxide emissions
Cowan et al., 2019	Midlothian (South-East)	Clay loam	Grassland	NBPT + urea	Reduced ammonia emissions
Dobbie & Smith, 2003	Glencorse (South-East)	Clay loam	Perennial ryegrass	DCD & NBPT (combined) + urea DCD + urea NBPT + urea	DCD reduced emissions, NBPT had little impact
Hinton, 2015	Gilchriston (South-East)	Sandy loam	Spring barley	DCD + AN DCD + urea	Reduced nitrous oxide emissions

5.2 Applicability of evidence to Scotland

The efficacy of both nitrification inhibitors and, to a lesser extent, urease inhibitors, have been reviewed under a variety of Scottish conditions and soils. Evidence generally shows the positive potential impact of inhibitors under Scottish conditions. Efficacy is impacted by factors such as pH, soil wetness and temperature. Table 7: Parameters that influence effectiveness of nitrogen inhibitors and Table 9: Field studies in Scotland. summarise the literature, identifying relevant studies and parameters which can impact upon inhibitor efficacy.

In addition to the literature, insight from stakeholders also suggested that there were no significant concerns for the efficacy of inhibitors in Scotland. Both nitrification inhibitors and urease inhibitors have been available for a considerable time and have been sold across Scotland for many years. The low uptake relates to the niche market; inhibitors are primarily supplied for agronomic benefit with relatively marginal economic gains in most circumstances. Manufacturers have not added significant additional trials work to the published literature in Scotland reviewed here. Research that has been more widely undertaken across varied agroclimatic zones with conditions akin to those present in Scotland is well represented,with this feedback provided for both nitrification inhibitors and urease inhibitors.

We highlight the extracts below from the literature:

- *Bell et al. 2016: DCD study in SW Scotland exploring ammonium nitrate and urea impact in Scottish grassland. This study concluded there was a lack of clear consensus in the relevant literature (not Scotland related); there is wide variability on the measured impact consistent with the wide range of influences on inhibitor performance as identified in Table 6. Urea and DCD did have a significant impact – but fertiliser rate and rainfall had a greater influence. Emissions were very varied in the study; emissions reflected the relatively high application rates. Evidence in relation to ammonium nitrate and DCD was less clear. The study identifies the need for wider agronomic considerations with inhibitor use; there are many influences on emissions, all need to be considered for maximum abatement.*
- *Bell et al. 2015a: DCD study on one arable site in Scotland and two in England – concluded that DCD does have a significant impact on reducing emissions at all sites. There was no difference in impact between sites or between fertiliser type.*
- *Urease – Cowan et al. (2019) East Scotland. Shows significant benefit in ammonia reductions from urease inhibitor on urea, but notes the large pool of N unaccounted for and no significant yield improvement under this study.*
- *Dobbie et al 2003 – found the use of urea fertiliser with the addition of DCD was effective in Scottish conditions. This study explores the use of alternative N fertiliser forms to mitigate the nitrous oxide emissions from the relatively wet soils often found across Scotland particularly at early season applications. The addition of NBPT in this study did not find any benefits for nitrous oxide reductions.*

While there is limited specific literature relating to Scotland, there have been sufficient studies elsewhere which broadly reflect the wider evidence for inhibitors. Many of the studies reviewed include Scottish sites within broader studies. Evidence from stakeholders and the literature corroborate the primary influences on inhibitor efficacy. While there are undoubtably uncertainties in the specific abatement within the studies presented here, the underlying evidence is that inhibitors can have a positive impact on emission reduction.

5.3 Applicability of inhibitors in Scotland

Evidence identified within the literature as well as from the stakeholder discussions indicate that both nitrification inhibitors and urease inhibitors are already used within Scotland. Levels of uptake are relatively low (Communications, AIC). However, the evidence presented covers all relevant cropping and primary agricultural land use in Scotland. Much of the literature is focused on either grassland or arable production, while evidence from the stakeholders indicates that the use of inhibited nitrogen fertilisers within the higher value potato market is well established.

Nitrification inhibitors are widely available in all forms of nitrogen fertilisers including the primary sources used within Scotland: Ammonium Nitrate, Urea and Urea Ammonium Nitrate (UAN).

Recent developments in urease inhibitors offer a commercially more attractive product; there are treated products available within Scotland. However, there are greater uncertainties in relation to the shelf life and compatibility of inhibited urea. These challenges are being worked on within the supply chain and viable products are available.

The characteristics of fertiliser use in Scotland, as well as the climatic conditions, support the use of inhibitors in response to GHG emissions. The relatively wet and warm climate gives rise to greater risks of nitrous oxide emissions, particularly in the predominant grassland areas. It should be noted that the pH of Scottish soils is generally lower than for many parts of the UK; this can have implications for fertiliser use, efficiency and losses. The pH of soils can also affect the efficacy of inhibitors. However, with generally more acidic conditions in Scottish soils, these impacts are unlikely to reduce the efficacy of nitrification inhibitors

It should, however, be noted that there may be other factors of management which could contribute to the mitigation of nitrous oxide and ammonia losses. These include fertiliser product choice, timing of application, soil and rainfall conditions and temperature.

6 Conclusions

Use of nitrification inhibitors is an effective mitigation measure for nitrous oxide emissions. While there are uncertainties over the degree of abatement within the studies analysed, the underlying evidence is that inhibitors can have a positive impact on emission reduction. Evidence from stakeholders and the literature corroborate the primary influences on inhibitor efficacy.

Use of urease inhibitors is an effective mitigation measure for ammonia emissions, but efficacy for GHG mitigation is uncertain and probably low.

For nitrification inhibitors, since there is strong evidence for efficacy, the main concerns from a policy development perspective are:

- *Environmental risks*
- *Practical and commercial considerations*
- *Mechanisms for encouraging use/uptake*
- *Industry knowledge, understanding and training in use*
- *Better integration into agronomic practice, and into improved nitrogen utilisation systems*
- *Improved understanding of the risks and limitations of inhibitors (e.g. are there food safety concerns?)*

Both nitrification and urease inhibitors are likely to be adversely impacted by warming climatic conditions, There are no specific studies relevant to Scottish conditions but, based on the evidence and projected climate changes, it is likely that any impact will be minimal. The relevance of inhibitors becomes of greater importance under climate warming with   increased emissions from unabated fertilisers expected.. Under these conditions, the role of inhibitors as a tool in mitigating nitrous oxide and ammonia emissions becomes increasingly important.

The main environmental risks are:

- *There is little evidence for the impacts of N inhibitors on soil health. This is a concern raised by industry stakeholders with uncertainty over impacts to non-target and nitrifying organisms in soils' studies.*

- *Use of nitrification inhibitors can increase ammonia emission, but wider benefits on other environmental considerations need to be considered – use of nitrification inhibitors and urease inhibitors together can offset these limitations.*
- *Some research highlights the risk of DCD leaching into surface and ground waters, particularly if application is poorly timed around rainfall.*
- *Leaching of DCD can have adverse effects on aquatic systems by blocking nitrification processes.*
- *There are concerns over application through animal consumption (directly or via traces found on grass/hay), as traces have been found in dairy products in New Zealand. These led to DCD being banned in New Zealand, as a precaution, while wider environmental and food safety concerns were investigated.*
- *Increased risk of ammonia release will have adverse impacts on ecosystem biodiversity through deposition and increased N loading to sensitive sites.*

The main practical/commercial considerations are:

- *Both nitrification and urease inhibitors are available and effective in Scotland. Their use is not widely adopted due to marginal or negative cost effectiveness under conventional economic analysis at farm gate (i.e. not considering externalities of environmental or societal costs). Current use relates to minor crops or alternative systems for nutrient campaigns (e.g. single application early in the season with inhibitors effectively acting as slow release/controlled availability mechanisms).*
- *In the agriculture industry there remains a significant amount of misunderstanding and confusion over the roles and practical application of inhibited fertilisers. Efficacy has been confirmed but there is little investment in understanding the economic and agronomic benefits of inhibitors or to encourage new technologies and guidance of their use.*
- *Investment in nitrification inhibitors will not be driven by market pull. Stakeholders feel N inhibitors are not currently attractive prospects for increased investment.*
- *Urease inhibitors are more commercially viable (compared with nitrification inhibitors) and have potential economic benefits due to the potentially high emissions of ammonia losing significant N content. Interest and awareness of urease inhibitors is greater, both in the farming and advisory/supply networks.*
- *Limited interest and marginal economic returns have discouraged investment in technology and training/system development.*
- *Price sensitivity: farmers in the UK are very sensitive to fertiliser price and will seek the most cost-effective source of N. A perception of little or no economic value in inhibited fertilisers will discourage adoption.*
- *Increased cost of urease-treated urea can lead to product substitution by ammonium nitrate; there is a perception in the industry that this can lead to increased leaching of nitrate and increased nitrous oxide emission.*

7 References

Abalos, D., Jeffery, S., Sanz-Cobena, A., Guardia, G. and Vallejo, A. (2014). Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency. Agriculture Ecosystems & Environment 189, 136-144.

