NEW Harmonica

The Development of a "BMP Matrix" for Mitigation Options in NW European Catchments

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SUMMARY

Best Management Practices (BMPs) to mitigate against losses of nitrogen (N) and phosphorus (P) to waterbodies are now embedded within both policy measures and agri-environment schemes in NW Europe, and research has advanced considerably in the last decade.

To ensure BMPs considered within the various work streams within the New-Harmonica project reflect these developments and are optimised to the landscape, land use and climate of the four catchments involved, a comprehensive review was undertaken. A longlist of options to reduce N and P pollution was produced, drawing on previous reports and project outputs, along with new ideas suggested in project meetings and through consultations with the Policy Group in WP1. In all, 72 different BMP options were evaluated, and for each consideration was given to trade-offs and synergies in N and P load reductions relative to gaseous emissions and carbon sequestration in soils. Leading on from this, each catchment working group (within the partner institutions) shortlisted key BMPs for their catchments into a set of scenarios which will be utilised within the other work packages in the project. This process involved informal consultation with local stakeholders (farmers, NGOs, policymakers and unions) on the feasibility of the measures that should be prioritised with respect to effectiveness, affordability, potential for adoption and trade-offs.

Phosphorus has long been considered the main cause of eutrophication in NW European freshwaters catchments since the research into BMPs commenced in the early 2000s. Buffering measures and constructed wetlands were among the earliest measures implemented to mitigate P loss through pathway interception and "next generation" developments of these measures continue to be popular and are deemed effective when sited correctly. Measures for nitrogen focus more on source control measures such as optimal fertilisation levels and improved slurry/ solid manure management and application techniques, with only denitrification an option once N reaches the soil matrix. Across the four catchments there was considerable alignment in terms of the options selected for further scenario evaluations. The Neagh Bann and Wye share many similarities in land use and farming practices; as do the Meuse catchments in Flanders and the Netherlands where N has been the focus of BMPs to achieve "Good" WFD status targets. Issues with P loading in the Neagh-Bann and Wye catchments meant that N was given less priority until recently when the impact of ammonia gas emissions from intensive livestock operations were recognised and elevated nitrate concentrations in surface waters following drought conditions highlight potential future climate impacts.

The BMP Options Matrix developed in this work can be enhanced or modified during the lifetime of the project and following modelling of the selected scenarios in the next work period. Further research and modelling will be required to consider the function of BMPs over longer periods and to deal with their maintenance and renewal. Those installed as part of agri-environment schemes, with agreements often lasting only 5 years, may end up neglected and could begin to contribute to water quality issues as their function declines. As this research develops, an additional entry in the Options Matrix may be needed to indicate the potential longevity of measures and impacts.

In addition, future work leading on from this project should consider the development of decision support tools to assist catchment stakeholders in the selection of BMPs and evaluation of trade-offs. An option would be a web-based tool with a user-friendly interface, similar to the Irish EPA/Teagasc funded SloWaterZ project's Riparian Measures Selection Tool. Simplifying the selection process would go some way to ensuring the right measure in the right place at the right time.

1. INTRODUCTION

The use of Best Management Practices (BMPs) to mitigate against nitrogen (N) and phosphorus (P) loading to waterbodies has become well-established across the world since the early 2000s, starting with the pioneering work carried out to mitigate phosphorus losses in agricultural fields (USDA ARS, 2006). In the context of diffuse pollution mitigation, the science has matured and developed with both a plentiful literature base of existing studies and the dissemination of the findings of numerous research projects through conferences and websites. In this context, the aim of this review report is two-fold. Firstly, the existing BMPs that have been developed as a suite of "measures" e.g. riparian buffer strips, and mostly to mitigate diffuse N & P pollution, are reviewed and added to a "Longlist" of different options. In this study carbon (C) was included too, mostly in terms of considering the ability of agricultural soils to sequester C, and the need to reduce national-scale gaseous emissions of C (mostly methane in the agricultural setting). Secondly, these measures are combined into a "Shortlist" of BMPs leading onto a set of scenarios, which links to other work packages in the project. The chosen scenarios were also influenced through the outcome of discussions held with the "Policy Group" comprising experts on nutrient management and policy in all four study catchments. This report includes a summary of trade-offs and synergies of the use of the selected BMPs to achieve the load reductions predicted elsewhere in the project in the four catchments. These trade-offs can be summarised as (i) pollution swapping between different forms of N & P and (ii) exchanges and swapping between the N, P & C, which may lead to unexpected consequences (Kleinman et al., 2022). Lastly, the BMPs considered for the scenarios also must take into account (where technically feasible) the gaseous emission abatement techniques that can be modelled using MITERRA-EUROPE (Velthof et al., 2007).

2. Review of the literature

This section reviews the most recent literature on BMPs from Western Europe for nutrient reduction, considering nitrogen (N), phosphorus (P) and carbon (C). The review briefly covers some earlier BMP studies completed before 2012 (or which were published later but the studies reviewed, and projects completed, around 2012, e.g. Schoumans et al. (2014)). Most of the literature has already been comprehensively reviewed by the outputs of other research projects (e.g. Fairway; Oenema et al. (2018)). The focus is generally on diffuse sources rather than point sources of nutrient pollution however it is recognised that some point sources exist that are often overlooked when making the distinction somewhat arbitrarily between diffuse and point sources for phosphorus (P) pollution (Stutter et al., 2021a). The case can be made that farmyards, septic tanks and associated land and farm track drains can operate as point sources, however the general land use of fields and farmland is considered a diffuse source. Land use change (LUC) was another BMP proposed for this project in most of the catchments, which has a wealth of literature on different scenarios including modelling exercises, however it has only been reviewed here in broad terms as an additional BMP. LUC was also considered by the pre-2012 literature reviews. BMPs originally were constructed (around 2005 onwards) for flooding mitigation (e.g. Belford Burn, NE England, Wilkinson et al., 2010) and subsequently adopted and adapted for diffuse pollution mitigation, probably because it was clear from the start that retaining water on farmland should also reduce the sediment and nutrient loads being washed off into watercourses as a multiple benefit of "Nature Based Solutions" (NBS).

2.0 Key Works

The study of Collins et al. (2018) reviewed the outputs of earlier research in NW Europe into BMPs and found over 700 different measures that the English WFD (Water Framework Directive) Joint Implementation Group examined. These were sourced in turn from EU research projects such as COST 869 (with nearly 100 different factsheets; Schoumans et al., 2011), and DEFRA's WQ0106 project (Newell Price et al., 2011) which looked at over 100 different BMPs. Extensive modelling of the BMPs was carried out using data from the 4 Demonstration Test Catchments (DTC) sites in England. A common theme of the researchers on this study was that the scenario modelling, particularly using FARMSCOPER, could demonstrate in a cost-benefit analysis (CBA) framework that BMPs could be effective at mitigating diffuse pollution from agricultural catchments. However, the improvements in water quality came at a predicted costs of 100s of millions of £ to the farming sector which the UK government would probably end up paying. The cost would have been applied either directly or indirectly through grants to farmers for Countryside Stewardship, Catchment Sensitive Farming (CSF; Environment Agency, 2019) and other schemes. The Wye catchment has been in a CSF partnership as a "High Priority" catchment for several decades albeit with questionable results in terms of the scheme actually improving water quality. The CSF scheme offered farmers a longlist of different BMPs evaluated by Newell–Price et al. (2011) with restrictions on fertiliser spreading during high rainfall/runoff periods being the most popular (in terms of the likelihood of actual farmer uptake) and engineering measures such as constructing bridges to remove livestock access to watercourses and moving gateways away from critical source areas for diffuse pollution being rated the least popular (presumably because of the cost incurred by the farmer both in labour, potential loss of land and expense).

Prior to the 2018 modelling study cited above, Collins et al. (2016) had looked at baseline farm surveys as a tool to investigate whether 29 low-cost BMPs would be cost effective or not. The conclusions of this study, which also used FARMSCOPER, were that those favoured by the farmers themselves would be the most effective. The DTC research programme was then planned to evaluate how effective these measures were in the field. Their catchment modelling showed that with a 95% uptake of the BMPs there could be reductions of 20% (sediment), 16% (ammonia), 15% (TP), 11% (nitrate and methane) and 7% (nitrous oxide). Achieving such a high uptake of measures was, in the end, not possible in the DTC study catchments for various reasons. Once again, Zhang et al. (2017) used FARMSCOPER to model 105 different measures that would be applicable to both arable and grassland farms in England, based on data from North Wyke in Devon (Rothamsted site). They found that some farm types, especially livestock farms, were more expensive and difficult to implement effective measures on than others. Again, a very high 95% uptake rate was assumed. We will return to the modelling vs BMP field studies debate below.

Returning to the key sources of BMP information prior to 2014, the comprehensive review of Schoumans et al. (2014) also drew on the COST 869 factsheets of measures to classify these into three different scales of measures: field, farm and catchment, and this structure was adopted in the development of the New Harmonica BMP Matrix as an initial screening tool to classify BMPs into three broad categories. This is described in more detail below when the BMP Matrix is introduced.

Over broadly the same time period as the COST 869 project, Velthof et al. (2009) developed the MITERRA-EUROPE (ME) model with an emphasis on modelling BMPs related to nitrogen, in particular nitrate reduction in leaching and ammonia gas abatement. ME was also able to simulate BMPs for P in a more restricted manner through reductions of P in fertiliser and animal feed (leading to a lower P loading in manure). These were seen as an indirect benefit of the main objective of the modelling which was to simulate 8 main BMP measures to tackle aqueous and gaseous N pollution. Balanced N fertilisation performed the best out of all the N leaching scenarios, as it led to improvements in the plant-available N balance which in turn lowered the N surplus in the fields. This modelling outcome could be brought about by reducing the N content in feed. The modelling work was supported by research platforms at experimental sites in the Netherlands managed by ALTERRA (later Wageningen Environmental Research).