AHDB. 2020. Nutrient Management Guide (RB209), updated February 2020. Section 1 Principles of nutrient management and fertiliser use. AHDB, Kenilworth, UK. https://ahdb.org.uk/knowledge-library/rb209-section-1-principles-of-nutrient-management-and-fertiliser-use

Barneze AS, Minet EP, Cerri CC and Misselbrook T. 2015. The effect of nitrification inhibitors on nitrous oxide emissions from cattle urine depositions to grassland under summer conditions in the UK. Chemosphere 119: 122–129.

Bell MJ, Cloy JM, Topp CFE, Ball BC, Bagnall A, Rees RM and Chadwick DR. 2016. Quantifying N_2O emissions from intensive grassland production: the role of synthetic fertilizer type, application rate, timing and nitrification inhibitors. The Journal of Agricultural Science, 154: 812–827.

Bell, M.J., Hinton, N., Cloy, J.M., Topp, C.F.E., Rees, R.M., Cardenas, L., Scott, T., Webster, C., Ashton, R.W., Whitmore, A.P., Williams, J.R., Balshaw, H., Paine, F., Goulding, K.W.T. and Chadwick, D.R. (2015a). Nitrous oxide emissions from fertilised UK arable soils: Fluxes, emission factors and mitigation. Agriculture Ecosystems & Environment 212, 134-147.

Bell, M.J., Rees, R.M., Cloy, J.M., Topp, C.F.E., Bagnall, A. and Chadwick, D.R. (2015b) Nitrous oxide emissions from cattle excreta applied to a Scottish grassland: Effects of soil and climatic conditions and a nitrification inhibitor. Science of the Total Environment, 508, pp.343-353.

Bibby, J.S., Douglas, H.A., Thomasson, A.J., and Robertson, J.S. (1991). Land Capability Classification for Agriculture. Macaulay Land Use Research Institute, Aberdeen. 84pp.

Cantarella, H., Otto, R., Soares, J.R. and de Brito Silva, A.G. (2018) Agronomic efficiency of NBPT as a urease inhibitor: A review. Journal of advanced research, 13, pp.19-27.

Cardenas LM, Ma Yan, Misselbrook T and Chadwick DR. 2019. Impacts of inhibitor use on nitrous oxide and ammonia emissions, nitrate leaching and resulting crop yields. Proceedings International Fertiliser Society 836.

Chadwick, D.R., Cardenas, L.M., Dhanoa, M.S., Donovan, N., Misselbrook, T., Williams, J.R., Thorman, R.E., McGeough, K.L., Watson, C.J., Bell, M., Anthony, S.G. and Rees, R.M. (2018). The contribution of cattle urine and dung to nitrous oxide emissions: Quantification of country specific emission factors and implications for national inventories. Science of the Total Environment 635, 607-617.

Chen, D., Suter, H., Islam, A., Edis, R., Freney, J.R. and Walker, C.N. (2008). Prospects of improving efficiency of fertiliser nitrogen in Australian agriculture: a review of enhanced efficiency fertilisers. Australian Journal of Soil Research 46, 289-301.

Cowan N, Levy P, Moring A, Simmons I, Bache C, Stephens A, Marinheiro J, Brichet J, Song L, Pickard A, McNeill C, McDonald R, Maire J, Loubet B, Voylokov P, Sutton M, and Skiba U. 2019. Nitrogen use efficiency and N_2O and NH_3 losses attributed to three fertiliser types applied to an intensively managed silage crop. Biogeosciences, 16: 4731–4745.

Dobbie, K.E. and Smith, K.A. (2003) Impact of different forms of N fertilizer on N 2 O emissions from intensive grassland. Nutrient cycling in Agroecosystems, 67(1), pp.37-46.

Dong, D., Kou, Y., Yang, W., Chen, G. and Xu, H. (2018) Effects of urease and nitrification inhibitors on nitrous oxide emissions and nitrifying/denitrifying microbial communities in a rainfed maize soil: A 6-year field observation. Soil and Tillage Research, 180, pp.82-90.

Feliciano D, Hunter C, Slee B and Smith P. 2013. Selecting land-based mitigation practices to reduce GHG emissions from the rural land use sector: A case study of North East Scotland. Journal of environmental management, 120: 93-104.Gilsanz C, Baez D, Misselbrook TH, Dhanoa MS and Cardenas LM. 2016. Development of emission factors and efficiency of two nitrification inhibitors, DCD and DMPP. Agriculture Ecosystems & Environment 216: 1–8.

Guardia G, Marsden KA, Vallejo A, Jones DL and Chadwick DR. 2018. Determining the influence of environmental and edaphic factors on the fate of the nitrification inhibitors DCD and DMPP in soil. Science of the total environment, 624: 1202-1212.

Hinton, N.J., Cloy, J.M., Bell, M.J., Chadwick, D.R., Topp, C.F.E. and Rees, R.M. (2015) Managing fertiliser nitrogen to reduce nitrous oxide emissions and emission intensities from a cultivated Cambisol in Scotland. Geoderma Regional, 4, pp.55-65.

Kim D-G, Saggar S and Roudier, P. 2010. What are nitrification inhibitors? http://niandnh3.blogspot.com/ last accessed 10 March 2020.

Kim D-G, Saggar S and Roudier, P. 2012. The effect of nitrification inhibitors on soil ammonia emissions in nitrogen managed soils: a meta-analysis. Nutr Cycl Agroecosyst 93: 51–64.

Lam SK, Suter H, Mosier AR and Chen D. 2017. Using nitrification inhibitors to mitigate agricultural N2O emission: a double-edged sword? Global Change Biology, 23: 485-489.

Li TY, Zhang WF, Yin J, Chadwick D, Norse D, Lu YL, Liu XJ, Chen XP, Zhang FS, Powlson D and Dou ZX. 2018. Enhanced-efficiency fertilizers are not a panacea for resolving the nitrogen problem. Global Change Biology 24: E511-E521.

Li, Y., Shah, S.H.H. and Wang, J. (2020) Modelling of nitrification inhibitor and its effects on emissions of nitrous oxide (N2O) in the UK. Science of The Total Environment, 709, p.136156.

MacLeod M, Eory V, Gruère G and Lankoski J. 2015. Cost-Effectiveness of Greenhouse Gas Mitigation Measures for Agriculture: A Literature Review, OECD Food, Agriculture and Fisheries Papers, No. 89, OECD Publishing, Paris. http://dx.doi.org/10.1787/5jrvvkq900vj-en

MarketWatch. 2019. Press Release, 02-Apr-2019. https://www.marketwatch.com/press-release/nitrification-inhibitors-market-2019-global-industry---key-players-size-trends-opportunities-growth-analysis-and-forecast-to-2026-2019-04-02 Last accessed 09 March 2020.

MarketWatch. 2020. Press Release, 06-Sep-2019. https://www.marketwatch.com/press-release/nitrification-and-urease-inhibitors-market-to-attain-a-value-of-2136-billion-by-the-end-of-2023-2019-09-06 Last accessed 09-Mar-2020 Last accessed 09 March 2020.

Marsden, K.A., Scowen, M., Hill, P.W., Jones, D.L. and Chadwick, D.R. (2015). Plant acquisition and metabolism of the synthetic nitrification inhibitor dicyandiamide and naturally-occurring guanidine from agricultural soils. Plant and Soil 395, 201-214.
Mathialagan, R., Mansor, N., Al-Khateeb, B., Mohamad, M.H., Shamsuddin, M.R., 2017. Evaluation of Allicin as Soil Urease Inhibitor. In: Choudhury, I.A., Metselaar, H.S.C., BinYusoff, N. (Eds.), Advances in Material & Processing Technologies Conference, pp. 449-459.
McGeough, K.L., Watson, C.J., Mueller, C., Laughlin, R.J. and Chadwick, D.R. (2016). Evidence that the efficacy of the nitrification inhibitor dicyandiamide (DCD) is affected by soil properties in UK soils. Soil Biology & Biochemistry 94, 222-232.

Minet, E.P., Jahangir, M.M.R., Krol, D.J., Rochford, N., Fenton, O., Rooney, D., Lanigan, G., Forrestal, P.J., Breslin, C. and Richards, K.G. (2016a). Amendment of cattle slurry with the nitrification inhibitor dicyandiamide during storage: A new effective and practical N2O mitigation measure for landspreading. Agriculture Ecosystems & Environment 215, 68-75.

Minet, E.P., Ledgard, S.F., Lanigan, G.J., Murphy, J.B., Grant, J., Hennessy, D., Lewis, E., Forrestal, P. and Richards, K.G. (2016b). Mixing dicyandiamide (DCD) with supplementary feeds for cattle: An effective method to deliver a nitrification inhibitor in urine patches. Agriculture Ecosystems & Environment 231, 114-121.

Misselbrook, T.H., Cardenas, L.M., Camp, V., Thorman, R.E., Williams, J.R., Rollet, A.J. and Chambers, B.J. (2014). An assessment of nitrification inhibitors to reduce nitrous oxide emissions from UK agriculture. Environmental Research Letters 9, 11.

Menéndez, S., Barrena, I., Setien, I., González-Murua, C. and Estavillo, J.M. (2012) Efficiency of nitrification inhibitor DMPP to reduce nitrous oxide emissions under different temperature and moisture conditions. Soil Biology and Biochemistry, 53, pp.82-89.
Modolo, L.V., da-Silva, C.J., Brandão, D.S. and Chaves, I.S. (2018) A minireview on what we have learned about urease inhibitors of agricultural interest since mid-2000s. Journal of advanced research, 13, pp.29-37.

Ni, K., Pacholski, A. and Kage, H. (2014) Ammonia volatilization after application of urea to winter wheat over 3 years affected by novel urease and nitrification inhibitors. Agriculture, Ecosystems & Environment, 197, pp.184-194.Pal, P., McMillan, A.M., & Saggar, S. (2016). Pathways of dicyandiamide uptake in pasture plants: a laboratory study. Biology and Fertility of Soils, 52: 539-546.

Qiao-Gang, Y. et al., 2014. Effects of Nitrification Inhibitor DMPP Application in Agricultural Ecosystems and Their Influencing Factors:A Review. *Journal of Agro-Environment Science,* Volume 6.

Qiao, C., Liu, L., Hu, S., Compton, J.E., Greaver, T.L. and Li, Q. (2015) How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input. Global change biology, 21(3), pp.1249-1257.

Rees RM, Baddeley JA, Bhogal A, Ball BC, Chadwick DR, Macleod M, Lilly A, Pappa VA, Thorman RE, Watson CA, and Williams JR. 2013. Nitrous oxide mitigation in UK agriculture, Soil Science and Plant Nutrition, 59: 3-15.

Roche, L., Forrestal, P.J., Lanigan, G.J., Richards, K.G., Shaw, L.J. and Wall, D.P. (2016) Impact of fertiliser nitrogen formulation, and N stabilisers on nitrous oxide emissions in spring barley. Agriculture, ecosystems & environment, 233, pp.229-237.

Rose, T.J., Wood, R.H., Rose, M.T. and Van Zwieten, L. (2018) A re-evaluation of the agronomic effectiveness of the nitrification inhibitors DCD and DMPP and the urease inhibitor NBPT. Agriculture, Ecosystems & Environment, 252, pp.69-73.

Ruser, R. and Schulz, R. (2015) The effect of nitrification inhibitors on the nitrous oxide (N2O) release from agricultural soils—a review. Journal of Plant Nutrition and Soil Science, 178(2), pp.171-188.

Singh, J., Kunhikrishnan, A., Bolan, N.S. and Saggar, S. (2013) Impact of urease inhibitor on ammonia and nitrous oxide emissions from temperate pasture soil cores receiving urea fertilizer and cattle urine. Science of the total Environment, 465, pp.56-63.

Smith, K.A., Dobbie, K.E., Thorman, R., Watson, C.J., Chadwick, D.R., Yamulki, S. and Ball, B.C. (2012). The effect of N fertilizer forms on nitrous oxide emissions from UK arable land and grassland. Nutrient Cycling in Agroecosystems 93, 127-149.

SRUC. 2013, Technical Note TN651 Nitrogen recommendations for cereals, oilseed rape and potatoes. SRUC, Aberdeen, Scotland, https://www.sruc.ac.uk/downloads/file/1271/tn651_nitrogen_recommendations_for_cereals_oilseed_rape_and_potatoes van den Broek, JA, van Hofwegen G, Beekman M and Woittiez M. 2007. Options for increasing nutrient use efficiency in Dutch dairy and arable farming towards 2030: an exploration of cost-effective measures at farm and regional levels (No. 55).

Wang, H., Köbke, S. and Dittert, K. (2020) Use of urease and nitrification inhibitors to reduce gaseous nitrogen emissions from fertilizers containing ammonium nitrate and urea. Global Ecology and Conservation, p.e00933.

Watson CJ, Laughlin RJ and McGeough KL. 2009. Modification of nitrogen fertilisers using inhibitors: opportunities and potentials for improving nitrogen use efficiency. Proceedings International Fertiliser Society 658

.Zaman, M. and Blennerhassett, J.D. (2010). Effects of the different rates of urease and nitrification inhibitors on gaseous emissions of ammonia and nitrous oxide, nitrate leaching and pasture production from urine patches in an intensive grazed pasture system. Agriculture Ecosystems & Environment 136, 236-246.

Acknowledgements

We wish to thank the following individuals and organisations for their contributions to this report, their time was given freely and their insight was of great value in the production of this review.

David Booty – Omex Agriculture Ltd.

George Fisher – CF Fertilisers UK Ltd.

Jane Salter – Agricultural Industries Confederation

Mark Tucker – Yara UK Ltd.

Richard Corden – BASF Plc.

Robert Meakin – Sirius Minerals Plc

Tim Kerr – HL Hutchinsons Ltd.

climateXchange

Scotland's centre of expertise connecting climate change research and policy

info@climatexchange.org.uk
+44(0)131 651 4783
@climatexchange_
www.climatexchange.org.uk

ClimateXChange, Edinburgh Centre for Carbon Innovation, High School Yards, Edinburgh EH1 1LZ

List of appendices

Appendix 1: Reactions affected by inhibitors

Appendix 2: Efficacy of nitrogen inhibitors

Appendix 3: Climate change projections

Appendix 4: Co-benefits

Appendix 5: Uses of nitrogen inhibitors with livestock and their manures

Appendix 6: Land Capability for Agriculture Classifications

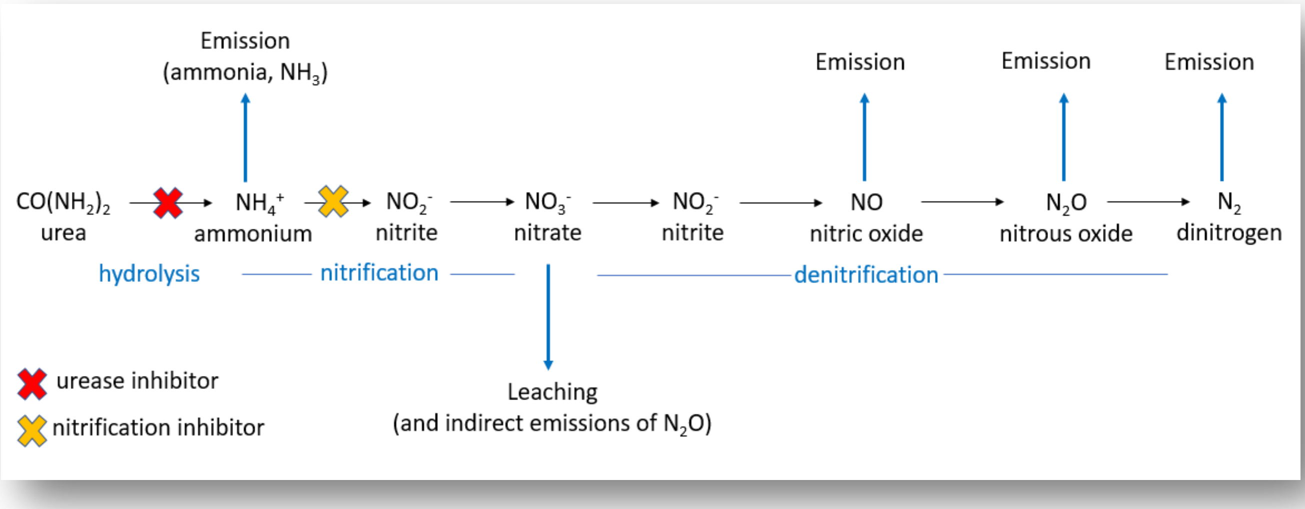
Appendix 7: Scottish-focused research papers

Appendix 1: Reactions affected by inhibitors

Urea and ammoniacal N are applied to soil in fertilisers or as constituents of livestock manures,which are either applied after collection from housed livestock, or directly deposited by animals during grazing.

Figure 1 shows the processes of urea hydrolysis, nitrification (oxidation of NH_3 to NO_3^-) and denitrification (the reduction reactions from NO_3^- to nitrogen gas, N_2). Losses to the environment are shown as emissions and leaching, and the reactions blocked by N inhibitors are indicated for urease inhibitors and nitrification inhibitors.