2.1 More Recent Studies

The next section presents the findings of the most recent (i.e. last six years or so) research into BMPs in agricultural catchments, some of which link back to earlier research.

The island of Ireland has recently yielded some good examples of research projects into BMPs providing field evidence to support the construction of field-watercourse margin features such as "smarter buffers", "3D buffers and "Integrated Buffer Zones" (Zak et al., 2019, Stutter et al., 2021), in the "SmarterBufferZ" project (http://www.smarterbufferz.ie/). Their research has led to a web-based tool for measure selection, aimed at scientists and catchment managers, which is an exemplar of how this can be achieved (https://measure-selection-tool.hutton.ac.uk/). The project also introduced the concept of "3D Buffers" (as opposed to grassed fixed-width riparian buffer strips (RBS) that only intercept and treat lateral surface flow). Three-dimensional buffer zones extend functionality from surface runoff interception to sub-surface pathways through integration of trees and deep-rooted vegetation. They have additional functions of being able to intercept airborne pollution (e.g. airborne herbicides/pesticides) above ground in the vegetation canopy and through delivery of enhanced biodiversity potential. These functions combined maximise multiple environmental, farm (business and profitability), ecosystems services and public goods outcomes. In New Zealand, Tanner et al. (2023a, 2023b) have also reviewed the performance of 8 field-edge BMPs based on over 20 years of research. They introduce the concept of a "Hydrologic Landscape Type" (HLT) which contains information such as slope and soil type. The HLT has a large effect on how effective a particular type of BMP can be when implemented correctly on a site-specific basis. Involving the farmers in the process of designing and constructing the BMPs on their land has been key to the success of the mitigation outcomes.

The concept of integrated buffer zones (IBZ) is not a particularly new one (Zak et al., 2019) reviewed studies from NW Europe which started around 2010, for example) but IBZs aim to improve on fixed-width grassland buffers, which take up quite a large area of the farmer's land (Stutter et al., 2021b) making them unpopular and expensive (both in terms of cropping area lost and if a farm's area-based payments are reduced due to the land take). The IBZs can also intercept field drains if these are disconnected from the watercourse and allowed to drain into a constructed wetland which forms part of the integrated system and add more capacity to treat "edge of field" pollution issues. Incorporating areas with wetlands into IBZs also encourages the take-up and removal of soluble nutrients (e.g. soluble reactive P (SRP) and nitrate). "Two Stage Channels" are a way of reprofiling deep agricultural ditches that have historically been constructed to rapidly drain fields especially where soils are poorly drained (as is the case in many of the New Harmonica study areas). The additional stages also encourage removal of nutrients in between runoff events (in the lower part of the ditch) whilst trapping and removing sediments and nutrients during the events (in the vegetated side "benches" which are activated during higher flow periods). Within the ditch itself, additional wetlands can be constructed by widening the ditch and introducing shallower areas where water is retained in between events, these are termed "Multi Stage Ditches".

Lintern et al. (2020) produced a very convenient table of 94 publications relating to BMPs in both urban and natural settings, dating back to the late 1990s (their most recent paper reviewed was from 2019). A table of sources (from their *Supplementary Materials*) of the cited works is available. They summarised their literature review as follows; in that despite the efforts of BMPs, many catchments failed to detect substantial improvement in water quality. From 94 studies identified in the academic literature, their findings were that although 60% of studies indicated improvements in water quality after implementation of Best Management Practices (BMPs) within the catchment, those were mostly taken from the improvements predicted by the modelling rather than evidenced by field monitoring. For the studies that were unable to identify any improvements in water quality after the implementation of BMPs, the lack of improvement was attributed to several factors namely: lack of knowledge about how the BMPs were functioning; lag times; suboptimal BMP placement and the distribution of BMPs in the catchment. Post-implementation there was also BMP failure, combined with socio-political and economic challenges.

It must also be considered that farmers in some regions are hesitant to allow large parcels of their productive fields to be taken up by mitigation measures that may be several metres wide along a considerable length of field or watercourse boundary. In Northern Ireland (NI), the Environmental Farming Scheme (EFS) (voluntary agri-environmental scheme part-funded by the EU Rural Development Programme) has offered farmers measures ranging in complexity from simple riparian fencing to limit cattle access to water, to either 2m or 10m wide buffer strips which can be left as grass or planted with native trees. There has been some criticism of fixed-width RBS in terms of their effectiveness in intercepting critical source area pollution (during extreme events, runoff may "short circuit" the RBS and flow directly into the watercourses (Stutter et al., 2021a). Where cattle access is an issue, however, Scott et al. (2022) showed that basic fencing can be cost-effective at targeting diffuse pollution "hotspots" by removing access points for cattle to access watercourses (causing bank erosion and entrainment of phosphorus and sediment from the access points).

The concept of trade-offs between different forms of pollution was investigated by Kleinman et al. (2022). The BMPs under consideration were: conservation practices (zero tillage and cover crops), RBS (vegetated), constructed wetlands and sediment traps. An example of a trade-off would be P lost through sediment transport in overland flow being replaced (after BMP implementation) by dissolved reactive P lost from mitigation measures such as zero tillage arable fields. The factors controlling these trade-offs were found to be complicated and dependent on climate change with lots of uncertainties that ideally should be quantified. The study looked at P and not N or C and several examples were given where levels of maintenance and limited longevity could lead to poor performance; for example constructed wetlands that can switch from being a sink to a source of P, as can the cover crops frequently listed as a desirable arable BMP to reduce P losses from runoff. Zhang et al. (2022) also modelled the co-benefits and trade-offs between different BMPs that targeted diffuse pollution from grazing livestock in SW England. They found that mechanistic based modelling achieved the best outcome but admitted that "Business as Usual" (BAU) best management was not achieving the intended reductions in diffuse pollution in England. Another finding was that livestock farming on free-draining pastures was cheaper and easier to mitigate than on poorly draining pastures. The co-benefits included reductions in nitrous oxide and improvements in the soil quality, but at the expense of increased ammonia emissions due to compaction management.

Lastly, the recent review of Jebari et al. (2024) has looked at the feasibility of mitigation measures targeted specifically at greenhouse gas emissions from agriculture in the UK. The study reviewed 52 other studies that covered major food production across the UK and found that many mitigation measures could contribute to net zero through reducing emissions, if farmer uptake permits this to happen. The datasets reviewed by this study are open-access and can be downloaded for further studies.

3. Recommended Best Management Practices (BMPs)

This section will summarise the "Longlist" of mitigation options which have been presented to the catchment groups in the first phase of WP3. The Longlist was developed in the form of an Excel spreadsheet using the information from the literature review and previous research projects (e.g. COST 869/ADAS, Fairway, Demonstration Test Catchments etc) to populate it. It was further developed following meetings between the catchment teams to add additional novel BMPs not considered by the previous research, which is an attempt to go beyond evaluating just the well-known BMPs such as Riparian Buffer Strips and drive the research forwards under this project.

The complete Longlist (MS Excel) is available at:

https://www.afbini.gov.uk/sites/afbini.gov.uk/files/publications/HENH1_0.xlsx

The headings relate to the different functions and capabilities of the evaluated BMPs, and these are grouped both by physical category (e.g. reducing diffuse pollution to water) and the nutrient targeted (N, P or C). BMPs are numbered so that those listed in the catchment-specific BMP matrix (Section 4.1) which were developed for each of the four study catchments can be cross-referenced back to the Longlist of BMPs.

Following discussions held during the first year of the project the following categories were added to the longlist matrix:

- **Name of BMP evaluated** (including a brief description and a cross-refence to (i) the ADAS Newell-Price (2011) BMPs; ii) "FS#" which are the numbered Factsheets referred to in Schoumans et al (2014) originally obtained from the COST action 869 project). The Longlist is divided into blocks depending on the source of the BMP, the last block (highest numbers) were measures suggested by the catchment teams in late 2023.
- **Target**: Following the standard classification of Source, Receptor and Pathway used for point and diffuse source mitigation classification. One, two or all three targets can be addressed by the specific BMP.
- **Scale** (of BMP) field > farm > catchment, where a "farm" contains multiple fields and a "catchment" one or many farms.
- **Impact on diffuse nutrient loads in rivers** from the BMP (N and P). The impact is assumed to reduce these relative to baseline conditions unless indicated by a "+" sign. Here, *C may be included at a later date if the literature supports C being treated as a pollutant or nutrient causing issues in freshwaters but this has not been flagged up to date (except in the Wye) as a potential pressure*).
- **Impact on soil nutrient balance** from the BMP (positive or negative, i.e. increasing or decreasing the quantity of the nutrient in question in the upper soil relative to baseline conditions).
- **Impact on losses of nitrate to groundwater** from the BMP, either "Shallow" or "Regional". The definition of these categories was: "Shallow" being groundwater which then flows back into the local streams within the catchment and thus contributes to the nutrient loading at the monitored outlet; whereas "Regional" groundwater may flow out of the catchment or even discharge to coastal waters.
- **Timescale for effectiveness** (Short or Long) of the BMP, "Short" would be to achieve an effective, demonstrable solution in less than 5 years (*although this is subjective and open to debate*).
- **Impact on Gaseous emissions** (N and C only) due to the BMP, the main emissions from agricultural catchments being: ammonia, nitrous oxides and methane (positive or negative changes to the fluxes of these pollutants under baseline conditions)
- **Risk of Pollution Swapping** (N and C only), this is related to the previous category and to the risk of an aqueous nutrient discharged (e.g. nitrate) being converted or "swapped" by the BMP to a gaseous pollutant (e.g. ammonia), or vice-versa.
- **Supporting Literature** including websites and reports (in terms of the citeable papers and reports - these have been reviewed above).
- **Datasets**, for example catchment monitoring data to support the effectiveness of riparian fencing.