Figure 1: Reactions affected by inhibitors (adapted from Cardenas et al., 2019)



Nitrification inhibitors deactivate the ammonia monooxygenase enzyme responsible for the oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) (Kim et al., 2012; see Figure 1 and work by slowing the activity of *Nitrosomonas*, the genus of nitrifying bacteria responsible for the oxidation (nitrification) reaction (Kim at el., 2010). The inhibition of nitrification results in less leaching of nitrate, and also results in less denitrification with less nitrous oxide (N_2O) emission.

Urease inhibitors decrease NH_3 volatilisation after application of urea to soil, by inhibiting the enzyme urease which catalyses urea hydrolysis (Rochel et al., 2016; see Figure 1).

Appendix 2: Efficacy of nitrogen inhibitors

Nitrification inhibitors

The efficacy of nitrification inhibitors as a means of abating N_2O emissions is highly variable because:

- *nitrogen is applied to land or crops in different forms*
  (most N fertiliser in Great Britain, and Scotland, is applied in the form of ammonium nitrate; other forms include urea, urea ammonium nitrate, calcium ammonium nitrate, ammonium sulphate, ammonium phosphate, and many fertiliser blends (AHDB, 2020));
- *there are different nitrification inhibitors*
  (see section 4);
- *nitrification inhibitors may be applied in different ways and formulations*
  (for example, they may be applied with the fertiliser either as a coating or blend or applied to the soil separately from the fertiliser; they may also be applied to or with animal manures in various ways (Cardenas et al., 2019));
- *soil types vary (fertiliser recommendations vary by soil type (AHDB, 2020; SRUC, 2013); soil type influences pH, drainage and aeration, which in turn influence the soil processes that lead to N_2O emission (see Smith et al., 2012 for effects of soil wetness on N_2O emission); soil clay and organic matter contents also influence DCD efficacy (McGeough et al., 2016));*
- *climatic conditions vary (temperature influences N_2O emission (Barneze et al., 2015), and therefore the abatement potential); and*
- *the rate of N uptake by crops varies (this influences the concentration of available N in the soil (AHDB, 2020), and therefore the processes of nitrification and denitrification).*

It is therefore to be expected that efficacy values are often provided as ranges. Here (Table 5) we give ranges where available, and we express efficacy as a percentage decrease in emissions. In presenting these examples, we have given priority to studies from the UK and Scotland, and to recent studies.

The efficacy values given in Table 5 are further supported by studies that do not provide efficacy values as a percentage decrease in emissions. Feliciano et al. (2013) reported that nitrification inhibitors were one of seven measures selected based on mitigation potential, additionality, permanence, knowledge and uncertainty. These seven practices were: woodland planting, precision farming, incorporation of crop residues, controlled release fertilisers, nitrification inhibitors, avoiding N excess and using biological fixation to provide N inputs with clover.

There is evidence that the abatement of N_2O emissions by nitrification inhibitors can be accompanied by an increase in NH_3 emission: Lam et al. (2017) reported that nitrification inhibitors effectively and consistently decrease direct N_2O emission, but this can be negated or even reversed by indirect N_2O emission from deposited NH_3. When ammonia is deposited, nitrification and N_2O emission can follow (Figure 1) as it does following application of NH_3 in fertiliser or manures. We estimate, from data in the study by Lam et al. (2017) that in situations where the nitrification inhibitor has good efficacy (as in most studies), the decrease in efficacy through indirect N_2O emission from deposited NH_3 is less than 5%. However, further measurements under Scottish conditions would help to (a) confirm that this is not a major risk for nitrous oxide abatement efficacy, and (b) quantify the increase in ammonia emission, which leads to environmental impacts.

Urease inhibitors

Urea is the most widely used N fertiliser in the world (Modolo et al., 2018), but not in the UK, where ammonium nitrate dominates. Urea on the soil surface is rapidly hydrolysed with losses to the environment of up to 70% of the N applied (Modolo et al., 2018). Urease inhibitors are applied, principally, to mitigate emissions of NH_3, but there can also be effects on emissions of N_2O, both directly and indirectly. When ammonia is emitted to air, it is deposited elsewhere and nitrification and N_2O emission can follow (see Figure 1) by the same mechanism as it does following application of NH_3 in fertiliser or manures. Here, we focus mainly on the effect on GHG emissions, and therefore on N_2O emissions, but efficacy for abatement of NH_3 emission is also considered. In Table 6 we give ranges where available, and we express efficacy as a percentage decrease in emissions. In presenting these examples, we have given priority to studies from the UK and Scotland, and to recent studies.

The evidence for effects of urease inhibitors on N_2O emissions (examples in Table 5) is less strong than for effects of nitrification inhibitors. Effects of urease inhibitors on N_2O emissions reported in the literature are not consistent and there have been fewer studies than for nitrification inhibitors. This is to be expected since the main purpose of using urease inhibitors is to mitigate NH_3 emissions, and there is strong and consistent evidence that urease inhibitors are effective for NH_3 mitigation.

The efficacy values given in Table 6 are further supported by other studies. In a recent review, Cantarella et al. (2018) state that the efficacy of NBPT to reduce NH_3 loss is well documented, but there is a need for improvement to the shelf life of NBPT-treated urea, and the period for which it is active after application.

Nitrification and urease inhibitors used together

Nitrification and urease inhibitors have been used together with the aim of increasing nitrogen use efficiency (NUE). Zaman and Blennerhassett (2010) showed that nitrification and urease inhibitors used together with urine applications decreased emission of NH_3 (48% and 51%) and N_2O (55% and 63%), and leaching of NO_3 (56% and 42%) in autumn and spring, respectively. There were also increases in pasture production (13% and 17%) and N uptake (7% and 18%) in autumn and spring, respectively.

Cantarella et al. (2018) reported that nitrification inhibitors usually increase NH_3 volatilisation, but that mixing them with urease inhibitors reduced this NH_3 emission.

Efficacy in a changing climate

In this review we have been asked to assess the implications of future climate change scenarios on the efficacy of nitrogen inhibitors. The two groups of inhibitors are described separately below. The UKCP09 medium emission scenario has been used in the assessment of the likely changes in rainfall and temperature and is presented in Appendix 3: Climate change projections.

Climate change implications for Nitrification inhibitors

Li (2020) identified the interaction of temperature, precipitation and fertilisation combined as critical factors controlling the losses of N_2O. The timing of fertilisation and of precipitation have a significant impact upon the peaks of N_2O loss. If precipitation increases and corresponding temperature also increases then losses will increase; conversely if temperature increases while precipitation decreases then N_2O emission will also decrease. Rainfall in the days immediately after fertiliser application can cause a significant spike in N_2O emissions, and this will drive most of the losses within a relatively short period after fertiliser application. The study by Li (2000) concluded that increased warming is the critical factor impacting nitrification inhibitors (DCD) and, under warmer conditions, the efficacy of nitrification inhibitors will be reduced and N_2O emissions increased. The reduction in impact of nitrification inhibitors under increasing temperature has been described by Gilsanz et al (2016); in their work both DCD and DMPP were shown to be very effective below 5^oC with inhibitory effect lasting up to six months. As soil temperatures increase above 10^oC they identified a linear decrease in effectiveness largely due to a decrease in inhibitor persistence and increasing biological activity within the soil. DCD and DMPP were seen to last for up to three months at 10^oC, falling to just two to three weeks at temperatures of 25°C and just a week at 30°C. In their work on DMPP, Menéndez et al (2012) did not find any direct impact of temperature on DMPP persistence but rather identified soil moisture status as being the critical driving factor on the concentration of DMPP. Under greater saturation the degradation of DMPP was reduced, retaining greater proportion within the soil. It was suggested this is associated with reduced oxidation of the molecule; moisture state does not directly impact upon the inhibiting properties but slows breakdown, retaining the inhibitor in the soil for longer.

In their studies on DCD and DMPP Guardia et al (2018) corroborate these impacts and again confirm the reduction in inhibitor activity; reduced concentrations are the critical factor linking climatic conditions, degradation/metabolism of the molecules and inhibition effect.

In Scottish conditions, with fertiliser application from February to June and with the cool Scottish climate, the projected increases in temperature under climate change are unlikely to have a significant impact such that the overall efficacy of N inhibitors will negate their effectiveness as N_2O mitigation. The most likely warming scenarios across Scotland project an average increase in temperature to no higher than 17 ºC in the summer. A slight increase in winter average temperature may encourage earlier biological activity encouraging nitrification. However, as the temperature ranges are well within the optimum for nitrification inhibitor efficacy, inhibitor degradation will not be significantly increased; the presence of inhibitors during the critical phase immediately post fertiliser application is likely to be sustained under these scenarios. There may be a requirement to review practices and to collate additional data on soil temperature in light of the above evidence and possible future warming under climate change. It can be concluded, however, that the primary driving factor for inhibitor efficacy under a warming climate will be temperature rather than precipitation.