These categories were elucidated in the matrix by a simple "Y" or "N" or "+ -" indicator rather than a full quantitative assessment, and some categories are rather subjective and open to debate, especially if new evidence from BMP studies comes online during the next few years (for example to clarify if constructed wetlands several decades old can become a source of P if they become full of sediment and are not maintained properly). The COST869 Factsheets provided a useful summary of each BMP for most of the categories listed above and can be accessed here: https://www.cost869.alterra.nl/Fs/List_of_options.htm. A short description of specific changes brought about by the BMP has been included (for example if a particular form of gaseous N is associated with the BMP). Arguably, an additional column could be added for "unexpected consequences", which is similar to pollution swapping but relates to the BMP causing a different pollutant to be emitted to the "baseline" conditions. This could for example represent pollution swapping from releasing soluble reactive P under baseline conditions to releasing ammonia gas after the BMP is introduced (according to Kleinman et al., (2022)).

3.0 Phosphorus

In order to define appropriate measures to reduce phosphorus (P) load to surface water both the contribution of the main sources of P loads to surface waters as well as the main pathways should be distinguished. A mandatory Riverine Inputs and Direct Discharges (RID) programme of OSPAR for the North-East Atlantic countries has run for decades to monitor and assess all inputs and discharges of selected contaminants via rivers into tidal waters, or which are discharged directly into the sea. Figure 1, below, shows the main sources of phosphorus loading of freshwater systems (from *EUROHARP)*.

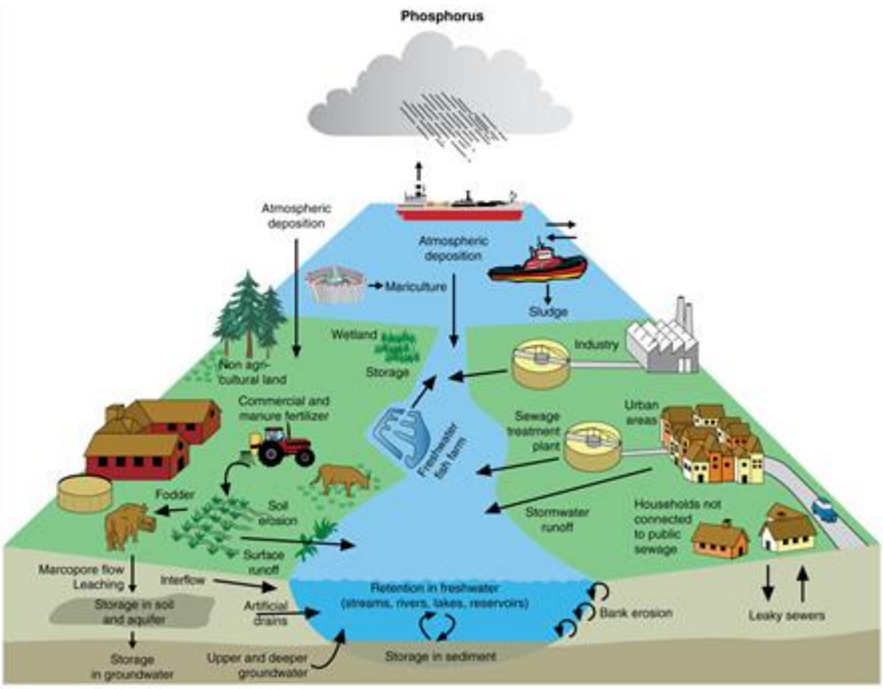

Figure 1: Phosphorus loads from different sources (after EUROHARP project)

The contribution of point sources can often be quantified reasonably well, and their contribution has reduced considerably in the period 1992-2012, mainly because of the reduction of phosphorus in detergents and the improvements in wastewater treatment. As a result, diffuse phosphorus loss from agricultural land has become the major phosphorus source in European lakes and freshwater systems.

Since phosphate is highly reactive with soil particles, most of the phosphate is accumulated in the topsoil of agricultural land. Consequently, changes in input of P fertilisers will have a weakened effect on improving water quality, because the soil P storage buffers the P losses. In addition, the phosphorus stored in the sediments of surface waters can keep P concentrations in surface water high despite a reduction in P loads to the surface water. This post-leaching effect depends heavily on the extent to which the soils and sediments are saturated with phosphate ('legacy P'). However, during high rainfall events, short term high P losses can occur due to surface runoff and erosion flooding directly to surface water. Although P accumulates in the soil, due to soil-physical/chemical/biological transformation processes, nutrient losses in soluble and/or particulate forms can occur from the field to surface water (Figure 2). Within COST Action 869 a long list of 80 measures were described and grouped into eight types of 'categories of management' (Schoumans et al, 2014) as:

1. Nutrient management (25)
2. Crop management (1)
3. Livestock management (7)
4. Soil management (18)
5. Water management within agricultural land (11)
6. Land use change (1)
7. Landscape management (8)
8. Surface water management (9)

3.1 Nitrogen (including gaseous forms)

Nitrogen is somewhat more complex than P due to the risk of pollution swapping between different forms of N, which comprise ammonium and nitrate in streams and rivers plus a range of different gaseous forms which can contribute to Greenhouse Gas (GHG) emissions instead of directly leading to diffuse pollution to watercourses. Nitrogen as nitrate also has a legacy effect where high agricultural loadings of N from fertilisers, which intensified after World War Two, have taken many decades to be observed as a high nitrate "pulse" in shallow groundwater and streamflow which can, even then, exceed drinking water limits in some catchments (50 mg NO_3/L). Any mitigation measures to tackle nitrogen in permeable, well-drained catchments with a significant groundwater component must take into account this apparent lag time of several decades. Moreover, due to natural denitrification in surface waters, surface runoff as a nutrient transfer pathway is less of an issue for N than P although mitigation measures to reduce N in surface runoff could lead to pollution swapping in certain cases. Similar to phosphorus, nitrogen (N) measures are also needed to reduce nitrogen losses to surface water to improve water quality to meet with the ecological boundary conditions. The RID programme has also enlisted N. Figure 2 shows the main sources of nitrogen loading and pathways of freshwater systems.

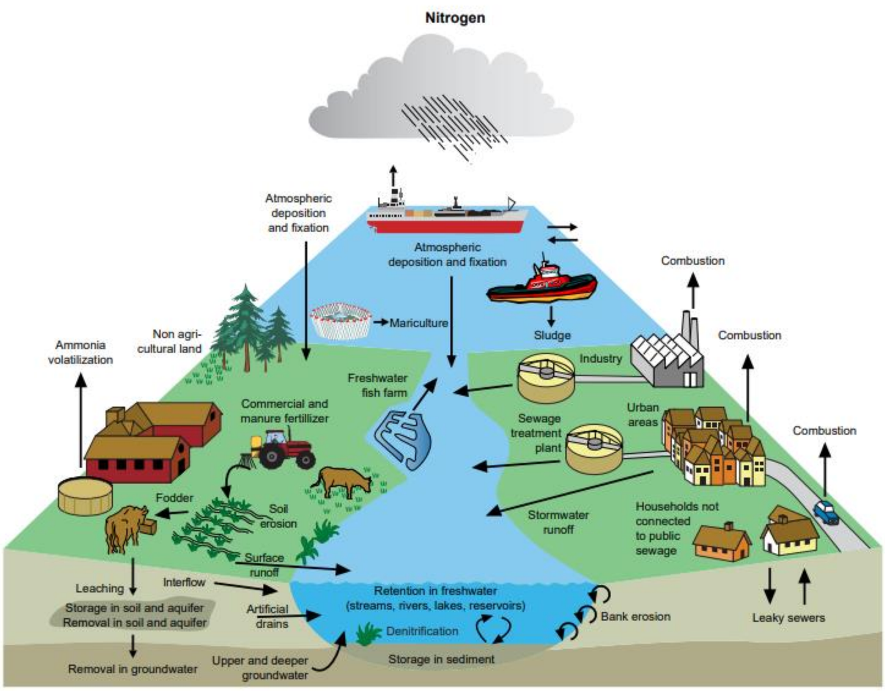

Figure 2 Nitrogen loads from different sources (after HARP guideline 6)

Nitrogen, crucial for crop growth, is primarily absorbed by crops in the form of nitrate, sourced from manure, organic soil conditioners, and mineral fertilisers, which predominantly contain ammonium and nitrate. Throughout the year, organic matter decomposition releases ammonium as a mineral nitrogen source, with biological processes rapidly converting available ammonium into nitrate via nitrification. However, the soil's ability to retain ammonium is limited, and both ammonium and nitrate can easily leach into groundwater and surface water post-rainfall due to their mobility. Although not all excess nitrate leaches out, as denitrification processes in soil convert some nitrate into nitrogen (N_2) and nitrous oxide (N_2O), particularly under wet conditions, with N_2O being a potent greenhouse gas. Additionally, depending on application methods and weather conditions, a portion of ammonium may be emitted as ammonia (NH_3) into the air, constituting a loss from the nitrogen input to the soil system.