Climate change implications for urease inhibitors

We have not been able to identify any specific studies which review the efficacy of urease inhibitors under future climate scenarios, either for Scotland or elsewhere. This analysis has therefore reviewed the primary drivers for inhibitor efficacy and degradation. The assessment of the likely impact of climate change on the efficacy of urease inhibitor has been inferred from the potential increase in temperature and the sensitivity of inhibitors to increased metabolism and reduced duration of the inhibiting effect within the soil.

The critical factor for ammonia loss is incorporation: providing mechanical incorporation or precipitation occurs within the first few days after application, the majority of NH_3 losses will be prevented (Cantarella et al., 2018).

The climate implications for efficacy directly relate to the duration/persistence of urease inhibitors within the soil. Temperatures influence the decomposition of urease inhibitors. With higher temperatures, the decomposition of commonly used urease inhibitors begins earlier. In temperate conditions breakdown will typically begin at 10-15 days after fertilisation, but under hot soil conditions this can be as short as one to two days (Canterella et al., 2018). Under warming climate scenarios, the impact of increased soil temperature will negatively impact upon the efficacy of urease inhibitors. Inhibitors will still be able to reduce the losses of ammonia; however, there may be implications for the level of abatement potential. Reduction in the duration of inhibiting impacts can be offset through increases in the quantity of inhibitor present, in the formulation and in the timing of fertiliser application.

Increased temperature will reduce the efficacy/persistence of urease inhibitors. These characteristics are well known and were widely reported in the stakeholder interviews. Under warming climate scenarios, this may be expected to reduce the efficacy duration into the 10-15 day window after application. However future warming and rainfall scenarios would indicate climate conditions similar to sites reported within the literature; efficacy of urease inhibitors could be expected to remain. In temperate conditions with relatively high rainfall during the application period, there is unlikely to be a significant impact on the efficacy of urease inhibitors.

Increased rainfall during the application period would be expected to support incorporation of urea fertiliser reducing NH_3 emissions. However, drier, hotter potential summer conditions could both reduce the duration of inhibitor impact and also reduce the impact of rainfall incorporating urea fertiliser into the soil. These potential implications for warmer future climate impacts are unlikely to significantly reduce overall efficacy and could be mitigated by improved formulations, understanding of the use of inhibitors by farmers and advisers, and better use of technology and best practice in nutrient management (stakeholder insight).

Appendix 3: Climate change projections

Scotland benefits from a temperate, mild climate, with cool summers and mild winters with rainfall spread throughout the year. Regional variation, in both temperature and rainfall, are driven by factors such as latitude, distance from the sea, altitude and ocean currents.

These regional variations are generally described as three distinct zones, Northern, Eastern and Western Scotland. The south is generally warmer than the north in summer, mainly due to the influence of latitude. The west is generally milder, cloudier and wetter than the east due to the prevailing winds from the south-west and the influence of the North Atlantic Drift. The east is also sheltered by the mountain ranges in the west, which create a rain-shadow effect. The west also has a smaller range of temperatures than the east because of the moderating influence of the Atlantic Ocean. The north and west Highlands usually have lower temperatures throughout the year than the low-lying areas in the south and east because of the influence of altitude. The west has more rain in winter.[6]

The UKCP09 climate predictions for the three areas of Scotland have been used with a medium emissions scenario with the 5%, 50% and 95% probabilities provided to show the range of possible changes in rainfall and temperature. This selection was based on the medium emissions scenario being the most likely to be realised (given current global efforts to curtail emissions) and the 5%, 50% and 95% probabilities giving the most likely climate outcome with the 5% and 95% scenarios presenting the more reasonable extremes possible scenarios while removing extreme outliers.

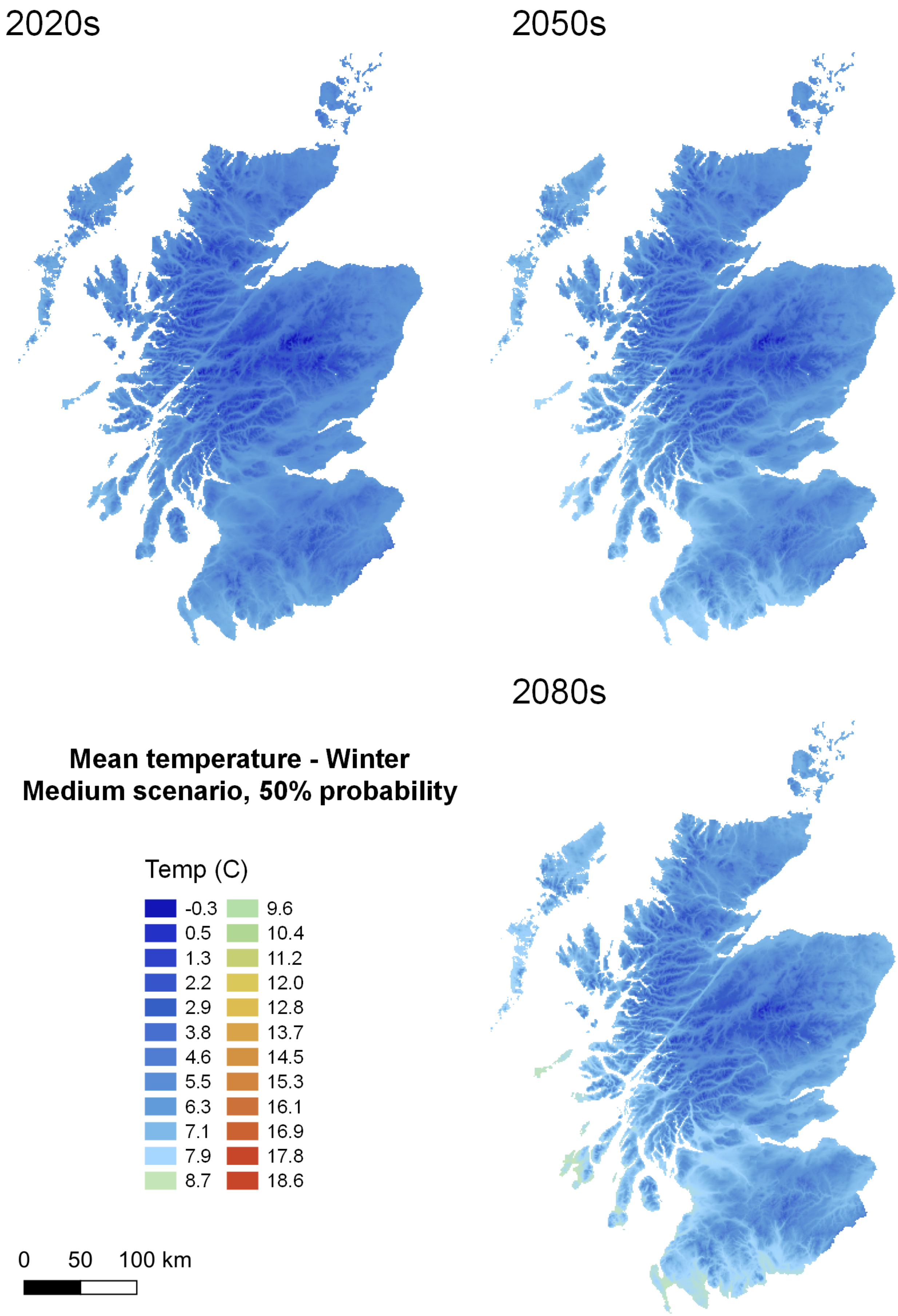
UKCP09 predictions are provided for 2020s, 2050s and 2080s (Table 10). More detailed maps of the projected temperature and rainfall projections are provided below.