Quantifying the contributions of point sources has become increasingly precise, leading to a significant reduction in their impact from 1992 to 2012. Consequently, diffuse nitrogen losses from agricultural land have gained prominence as key factors for enhancing water quality. Addressing nitrogen losses to groundwater and surface water entails consideration not only of distinct pathways but also of the various forms of nitrogen present, predominantly nitrate seepage into groundwater and primarily ammonium and dissolved organic fractions entering surface water. This diversity underscores the differing relevance of soil processes, which can significantly influence the efficacy of mitigation measures. At the farm level, strategic socio-economic decisions shape production systems, with both nutrient and livestock management influencing the farm's nutrient balance at the gate and nutrient utilization in the fields (I. Farm system). The spatial and temporal distribution of available nitrogen sources across fields hinges on crop cultivation practices and soil conditions affecting nitrogen release, including residual mineral nitrogen and organic matter decomposition (II. Field system). Actual nitrogen losses from fields to groundwater and surface waters are heavily influenced by hydrological systems and landscape characteristics, as these factors determine nutrient transfer and buffering capacities (III. Landscape and hydrological system). The ecological impact of nutrient loads on surface waters (IV. Ecological system) is contingent upon the existing nutrient pressure relative to the water body's critical threshold.

Measures designed to abate nitrate leaching were simulated using MITERRA-EUROPE *("MITERRA")* in a completed EU-funded research programme (Velthof et al., 2009). These are listed in Table 1 below which was extracted from their Table 2 in the publication.

3.1.1 Gaseous Forms of Nitrogen (including risk of pollution swapping)

The different mitigation options to reduce gaseous emissions of N have also been modelled as scenarios using MITERRA. The module of MITERRA-Europe includes a calculation of the gaseous emissions as N_2O, NH_3, NOx and also total denitrification (Figure 3). The gaseous emissions are calculated using emission factors for N_2O emissions (defaults of IPPC), and NH_3 and NO_x (from the GAINS model). In MITERRA leaching and surface runoff fractions are calculated using data on soil texture, land use, precipitation, and soil carbon content (Velthof et al., 2009). The balance between the N inputs and outputs (crop removal, N2O, NOx, and NH3 emissions, and N leaching and surface run-off), assuming no change in N stock of the soil, is considered to be lost as N_2.

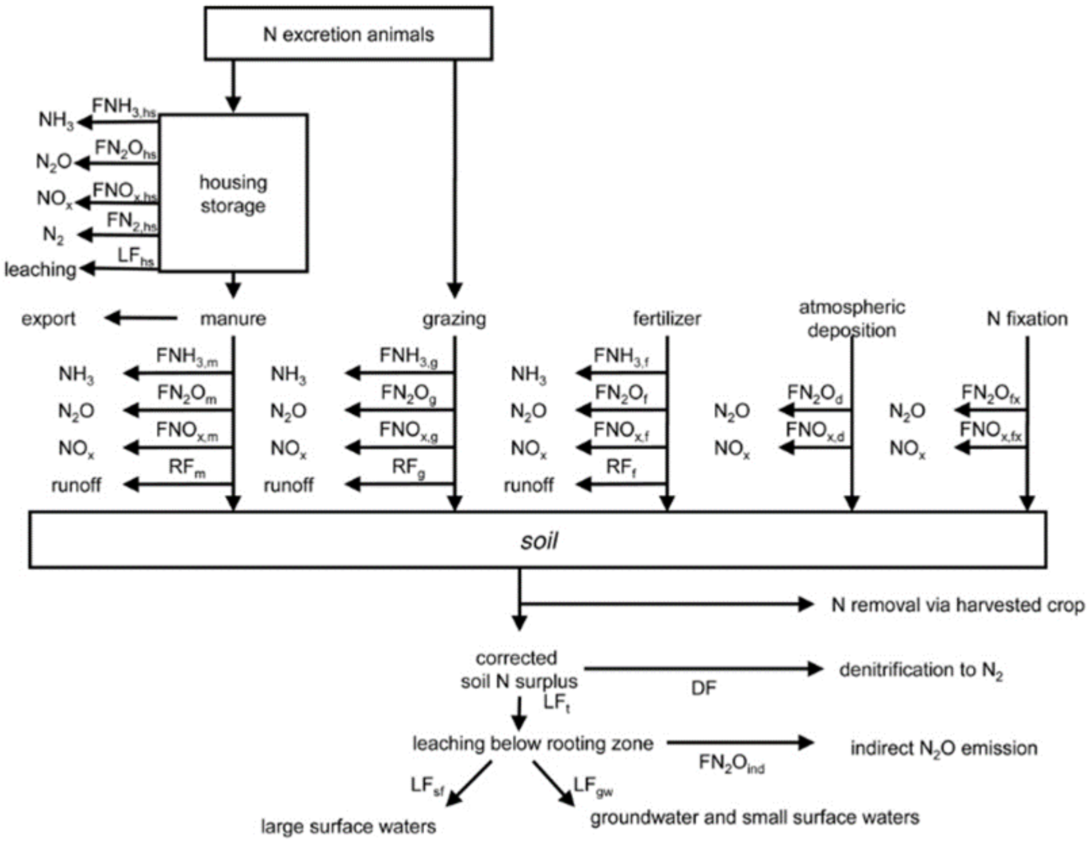

Figure 3. Schematic presentation of the N module of MITERRA-EUROPE (Velthof et al., 2009)

The most recent version of the model has evaluated measures to mitigate ammonia (gaseous) which are presented below in Table 1 (*from Velthof et al., 2009*). The next phase of research will be to identify which of the additional scenarios presented in the BMP Matrix can be modelled using MITERRA. MITERRA is also undergoing improvements to its diffuse P component so that different scenarios to reduce diffuse P loads to watercourses can also be evaluated using the software.

Table 1: Mitigation options for Nitrogen considered by MITERRA (from Table 2 in Velthof et al (2009) in which a fuller description of the measures can be found).

Ammonia Emissions Abatement Measures	**Description**
Low N fodder	Dietary changes and replacement of grass/grass silage by maize for dairy cattle
Housing adaptation	Applicable for cattle, pigs and poultry, e.g. improved construction of the floor. Wet and dry manure management systems for poultry.
Covered manure storage	
Biofiltration	Air purification to convert ammonia into nitrate or absorb the gas.
Low ammonia application of manure	Application of manure using techniques such as incorporation / injection of slurry to reduce ammonia.
Urea substitution	Substitution of urea-based fertilisers with ammonium/ nitrate-based fertilisers
Incineration of poultry manure	
Nitrate Leaching Abatement Measures	
Balanced N fertiliser applications	Tuning the applied N amounts to the crop N demand
Maximum manure N application standard	Transportation of excess manure to other regions, if the average amount exceeds 170 kg N/ha, which is the usual EU limit for N applications.
Limitation to N application in winter and wet periods	Application of manure in the growing season instead of winter periods to increase N availability and effectiveness for crops.
Limitation to N application on sloping ground	
Manure storage with minimum risk on leaching	Convert stores to have a concrete floor and cover.
Appropriate application techniques	Measures to improve N efficiency and reduce leaching.
Buffer zones	Here, 100m wide unfertilised buffer zones are constructed along watercourses to reduce N losses to surface waters.
Growing winter crops	Growing catch crops to reduce N leaching and losses to surface waters.

3.2 Carbon

This description of BMP measures to target Carbon has a sub-section for pollution swapping. It appears not be considered a pollutant (for aqueous forms of Organic and Inorganic C) to the same extent as N&P. Therefore, the focus is more on gaseous forms of C and the risk of pollution swapping. The catchment teams have not yet indicated if there will be any BMPs modelled that are specifically targeted at reducing the risk of C in causing diffuse pollution of rivers and groundwater. For the preliminary Scenarios discussed below, C was therefore not included in the category "Impact on diffuse nutrient loads".

3.2.1 Gaseous Forms of Carbon (including risk of pollution swapping)

MITERRA-EUROPE includes a module to calculate methane (CH4) emissions from enteric fermentation of livestock and CH4 from stored manure. Agricultural soils contain oxygen, and because of that these soils are not a source of CH4 (methanogenesis is an anoxic process).

The RothC model is incorporated in MITERRA-Europe to enable the assessment of changes in soil organic carbon (SOC). RothC (version 26.3; Coleman et al., 1997) is a model for the turnover of organic carbon in nonwaterlogged soils that takes the effects of soil type, temperature, moisture content and plant cover on the turnover process into account.

In the next phase, MITERRA-EUROPE will be used to calculate the effects of the BMPS on CH4 emission and changes in C stock in the soil.

4. MITIGATION SCENARIOS

4.1 Introduction

This section focuses on the set of scenarios developed by each catchment group in consultation with local stakeholders, which was then presented at the Policy Group Meeting in December 2023 for further and final comment.

Following the compilation of the longlist of BMP options, and during the period leading up to the Policy Group Meeting in December 2023, each catchment team engaged with experts and stakeholders within their own areas to canvas opinion on solutions to water quality issues and fed back into the BMP shortlisting. This was an informal process in each catchment, making use of existing networks and opportunistic links to ongoing projects and working groups that the project teams are involved with. These gave access to a range of stakeholders including policymakers from both agricultural and environmental perspectives, farmers union representatives, NGOs, catchment officers working on the ground to promote agri-environmental measures, fellow scientists and various industry representatives (e.g. grain trade and fertilisers).

Direct engagement with farmers was limited due to ongoing political issues (principally farmer protests in Europe, and the combined sensitivity around Lough Neagh pollution and lack of government in Northern Ireland), but pursued where opportunities presented themselves (e.g. at agricultural shows in Northern Ireland where farmers were asked during conversations about their feelings on nutrient source control or pathway interception measures). Information obtained was considered in the final shortlisting process. Discussion content depended on the parties involved but included consideration of implementation feasibility in terms of cost (e.g. could the investment be justified within voluntary agri-environmental schemes?), trade-offs and potential pollution swapping potential (with regard to N, P and C), and land/stock reduction requirements (e.g. should some catchments cut livestock numbers?).