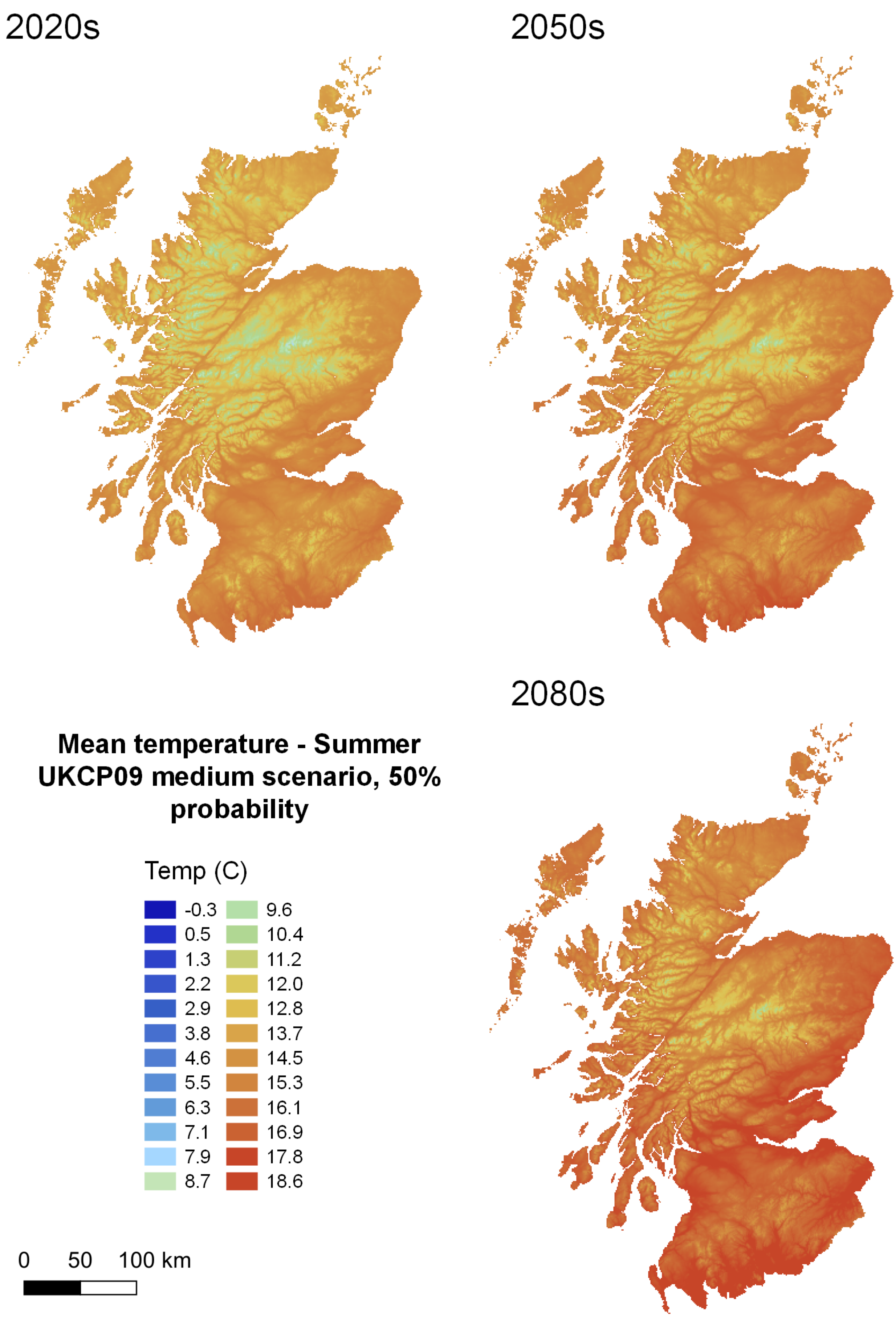
[6] https://www.environment.gov.scot/media/1185/climate-climate.pdf

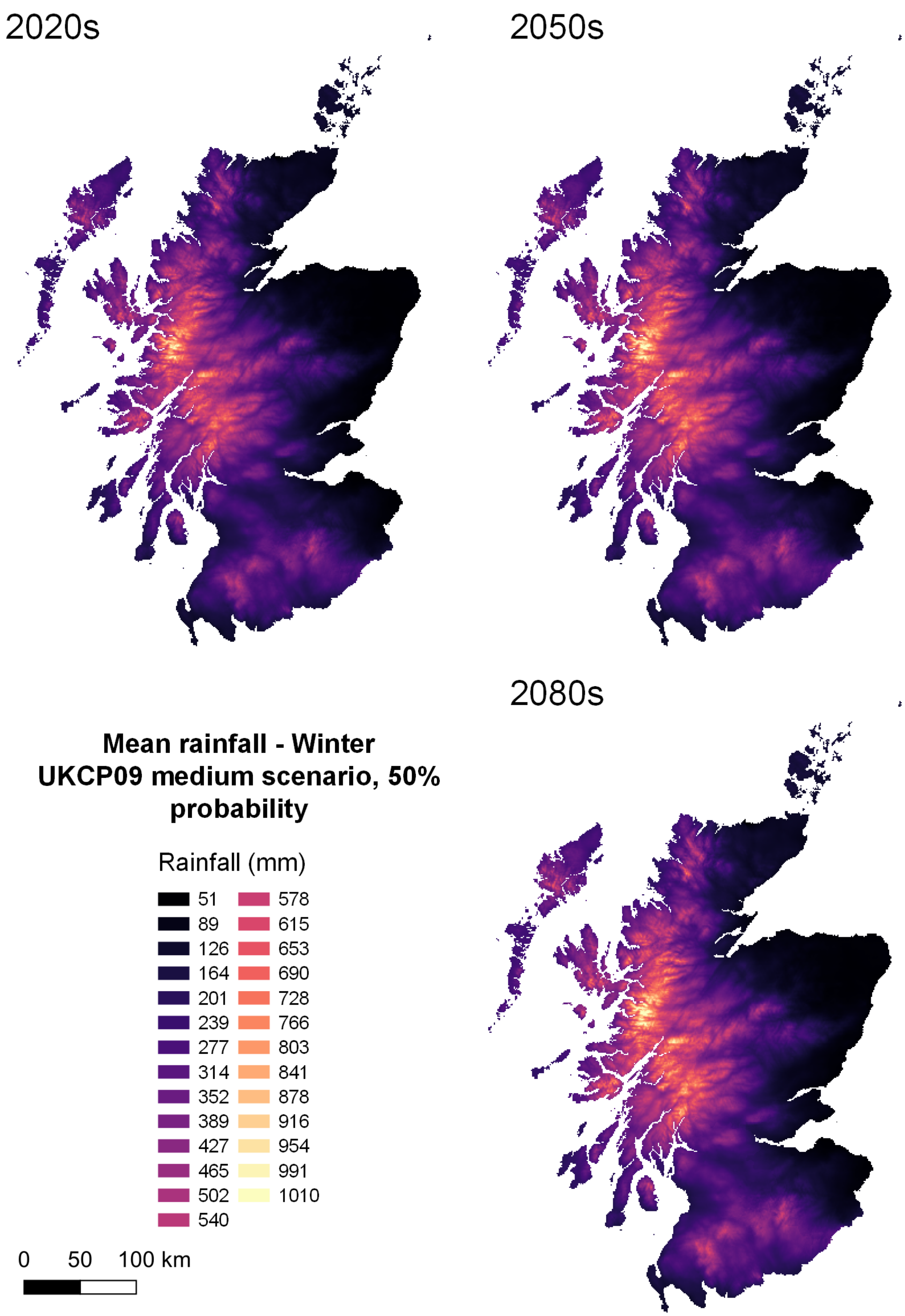
Table 10: UKCP09 predictions for changing summer and winter temperature and rainfall for Scotland; medium emissions scenario at 50% probability.