In the current political climate most stakeholder groups carry their particular perspectives and strong opinions, with occasional biases depending on their agenda. In light of this, the final BMP shortlist selection to progress to the Policy Group Meeting was undertaken by each catchment team, synthesising the stakeholder feedback using their expertise to those options which appear on balance the most viable for their area.

The shortlisted BMP options have been kept intentionally generic at this stage. Due to each catchment's large scale and the variability in landscape, hydrology, agricultural systems and governance within them, the specific details of each BMP to be implemented has not been defined at this stage. The modelling process will involve scenario development where catchment-and BMP-specific details will be assessed in more detail at the appropriate stage considering workable combinations of BMPS for sub-catchments, depending on Load Reduction Targets and a 'reality check' for feasibility (cost, operation) that will be provided by again consulting with stakeholders.

In this section a short introduction follows for each catchment. In the case of NL the introduction will be based on the detailed Phosphorus BMP report produced by Schoumans and others at WUR prior to this research project (Ref ALTERRA's project: Cost action 869). A summary of the full set of shortlisted scenarios is provided below in Table 2. Each scenario has one or more BMPs which are linked back to the full longlist. The spreadsheet containing the selected BMPs is available at:

https://www.afbini.gov.uk/sites/afbini.gov.uk/files/publications/HENH2_0.xlsx

A discussion of each scenario will follow the introduction for each catchment.

Table 2: Scenarios evaluated after the Policy Group meeting in December 2024: All catchments (see "*OptionsMatrixCatchments.xlsx*", above. The numbered "BMP#" can be found in the Longlist (*follow the embedded link to "BMP Matrix Longlist.xlsx"* in Section 3) ("N-B" = Neagh Bann)

Catchment	Scenario No.	Scenario Name	BMP 1	BMP2	BMP3
N-B	1	Runoff and Erosion Control	Integrated (smart) buffer zones	Restrict livestock access through fencing	2m wide Riparian buffer strip (fenced)
N-B	2	Improved Management of Fertiliser and Manures	Restrict Application of Slurry on High P Index fields	Improved Application of Slurry: More Efficient use	

N-B	3	Manure Processing and Recovery	Manure Processing and Recovery		
N-B	4	De-Stocking	De-Stocking		
Wye	1	Runoff and Erosion Control	Erosion Control: Arable Fields	Reduce Compaction	
Wye	2	Improved Management of Fertiliser and Manures	Reduce P Applications to High Risk Soils	Improved Management of Manure (esp. Poultry)	
Wye	3	Manure Processing and Recovery	Manure Processing and Recovery		
Wye	4	Land Use Change to less intensive	Land Use Change		
Meuse (NL)	1	Reducing Soil P and N	Taking into account soil P availability (P-mining) in fertilisation strategy	Taking into account soil N availability (N-mining) in fertilisation strategy	
Meuse (NL)	2	Improved Soil Management to reduce erosion/runoff and/or increase infiltration	Reduce Soil Compaction (Arable)	Arable: apply cover crops	Contour Ploughing
Meuse (NL)	3	Constructed Buffer strips & Ponding of Overland Flow	Constructed Riparian Buffer Strips	Ponding - Interception Measures / create barriers	
Meuse (NL)	4	Apply catch crops after harvest early autumn or Land use change to reduce Arable Crops or	Implementation of catch crops	Reducing Percentage arable in the crop rotation and/or the total arable area.	No leaching sensible crops on soils prone to nitrate leaching
Meuse (NL)	5	Control the water flow from fields to surface water	Controlled field drainage systems		
Meuse (FL)	1	Improved Soil Management	Arable Measures: Cover and Catch Crops		
Meuse (FL)	2	Reduction of Fertiliser Standards	Improved Fertiliser Management (Arable and Grassland)		
Meuse (FL)	3	Riparian Buffer Strips	Riparian Buffer Strips		

Meuse (FL)	4	Erosion Control Measures	General Erosion Control Measures
Meuse (FL)	5	Reduction in Cropping area to reduce Nitrate Leaching	Reduction of Cropping area in Sensitive Locations
Meuse (FL)	6	End-of-Pipe Solutions	End-of-Pipe Solutions

4.2 Meuse (Netherlands: NL)

4.2.1 Introduction

Based on the outcome of the assessment of the Load Reductions (LRs) required in the Netherlands Meuse catchment (WP2), the desirable BMPs were shortlisted (see below). However, *a priori* it is stated that the farmer will manage his/her field always according the 4R-stewardship (Good agricultural Practices) principle:

- Right place
- Right time
- Right form
- Right amount

Consequently, this implies that working according to 'right place, time and form' the P use efficiency will increase and often less P must be applied to the field. Furthermore, there is no need to always apply the maximum according to the P application standard if the P requirements of the soil-crop combination are in practice lower. Particularly in soils with a high soil P status the agricultural P recommendations are often much lower than the current maximum P application standard according to the legislation. The 4R-stewardship is not only important from an agronomic point of view but should also be used from an environmental point of view, namely to avoid the incidence and sites of high P losses. The advice is thus not to spread fertilisers and manure slurry to fields at high-risk times (if high rainfall events are expected) and avoid spreading very close to surface water (ditches) and compacted zones (often animal tracks and drinking water troughs).

The current EC policy (Circular Economy Action Plan and Farm to Fork Strategy) stimulates the use / reuse of manure and biobased fertilisers instead of using mineral fertilisers because the phosphate stock in the mines is limited, and during the production of nitrogen fertilisers high amounts of natural gas are used. However, it is well known that risks of P losses from fields where farmyard manure or solid (fraction of) manure are used (surface spreading) are much lower than from fields where liquid slurry is spread. However, in the Netherlands low-emission technologies are mandatory to apply liquid slurries in order to avoid ammonia emissions and furthermore, solid manure has to be ploughed into the soil within one day on arable land. Since the P-forms in solid manure are less soluble compared to liquid slurries, a lower P loss can be expected.

Finally, due to an increase in the intensive husbandry in the period 1950 -1985 in The Netherlands, which resulted in (not limited) high manure application, a substantial amount of phosphate is accumulated in the subsoil (25-50 cm and sometimes deeper), especially in those areas where the intensive husbandry is located (e.g. Meuse region). After the introduction of manure legislation (1984 onwards) gradually less phosphate in terms of manure was allowed to be applied. In the last period the P application rates decreased from 350 kg P_2O_5 per ha (1985) until P equilibrium fertilisation was adopted in 2015.

Therefore, in the Dutch part of the Meuse catchment the P legacy is of high importance. On arable land, crop rotation has been of importance for many decades to keep the soil healthy and stimulate good rooting conditions. This will also stimulate the uptake of phosphate from deeper layers. However, 50% of the grassland area is still permanent grassland with a shallow rooting system (ca. 20 cm). On soils with deep groundwater levels (several metres) the impact of accumulated P in the subsoil (0.25 - 1 m) will be of low importance. However, in areas with shallow groundwater fluctuations (often higher than 1 m below surface) this subsoil P source will determine the subsurface P losses to surface water. This P pool will remain relatively static since there are no roots for uptake of P and the P losses themselves are relatively low compared to the amount of P accumulated.

Additional BMPs were proposed to reduce diffuse N concentration and loads but not included in the five scenarios (Section 4.2.4). These were:

- Apply solid manure fractions on arable land (more stable; ploughed in manure) instead of injected liquid manure slurries

- Reduce application standards (for total N) (this is on top of existing rules regarding no derogation and 20% less N applied in the N polluted areas).
- Encourage different varieties of crops (high N uptake); cereals with deep rooting.
- Ensure no N application in fields below optimum yield; balance fertilisation.
- Ensure ploughing takes place only in spring / grassland renewal; 3-5 years; and N-applications are made after renewal.
- LUC from vegetable crops to wheat.
- Allow no grazing after 1st August. Plant catch crops (maize) on bare ground after this date.
- Extend the closed period when manure spreading is banned.

Appendix 1 and Appendix 2 contain the long list of measures to reduce N loss, in respect to groundwater and surface water. The effectiveness of the measures varies depending on nutrient type (NO_3 or N), crop type (mainly grassland vs. cropland), soil type (sandy/loamy/loess, clay and peat), availability of waterways (ditches/brooks) and pathway (to groundwater or surface water). In the following section, a distinction is made between the importance of specific measures to reduce (a) nitrate leaching and (b) total nitrogen leaching to surface waters.

4.2.1.1 Nitrate leaching

Excess nitrogen is the main cause of N loss to both groundwater and surface waters. High nitrate leaching occurs under long-term aerobic conditions because the denitrification capacity of the soil is then low. These situations often occur in sandy and loess soils (low water-holding capacity) with a deep groundwater system (>2 m). Under these conditions, nitrogen application must be tailored to the needs of the crop during the growing season and corrected for the ability of the soil to supply nitrogen during the year (available mineral nitrogen in the topsoil at the beginning of the growing season and N mineralization capacity of the topsoil).

After the crop is harvested, the remaining nitrogen in the soil must be absorbed by growing a "catch crop," otherwise abundant rainfall in the late autumn - early spring period will result in high nitrate losses from the root zone. It is important that catch crops be harvested or ploughed under in the spring and that the amounts of nutrients from the catch crop ploughed through the soil be included in the fertilization plan for the field. A similar philosophy should be applied when re-seeding grassland: the fertilization plan should take into account the amounts of nutrients that will be incorporated into soil organic matter by destroying the sward and will break down to mineral form.