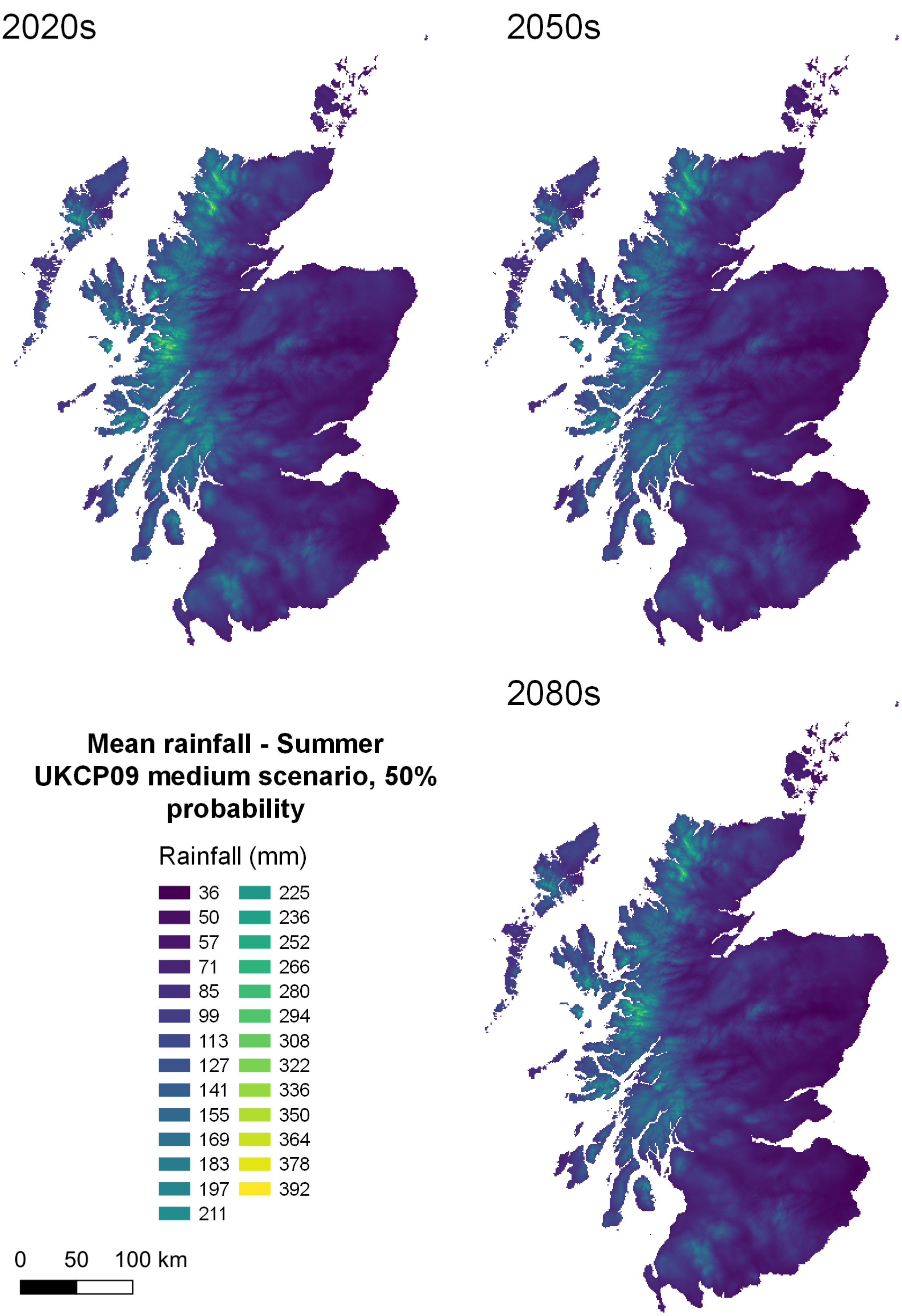
Area	Year	Temperature (C)						Rainfall (mm)					
		Summer			Winter			Summer			Winter		
		5th centile	50th centile	95th centile	5th centile	50th centile	95th centile	5th centile	50th centile	95th centile	5th centile	50th centile	95th centile
Eastern Scotland	2020	11.6	14.5	15.7	2.3	5.0	6.1	49.0	67.9	108.0	54.4	125.6	432.6
	2050	12.5	15.4	16.6	2.9	5.6	6.7	45.3	62.9	100.0	57.6	132.9	457.6
	2080	13.7	16.6	17.8	3.4	6.1	7.2	43.2	60.0	95.4	58.6	135.3	465.9
Western Scotland	2020	12.9	14.8	16.0	3.9	5.8	6.9	68.0	103.5	176.3	160.7	269.5	550.2
	2050	13.9	15.8	17.0	4.7	6.6	7.7	63.0	95.8	163.2	172.7	289.6	591.3
	2080	15.0	16.9	18.1	5.3	7.2	8.3	60.8	92.5	157.6	181.7	304.8	622.2
Northern Scotland	2020	10.9	13.4	14.5	2.2	4.9	6.3	65.7	102.8	195.7	95.8	259.7	584.9
	2050	11.7	14.2	15.3	2.7	5.4	6.8	60.9	95.3	181.4	102.1	276.9	623.5
	2080	12.7	15.2	16.3	3.3	6.0	7.4	60.3	94.2	179.4	105.7	286.6	645.6

Note: data show the 5th, 50% and 95th centile mean value projection to represent the average upper, lower and mid-range likely values for changing climatic conditions.


2020s
2050s
2080s
Mean temperature - Winter
Medium scenario, 50% probability
Temp (C)
-0.3
0.5
1.3
2.2
2.9
3.8
4.6
5.5
6.3
7.1
7.9
8.7
9.6
10.4
11.2
12.0
12.8
13.7
14.5
15.3
16.1
16.9
17.8
18.6
0 50 100 km


2020s
2050s
2080s
Mean temperature - Summer
UKCP09 medium scenario, 50% probability
Temp (C)
-0.3
0.5
1.3
2.2
2.9
3.8
4.6
5.5
6.3
7.1
7.9
8.7
9.6
10.4
11.2
12.0
12.8
13.7
14.5
15.3
16.1
16.9
17.8
18.6
0 50 100 km


2020s
2050s
2080s
Mean rainfall - Winter
UKCP09 medium scenario, 50% probability
Rainfall (mm)
51
89
126
164
201
239
277
314
352
389
427
465
502
540
578
615
653
690
728
766
803
841
878
916
954
991
1010
0 50 100 km


2020s
2050s
2080s
Mean rainfall - Summer
UKCP09 medium scenario, 50% probability
Rainfall (mm)
36
50
57
71
85
99
113
127
141
155
169
183
197
211
225
236
252
266
280
294
308
322
336
350
364
378
392
0 50 100 km

Appendix 4: Co-benefits

This report focusses mainly on effects of N inhibitors on greenhouse gas emissions. The reduction of nitrate leaching into water is therefore a co-benefit in the context of this study. The use of nitrification inhibitors has been identified as a mitigation for nitrate leaching in its own right (Cardenas et al., 2019). Although this has not been promoted within Scotland, the potential benefits should be considered within water quality policy. Peak soil nitrate concentration is decreased (see Error! Reference source not found. Figure 1), with decreased losses by leaching. Similarly, mitigation of ammonia emissions, with all the environmental consequences for sensitive ecosystems, may also be considered a co-benefit for this study, although it is primary reason for use of urease inhibitors.

There is the prospect that N inhibitors may increase yields and economic performance through decreased losses of nitrogen to the environment, and therefore decreased nitrogen inputs. Rose et al. (2018) concluded that, although yield benefits can be shown in trials with sub-optimal applications of nitrogen, more studies are needed to demonstrate these benefits in commercial situations.

A further co-benefit that has become apparent from stakeholder consultations in this project, is the practical advantage that can arise through using N inhibitors. With N inhibitors, nitrogen fertiliser applications may be made earlier than otherwise, and in a single application rather than in two or more applications because the risks of large losses through leaching and/or emissions of ammonia are decreased. This can reduce the number of field operations, and decrease risks of soil compaction.

Appendix 5: Uses of nitrogen inhibitors with livestock and their manures

Through the literature review, we have identified the use of nitrification and urease inhibitors within livestock systems. Although not a primary element of this review, a summary of these papers is given;a number of studies located within the UK and Ireland are relevant to Scotland.

Ruser and Schulz (2015) reviewed the evidence for nitrification inhibitors and conclude that they are an effective mitigation for nitrous oxide emissions, both from fertilisers and from manures and urine. The inhibitors can be applied either via direct application to fertiliser, to pastures or through mixing with slurry. This summary is a useful collation of over 140 datasets. However, there is still a degree of uncertainty in some more recent studies within the UK and Ireland. Bell et al. (2015b), in a single year study in Scotland, identified that DCD mixed with urine had no significant reduction in emissions, whereas Chadwick et al. (2018) identified DCD as reducing nitrous oxide from urine by 46%. These two studies were based on experimental trials and were not reflective of field practice.

Minet et al (2016a) identified that the amendment of slurry with DCD is an effective mitigation for nitrous oxide emissions from applied slurries, particularly in cooler wetter periods when ammonia emissions were low. This study also identified the potential for DCD to remain effective after six months within the slurry store, indicating its addition at any point of the storage could be an effective mitigation strategy.

Minet et al (2016b) concluded the use of powdered DCD added to cattle rations was a successful, potential mechanism for administering DCD more directly to urine patches (as significant sources of nitrous oxide emissions), with lower total application rates to the pasture.

The evidence indicates the addition of nitrification inhibitors to pastures, manures and urine can be effective in reducing emissions from livestock sources. The use of DCD, in particular, has been widely adopted in New Zealand and applied by spray or broadcast directly to pastures. However, there remain concerns that entry of DCD into the food chain may pose risks to food safety. This review has not identified evidence assessing these concerns, but, in the absence of any more evidence, and the 2013 withdrawal of DCD in New Zealand, caution should be exercised, and more research undertaken prior to promotion of these mitigations.

Appendix 6: Land Capability for Agriculture classifications

The agricultural sector in Scotland is strongly associated with the land's capacity to sustain the various production systems. Nearly three quarters (73%[7]), 5.56 million hectares, of Scotland's land is used for agricultural production). The land capacity drives strong associations with the primary production systems across the country. The Land Capability for Agriculture classification, as described by the Macaulay Institute in the 1960s and now managed by the James Hutton Institute, interprets the soil, climatic and landscape characteristics into a system used to assign the range of suitable land uses which the land can sustain. Figure 2 shows the distribution of land classifications across Scotland, with the classifications presented in Table 11.

A broad range of farming systems operate in Scotland, broadly described within the June agricultural census as: sheep farming on the poorer grade land, predominantly within the Highlands and Inner and Outer Hebrides; beef and sheep within the Orkney and Shetland Isles; more intensive beef and dairy in the south west and borders; and land more capable of supporting cereal, soft fruit and horticultural, and potato production along the eastern coast.