One rigorous measure is to ban the cultivation of crops on dry sand/loess soils that cause high nitrate leaching, such as potatoes, vegetables and corn (maize). Arable farmers could, for example, replace the cultivation of potatoes and vegetables with those of less leaching crops such as cereals and sugar beets. Since corn is used as animal feed in livestock production, which is difficult to replace, a catch crop should be mandatory after corn is harvested. The harvest of corn should be early to give catch crops a chance to grow vigorously in the fall and thus reduce nitrate leaching. From 2024 onward catch crops are mandatory (excluded a list of winter crops) and should be seeded at latest by the 1st of October. After this date, there is a reduction in the nitrogen application standard for next year. Growing field vegetables for human consumption is a fairly nutrient-intensive farming system to minimize the risk of yield or product quality loss. In addition, successive crops are often grown in one field. Although the production area is small, high nitrate losses can occur on dry sandy/loamy soils (Schipper et al., 2019; Boumans and Fraters, 2019; RIVM, 2021). Since it is a strong economic sector in the Netherlands, the main emphasis is on applying GAP rather than a sharp reduction in nitrogen application standards.

The following table shows the short list of the most important measures to reduce nitrate leaching (based on codes 4 and 5 as mentioned in appendix 1):

Table 3: List of BMPs targeting groundwater NO_3

Measure	Ground water level	Land use type	Landscape
Precision application that matches the quality of the soil; Manure application in accordance with the fertilization advice; Adjusts (artificial) fertilizer application to mineralization through additional sampling; Optimizes the Ph and Ca/Mg ratio for crop production	Deep (> 1.5m)	Permanent grass; Arable	Hilly; Flat

Recycled cultivation system	Deep (> 1.5m)	Arable	Hilly; Flat
Extension of the age of grassland (no grazing after the first of 1 August); grassland renewal every 3-5 years and no N-application after renewal	Deep (> 1.5m); Shallow (< 1m)	Permanent grass	Hilly; Flat
Remove N rich crop residues after harvest	Deep (> 1.5m); Shallow (< 1m)	Arable	Hilly; Flat

4.2.1.2 Nitrogen losses to surface waters

In the Netherlands, nitrogen losses to surface water occur during periods of excess precipitation or during heavy rainfall, especially in fields with ditches or directly adjacent to ditches or streams. The impact is greater under conditions with shallow groundwater levels. Several pathways may be relevant, such as (a) overland flow, (b) subsurface flow/interflow, or (c) via artificial drains. Surface water quality will respond relatively quickly due to the short residence time of water movement from the field to surface water and the low buffering capacity of the soil.

As a result, creating 'barriers' between fertilisation practices and surface water and/or changing lateral water movement into more vertical water transport are the key steps to reduce nitrogen losses. Non-fertilised buffer strips will help to reduce the direct overland nitrogen losses. The water flow rate will slow down, and a part of the nitrate will be denitrified. The broader the buffer strip the higher the impact will be. In the Netherlands in general 3 m buffer strips without fertilisation and harvesting of crop yield are mandatory from 2024 onward. It can be less in situations where the total surface of the strips is more than 4% of the area of the parcel (depending on the type of watercourse 0 - 3 m; e.g. zero for dry ditches). Along ecologically Vulnerable Watercourses the strips are always 5 m. Natural barriers will help to maintain the excess of water in the field. Also, at a more regional scale large, constructed wetlands will have a similar impact.

Applying cover crops to fallow fields or fields after harvest is an important measure to minimize overland flow, especially in hilly areas, where the slope is not too high.

An important infield measure is to increase the infiltration capacity of the soil by improving the soil structure of the plough layer or grass sod. Always avoid tramlined areas (drinking places, entrance of the field or driving ways of heavy tractors) because they highly contribute to local particles and nitrogen loss.

If overland flow is reduced by increasing the infiltration capacity of the soil, more nitrogen will be transported through the soil to groundwater and surface water.

The following table shows the short list of most important measures to reduce N losses to surface waters (based on Codes 4 and 5 as mentioned in Appendix 2):

Table 4: List of BMPs targeting surface runoff N

Measure	**Ground water level**	**Land use type**	**Landscape**
Lower application standards in general	Shallow (< 1m)	Permanent grass; Arable	Hilly; Flat
For clay: spring manure application instead of autumn	Shallow (< 1m)	Arable	Hilly; Flat
Extend closing period: 1. Shifting the spreading period of liquid manure on arable land; 2. Extending the period for spreading solid manure on grassland; 3. Later spring application of animal manure to grassland and corn)	Shallow (< 1m)	Arable	Hilly; Flat
Apply catch crops (maize) after 1 August; no additional N-application	Deep (> 1.5m); Shallow (< 1m)	Arable	Hilly; Flat

Apply cover crops (grass) to reduce erosion and runoff	Shallow (< 1m)	Arable	Hilly; Flat
Grass buffer strips, unfertilized strips along watercourses	Shallow (< 1m)	Arable	Hilly; Flat
Reactive barriers to increase retention (swamp filters, iron-coated drains, sludge collection in ditches, etc.)	Shallow (< 1m)	Arable	Hilly; Flat

4.2.2 Scenarios

Several situations can be distinguished within the Dutch Meuse catchment. These scenarios were developed in order to reduce diffuse loads of N and P.

In non-hilly areas with deep groundwater (> 2 m below ground) and a small number of ditches, no measures are needed to reduce P losses because losses will already be low due to the long pathways of the waterflow through the soil to surface waters and the capacity of the subsoil to bind P. Consequently, the impact of the measures would be negligible.

In non-hilly / flatter areas with shallow groundwater (<1 m) and nearby ditches, land use is mainly grassland combined with silage maize (dairy farms), but some arable land also occurs. Permanent grassland is in fact a cover crop, breaking the impact of precipitation on soil detachment all year round. In addition, the intensive root systems bind the soil very well, surface runoff is inhibited and most of the detached particles are retained by grass. Permanent grassland often has a good soil structure and infiltration capacity (root corridors, worm canals) and in the case of good grassland management recommendations are to avoid compaction of the topsoil and subsoil during mowing and avoid trampled areas by livestock. In general, grassland is considered as the most important crop to reduce overland P losses from runoff and erosion. In situations where grassland is not well managed resulting in a poor water infiltration capacity, the first step is to improve the management of the soil and as an ultimate solution to plough and re-seed.

On arable land in non-hilly /flat areas with shallow groundwater (1<m) and nearby ditches more attention should be given to preventing overland flow and situations where preferential pathways occur with high flow rates. Especially in periods with low crop cover (early spring and autumn, and also periods with regular rainfall), soils must be protected against erosive forces and clogging of the soil. In the Netherlands “catch crops” are compulsory only for maize fields on sandy and loess soils; however, to mitigate against N leaching they should be adopted for other arable fields. Catch crops are meant mainly to reduce nitrate leaching, however they will also have an impact on reducing runoff/erosion which will reduce particulate P loads.

The overall effectiveness of the chosen scenarios is described below.

4.2.2.1 Scenario 1: P Mining

Mining of the soil P accumulation is the first step to reduce P losses, since the P losses are strongly determined by:

1) the buffering capacity of the soil to release soluble P (relevant in runoff situations like surface runoff and interflow) and

2) high P content in eroded particles (during surface runoff events or in cracked soils directly transported to artificial drains).

Although the major part of phosphate in agricultural land is well fixed to aluminium and iron (hydr)oxides and clay particles (under oxidised conditions), once saturated by water reduced conditions can occur resulting in a rapid release of phosphate. This is because under reduced conditions (no oxygen) iron^{3+} phosphate will turn into iron^{2+}phosphate which has a much higher solubility.

4.2.2.2 Scenario 2: Improved Soil Management

A second important measure is related to reducing surface runoff/erosion in hilly regions within the catchment and in areas with shallow groundwater (< 1 m; high groundwater levels in the autumn – winter and spring period) as described in the introduction to these scenarios (4.2.4). Proper field management will contribute towards minimising P losses. The use of “catch crops” will also reduce nitrate leaching by uptake of N in addition to reducing soil erosion. In that case the focus of crop and soil management is on:

(1) increasing water infiltration to reduce runoff volumes and erosivity,

(2) strengthening topsoil resistance to detachment of soil particles, and

(3) protecting the soil surface against erosive forces (e.g. with plant or residue cover; the so called 'cover crops') but "catch crops" (refer to the above section) will also assist towards this goal and is also an important BMP for reducing nitrate pollution.

4.2.2.3 Scenario 3: Riparian Buffer Strips and Ponding Overland Flow.

In hilly areas of the Meuse catchments (often with deep groundwater > 2m) the focus should be on reducing P loss by surface runoff and erosion because subsurface P leaching to surface waters will be negligible. Additional measures are valuable mainly on arable land, because grassland is seen as the most important crop to reduce P losses by runoff/erosion. On arable land contour ploughing along the slopes is the most important measure to minimise overland flow of P (soluble and with sediments). However, rather than "in field" measures it is often better to implement some larger-scale (i.e. catchment scale) measures to reduce both N and P loads in the hilly sub-basins than to carry out ineffective measures on all fields. However, this requires a broader area-based approach where many actors are involved which often takes more time for implementation. Where the construction of large-scale measures is recommended as a BMP, this Scenario can include the construction of buffer strips/wetlands which can be up to 10m wide and take up 10% of the field area (maximum) and intercept all watercourses entering the rivers. The effectiveness of these BMPs strongly depends on the maintenance and management of the (riparian) wetland / vegetated buffer strips since the capacity to trap retain nutrients will change over time.

During extreme rainfall events, not only on arable land but also on grassland, surface runoff can still occur. It is always better to keep the water within the field (ponding) instead of creating water pathways over the field to allow surface water to drain rapidly to watercourses (e.g. ditches). Low ridges along the land parcel are a simple effective measure in inhibiting and temporarily storing of excessive amounts of water on the field, in Scenario 4. However, it is better to evaluate the whole drainage concept which leads on to Scenario 5.

4.2.2.4 Scenario 4: Land use change to reduce Arable Crops

In flatter areas with shallow groundwater, ditches and grassland, a reduction of the percentage of arable crops in the annual rotation is proposed. Increasing the prevalence of permanent grassland also introduces a "cover crop" which can reduce overland P losses and reduce N leaching to the shallow groundwater too.

4.2.2.5 Scenario 5: Controlled Drainage of fields

Waterboards and farmers can discuss together the options of more controlled water management by analysing the surface water level management and the drainage systems of agricultural land. Introducing controlled artificial drainage in combination with surface water level management can help to change the pathway of water to be via more deeper layers under wet conditions instead of over the surface (at least reduced water flow). Deeper pathways are often effective in reducing the P losses as well as promoting denitrification to reduce nitrate leaching to shallow groundwater. Therefore, modifying artificial drainage in combination with surface water management would be theoretically possible to change even the subsurface and interflow flow pathways to flow through very deep soil horizons (i.e. deeper groundwater).

4.3 Meuse (Flanders: FL)

4.3.1 Introduction

A selection was made for the top 5 BMPs for the Meuse catchment in Flanders. This top 5 was constructed for N and P separately and was based on current measures in action plans or measures discussed for future action plans. Preference was also given to measures where the effects on N and P loads and concentrations can be evaluated by using modelling tools (NEMO - Pegase). The shortlisted BMPs can be accessed using the above link to the Flanders Meuse worksheet in the catchments' BMP Matrix.

For N the shortlisted BMPs were:

1. Improved fertiliser management based on crop requirements and reduction of fertilisation standards at farm level
2. Arable measures: Cover and catch crops.
3. Riparian Buffer Strips: fertiliser-free zones, grassland strips
4. Crop restrictions in vulnerable areas: e.g. limits to crops with high nitrate leaching
5. Technical end-of-pipe measures aimed at nitrate removal from drainage water.

And for P the shortlisted BMPs were:

1. Improved fertiliser management with the aim of mining the P stocks from the soil.
2. Erosion control measures: cover crops, minimum soil cover, contour ploughing, no-till farming, erosion dams and sediment traps.
3. Riparian Buffer Strips: fertiliser-free zones, grassland RBS.
4. Crop restrictions in vulnerable areas: e.g. no erosion sensitive crops on slopes.
5. Technical end-of-pipe measures aimed at phosphorus removal from drainage water.

Besides the top 5, these are additional measures which can be considered:

- Construction of wetlands with the aim of nitrate removal.
- Restrictions on usage of drainage systems to minimise flow of nitrate and phosphate directly to ditch and river systems.
- Land use change to take arable land out of production to natural grassland or woodland.

4.3.2 Scenarios

Based on the "Top 5" BMPs shortlisted above, to reduce N and P loadings the following scenarios were developed. The proposed measures can replace current measures of the Manure Action Plans where needed, or be additional to the measures. The measures will be targeted based on the load reduction targets for meeting the WFD and Nitrates Directive, which were established in WP2. First the basic scenario will be considered. For water bodies where the basic scenarios are not sufficient to reach the target, additional measures will be modelled. The modelling will be done with the existing NEMO - Pegase modelling system.

4.3.2.1 Scenario 1: Improved Soil Management

An increase in catch crops area is proposed to reduce soil erosion as a source of P and reduce nitrate N leaching. Mandatory catch crops should be planted after main crops which are harvested before 1 September, if no after crop is planned.

4.3.2.2 Scenario 2: Reduction in Fertiliser Standards

In Scenario 2 the existing N and P fertiliser standards will be reduced by up to 30 % compared to standard reduction standards. The reduction will be scaled from 10 % to 30 %, depending on the reduction targets of the water body.

4.3.2.3 Scenario 3: Riparian Buffer Strips

In Scenario 3 it is proposed to construct up to 5 m wide buffer strips next to all waterways in all water body catchments with a reduction target for N or P. Restrictions on fertiliser usage and crops will apply in the buffer strips.

4.3.2.4 Scenario 4: Erosion Control Measures

Scenario 4 proposes to implement generic erosion control measures aimed at reducing erosion by 30% in erosion sensitive areas. No individual measures will be modelled, but rather modelled sediment loads will be reduced to take the effect of potential measures into account.

4.3.2.5 Scenario 5: Reduction in crops with high nitrate leaching

The first of two additional scenarios considers crops such as maize, potatoes and other vegetables which can cause high rates of nitrate leaching. It will limit the area of crops with high nitrate leaching risk in the water body catchment, depending on the N reduction target. Conversion to grassland or other crops with low nitrate leaching losses will be considered as a LUC.

4.3.2.6 Scenario 6: End of Pipe Measures

The second additional scenario will include the calculation of the potential effects of end-of-pipe measures aimed at reducing Nand P losses from artificial field drainage systems.

4.4 Wye (UK)

4.4.1 Introduction

The Wye catchment crosses the border between England and Wales and the major pressures are from point and diffuse sources of P. Intensive livestock farming, including indoor poultry units, has caused both an excess of P in the soils and an excess of manure is applied causing excessive N loadings too (Rothwell et al., 2023 *Wye Rephokus Report 2)*. There are high erosion rates from arable land due to intensive mechanised farming and from bare, highly erodible soils after harvesting, and from grassland due to trampling and compaction from intensive grazing. N leaching will be an issue in some areas especially those with arable cropping. However, the LR targets under the existing WFD (if it is still going to remain in place following Brexit) have been set only in terms of SRP not for any forms of N. Therefore, it is unlikely that MITERRA will be directly used in the Wye to model the shortlisted BMPs unless there are enhancements to the P generation and transport routines in the model. The shortlisted BMPs are grouped below according to land use and can be accessed using the above link to the catchments' BMP Matrix.

Arable Land only

- Erosion Control Measures on arable land.
- Restrict fertiliser (and manure) applications on high P index soils.

Arable and Grassland

- Reduce soil compaction from both farm equipment (arable) and livestock trampling the fields (grassland)

Grassland only

- Construct on-farm surface flow wetlands to mitigate P losses.
- Improved management of farmyards, including concrete floors and covers.
- The development and application of nitrification inhibitors to reduce the conversion of ammonium-N to nitrate-N. This should lower rates of nitrate leaching in the catchment from grassland.
- Riparian buffer strips, comprising unfertilised, ungrazed grassland along watercourses in intensive grassland systems.
- Achieve a zero P surplus and reduce soil P in grassland through improved manure management involving the exporting out of the catchment or processing within the catchment.
- Improved application rates and timing of manure application, especially of poultry manure.

4.4.2 Scenarios

The four scenarios put forward by the Wye catchment team are primarily aimed at reducing diffuse P concentrations and loads. There should also be improvements to N too as a knock-on beneficial result. Land use in the catchment is split fairly evenly between arable and grassland so these scenarios will address either or both. These scenarios should ideally be modelled using the CRAFT or HYPE modelling tools, and consideration was also given to the N and P MFA models for the Wye being developed in WP2 being used to simulate some of the scenarios which are more substance-flow based (e.g. manure processing) as opposed to catchment or riparian management ones.

4.4.2.1 Scenario 1 Runoff and Erosion Control Measures

In Scenario 1, runoff and erosion measures are needed for both arable and grassland fields, including Riparian Buffer Strips and targeted, localised in-field measures to reduce soil compaction. The scenario applies to both arable fields (e.g. due to mechanised harvesting activities which bring increasingly heavy agricultural equipment onto the land) and grassland (where stock trampling and compaction are a major issue). Also, cover crops are needed on high-risk arable fields to reduce runoff and limit erosion during the wetter periods of the year.

4.4.2.2 Scenario 2 Improved Management of Fertilisers

In Scenario 2 we considered improvements to the timing and amounts of N and P applied in fertilisers and manures (solid and slurry, including poultry litter) in the Wye catchment. The application rates need to be optimised to match crop offtake on P Index 2 soils, so that the overall P balance remains stable at Index 2 (or can be lowered down to this level). This applies to both arable and grassland fields and aims to reduce both the soil P status and excess P in the catchment which causes high P losses to water. There should also be a similar effect of the N balance and a reduction in N leaching due to this scenario.

4.4.2.3 Scenario 3: Manure Processing and Recovery

In this scenario the manures from livestock farming (pigs, poultry and cattle) needs to be either processed locally or exported out of the catchment, to reduce the surplus of manure in the catchment, this can involve using processing plants which ideally would generate solid forms of recycled P as a by-product that can be used as a fertiliser, breaking the reliance of importing P from the world fertiliser industry and relying on a resource-scarce commodity. Manure management was probably first considered as a novel source of P that could be used for crop production in England by Bateman et al. (2011), replacing expensive, imported chemical fertiliser products. Their study pointed out however that the treatment of manures to concentrate P can be an option but the environmental (including N emissions from manure transport) and economic impacts need to be considered too.

4.4.2.4 Scenario 4: Land Use Change

In Scenario 4 a set of potential LUCs can be evaluated, these will focus on taking land from intensive agriculture to less-intensive production, e.g unfertilized grassland or agri-forestry schemes. This scenario will depend partly in practice on what new schemes are trialled by the UK government to promote LUCs to de-intensify agricultural land use in the Wye, for example some variant of set-aside or tree planting.