The majority of land in Scotland is unsuitable for cultivation, although production of cereal and horticultural crops are a significant feature of Scottish agricultural production. Unimproved grassland accounts for approximately 55%[8] of the agricultural area in Scotland; it is suited to sheep and extensive beef production, representing a relatively low input system. Improved grassland accounts for 25% of the land area and supports more intensive beef, dairy and sheep production. The areas of rough grazing and improved grassland account for over 80% of all agricultural land use and sustain 1.73m cattle and 6.67m sheep.

Cropping is dominated by barley and wheat with less significant areas of oilseeds and oats together accounting for approximately 10% of the agricultural area. There is a relatively small area of potatoes grown, but this is a significant feature of the sector, both in terms of value and reputation for high quality seed potatoes. Smaller areas of vegetable and soft fruit production are also present. The majority of cropping is situated along the eastern coast, using high-quality land suitable for these production system[9].

The area of land utilised in agriculture is relatively stable, as are the different areas of each land use: rough grazing, grassland and cropland.[10] There are some gradual reductions in the area of rough grazing and grassland as increased planting of woodland continues, in line with government policy.

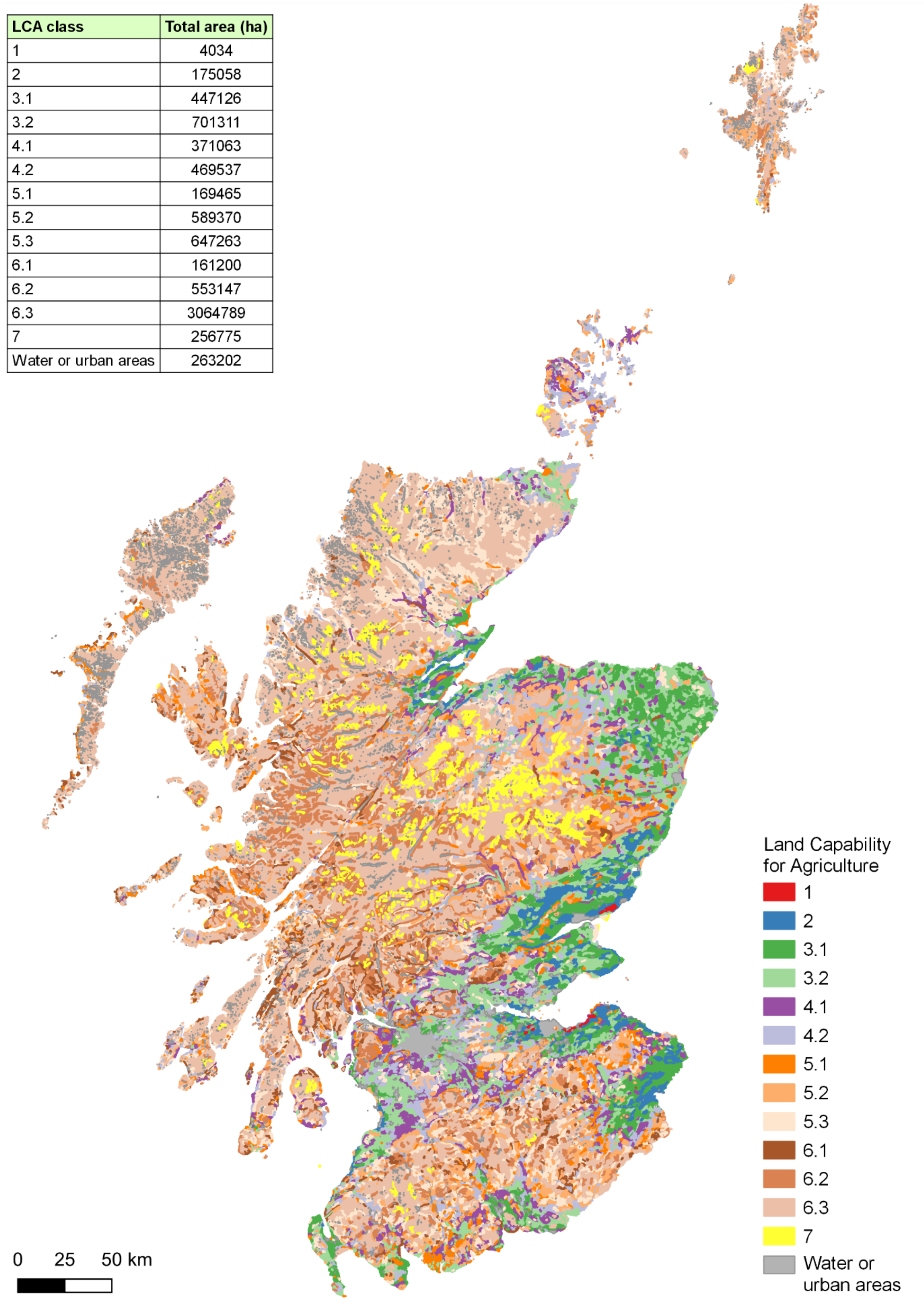
Approximately 1.9m hectares (33%) of land receive a dressing of inorganic nitrogen fertiliser[11]. This relates to the grassland and cropped areas; land used for rough grazing is not generally receiving any applications of fertiliser.

---

[7] https://www2.gov.scot/Topics/Statistics/Browse/Agriculture-Fisheries/agritopics/Grassland
[8] https://www2.gov.scot/Topics/Statistics/Browse/Agriculture-Fisheries/agritopics/Grassland
[9] https://www2.gov.scot/Topics/Statistics/Browse/Agriculture-Fisheries/agritopics/LandUseAll
[10] https://www.gov.scot/publications/key-scottish-environment-statistics-2016-9781786525505/pages/10/
[11] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/854404/fertiliseruse-report2018-20dec19.pdf

Figure 2: Land Capability for Agriculture in Scotland

LCA class	Total area (ha)
1	4034
2	175058
3.1	447126
3.2	701311
4.1	371063
4.2	469537
5.1	169465
5.2	589370
5.3	647263
6.1	161200
6.2	553147
6.3	3064789
7	256775
Water or urban areas	263202



Summary descriptions of all Land Capability for Agriculture classes are presented in Table 11 in order to help understand the differences between each land use class. These are summary descriptions only, since each of the actual descriptions are detailed and lengthy. The full original descriptions can be found in Bibby et al. (1991) with useful summaries and visual information presented in *Land Capability for Agriculture in Scotland*[12].

Table 11: Land Capability for Agriculture class descriptions

Land Capability for Agriculture class ID	Summary class description
1	Very wide range of crops.
2	Wide range of crops.
3.1	Moderate range of crops - high yield (cereals and grass), moderate yield (potatoes, field beans, root crops).
3.2	Moderate range of crops - average production. High yields barley, oats and grass.
4.1	Narrow range of crops - suited to rotations.
4.2	Narrow range of crops - primarily grassland, limited potential other crops.
5.1	Improved grassland - grass sward.
5.2	Improved grassland - grass sward, moderate to low trafficability issues.
5.3	Improved grassland - grass sward, serious trafficability issues.
6.1	Rough grazing - high proportions of palatable herbage.
6.2	Rough grazing - moderate quality of palatable herbage.
6.3	Rough grazing - low grazing values.
7	Very limited agricultural value.

[12] https://www.hutton.ac.uk/sites/default/files/files/soils/lca_leaflet_hutton.pdf (accessed 05/03/2020).

Appendix 7: Scottish-focused research papers

Of the literature reviewed for this study, eight papers included studies specific to Scotland, as shown in Table 9. The location of these studies was split evenly between South-West and South-East Scotland, with no evidence found for other locations. The majority of sources found were based on investigations involving the nitrification inhibitor, DCD, with just two papers including information on the urease inhibitor, NBPT. All the studies reported high rainfall. In the absence of an inhibitor, high rainfall shortly after fertiliser application leads to peaks in nitrous oxide emissions and, in the case of Scotland, this would mean there is a greater need for inhibitors. Generally lower temperatures were present at the Scottish study sites when compared with the majority of the research identified, these relatively cooler temperatures benefit DCD efficacy.

The study undertaken by Bell et al. (2016) can be used to aid emission estimations for other sites with similar soil type and climate. However, these results are taken from a year-long investigation and it is important to consider annual variations in weather. They explain how there is general uncertainty over the effectiveness of DCD expressed in the literature, with emission reductions ranging from 40% to 81%. It is stated that other studies report variance depending on the type of fertiliser DCD was added to. Here, it is emphasised that more specific research is required on different land-use and fertiliser types. The influence of annual variation in weather and the incidence of fertiliser application and precipitation should also be noted. Inhibitors are most effective in conditions where high N_2O emissions occur, confirming their potential importance in the management of emissions within the relatively wet climate in Scotland.