4.5 Neagh Bann (UK - IRL)

4.5.1 Introduction

Pressures in the Neagh Bann catchment come from both point and diffuse sources of P, and SRP is assessed as the form of P that requires load reductions to meet the WFD targets to meet “Good” status. A review of the current status of surface waters (Ref *Catchments Report D1*) provides an overview of the current WFD status of the catchment. Intensive livestock farming and low levels of nutrient management planning have caused both an excess of P in agricultural soils and an excess of manure which requires a strategy to improve how it is managed, and this applies to the whole of NI and the Irish Border Region. Around 60-70% of the total P load to Lough Neagh originates from agriculture (mainly livestock) with point sources comprising the balance. There are no known issues in the catchment with high concentrations and loads of N, and nitrate concentrations in surface waters are often below the UK average and similar catchments in GB. This is mainly due to the limited extent of arable farming and high denitrification rates in the widespread, poorly drained soils. Only one of the 55 groundwater monitoring stations in NI recorded nitrate concentrations close to the 50 mg NO_3-N /L standard for drinking water in the 2021 assessment, but this was in the Strangford area in the east of NI. This does not however prevent dissolved inorganic N (DIN) being considered as a potential cause of pollution of coastal waters, for example the Lower Bann discharges into coastal waters off the north coast of Ireland where DIN is considered a marine pollutant.

The shortlisted BMP measures can be accessed using the above link to the N-B worksheet in the catchments’ BMP Matrix, and are summarised below as:

- Restrict fertiliser application (particularly liquid slurries) on high P index soils.
- Improve application and timing of manure applications (incl poultry litter). This could also include low emission methods to apply slurry where the aim is to reduce the gaseous N emissions from the spreading process.
- Constructed on-farm surface water wetlands for N and P reduction.
- Integrated smart buffers including a riparian zone with ditch management, and a wetland which can intercept tile drains.
- Restrict livestock access through fencing along watercourses without an additional buffer strip.
- Fencing watercourses along with a 2m grassed, unfertilised, ungrazed buffer strip.
- Achieving zero P surplus in intensively grazed fields by exporting and/or processing manures to recover P.
- Reduce overall stocking rates on livestock farms.

4.5.2 Scenarios

In the Neagh Bann four scenarios are primarily aimed at reducing diffuse P concentrations and loads. There should also be improvements to N too. However, as the focus of the measures is on reducing P it is unlikely that MITERRA will be directly used in the Neagh Bann to model the solicited BMPs, unless there are (i) enhancements to the P generation and transport routines in the model (ii) an adoption of a finer-scale grid resolution than the NUTS 2 representation currently used. Land use in the Neagh Bann catchment is mostly grassland and accordingly the selected scenarios have prioritised those for grassland rather than arable land use, and LUC was not considered an option here at all. Around 90% of the productive farmland is currently used for livestock rearing, and DAERA census data indicate that, if anything, the proportion of arable land has actually reduced in recent years due to a switch over to grassland (especially dairy). There are proposals (a replacement for the “EFS” agri-environmental scheme) in consideration for 2025 onwards by the NI Government, that will propose and support farmers to implement limited areas of tree planting, however these are unlikely to be sufficiently large-scale to be considered as a LUC that can be simulated directly using the catchment models.

4.5.2.1 Scenario 1: Runoff and Erosion Control Measures

BMPs are needed for most fields, which can include multi-stage buffer strips with riparian zones and drainage ditch management. The ultimate aim of these BMPs is to slow, store and filter runoff in the ditch during storm events, and additionally provide inter-event storage in the form of riparian wetlands, where soluble nutrients (SRP and nitrate) can be taken up by aquatic plants and the wetland ecosystem community. In addition to the existing NI government schemes to fence off waterways to prevent stock access (EFS) these should be: (i) made mandatory in fields used for livestock and (ii) include a wider (unfarmed) buffer strip of at least 2m, but preferably one that is tailored in width to the local topography and runoff riskiness (i.e. intercepting critical source areas and pathways connecting these to the watercourses) to improve the effectiveness of these measures. Support for implementing such measures should be included in the future farm schemes being developed at present for NI.

4.5.2.2 Scenario 2: Improved Management of Fertiliser and Manure

This scenario will assess reduced fertiliser and manure applications to intensively grazed fields, including silage plots and reseeded grassland. Manure management plans for each farm should be developed ensuring adequate training and/or agronomic advice is provided on a one-to-one basis to farmers. Poor nutrient management planning on farms (low pH, imbalanced nutrients) results in sub-optimal performance of grass/crops and drives a dependency on concentrate feed imports (with high P levels) to farms, which ultimately return as a P surplus to fields through land application. The existing soil P surplus in many intensive grassland fields needs to be drawn down to Index 2+ (the agronomic optimum for intensive grassland based on RB209) or lower. The existing NAP rules may also need to be strengthened, particularly to control the application of slurry in the "Open" spreading season: (i) during wet periods; (ii) to steeply sloping fields or (iii) to riparian zones (Adams & Doody, 2022). Currently the rules exist but are poorly implemented and open to abuse. There are also limited requirements for use of low emission slurry spreading techniques (a requirement only for contractors and farms with >200 cattle livestock units and large pig farms) which need to be adopted at a larger scale to reduce ammonia emissions from grassland which is a major pollution concern in NI.

4.5.2.3 Scenario 3: Manure Management

In this Scenario it has been identified that the overall surplus of manure in the catchment needs to be reduced, and this can involve local processing and/or nutrient recovery through the circular bio-economy. Options being explored in ongoing research in NI at present are centred around on-farm separation using mobile equipment and centralised processing to produce energy and other products for use in NI and for export. This will lower the loading of N and P to the soils during the "Open" spreading season.

4.5.2.4 Scenario 4: Destocking

This last scenario is still under consideration as a more drastic solution – a last resort - to the issues described above. The destocking measures would have to pay farmers to implement a reduction in their stocking density, probably achieved by reducing the herd size (it would be harder to find additional productive grassland suitable for extending the area grazed in order to reduce the stocking density).

5. DISCUSSION

The process of developing the Matrix for Best Management Practices ("BMP Matrix") evaluated a broad range of options that had mostly been proposed by previous research projects, with some novel ideas suggested through project meetings and the Policy Group. This led to the "Longlist" of measures which attempts to be a comprehensive database of different BMP options. It was clear that across the four groups and their related catchments that there was considerable common ground in terms of the options selected. Nitrogen (both nitrate and ammonia) had not been examined in any depth as a pollution source in the Neagh Bann and Wye catchments before; however there has been recent recognition of the pollution risk caused by livestock wastes generating ammonia gas at concentrations above safe limits, in regions with intensive farming. There are some similarities between this pair of catchments in terms of the farming methods and land use, and between the two Meuse catchments in the Netherlands and Flanders. This has led to the BMPs also being quite similar in both pairs, and in the Meuse overall, nitrogen has been considered as the pollutant requiring BMPs to achieve "Good" WFD status to be implemented.

Phosphorus has always been viewed as the main cause of eutrophication in NW European catchments since the research into BMPs started in the early 2000s, with riparian buffer strips (RBS) and constructive wetlands being amongst the earliest measures. In fact, RBS or variants of this including "Smarter Buffers" (Stutter et al., 2021b) and "integrated buffer strips" were popular measures common to all four catchments, reflecting perhaps the encouraging research findings of recent projects (http://www.smarterbufferz.ie/). Nitrogen may be mitigated by general source control measures such as optimal fertilisation levels (for arable crops) and improved slurry/ solid manure management and application techniques (for grassland), since once nitrogen (as nitrate) becomes soluble it is highly mobile with only denitrification an option that can readily be applied to tackle the pollution pathway.

The older BMPs may now be almost twenty years old in some cases (e.g. the Belford NFM scheme developed in NE England around 2007-2010, Wilkinson et al., 2010) and nearing the end of their useful life, or simply clogged with sediment and no longer functioning to their optimal extent. Further research and perhaps an entry in the Matrix similar to the "Timescale" column may be needed to indicate the potential longevity of these and what maintenance would be required to extend their function. The Matrix developed could be enhanced or modified during the lifetime of the project and modelling these scenarios will be a task undertaken in the next work period.

5.0 Further recommendations for developing a decision support "Matrix" for BMP selection

The web-based tool developed in the "SmarterBufferZ" project by JHI and Teagasc was reviewed above. It is currently limited to field-watercourse margin BMPs which are of varying effectiveness. Within the BMP Matrix these are mostly measures that address the diffuse pollution pathways, not the sources of nutrients. The scale of the BMPs is broadly field to catchment scale although the farm scale is also considered. It would be interesting to see if a similar tool could be developed for field-based BMPs such as improved fertiliser and nutrient addition rates.

Alternatively, a further development of an Excel-based tool could be explored, however a web-based tool can be tailored and adapted for different catchments and their characteristics if it makes use of catchment data. For example, a GIS-based tool could be developed based on the algorithms of Thomas et al. (2021) which can take a digital elevation model (DEM) of a catchment, identify the key flow pathways for nutrient transport as well as "Hot Spots" and ultimately, make recommendations of where BMPs can be constructed in the field.

6. CONCLUSIONS

- Scenarios evaluated a series of BMPs listed in a "Longlist" largely sourced from available options evaluated by research projects which started earlier this century and have been gradually developing and researching improved BMPs.
- There was some commonality between the BMPs selected by the different catchments, perhaps relating to the similar characteristics of the two pairs (Wye being similar in terms of its livestock farming to the Neagh Bann, and the Meuse being similar in both NL and Flanders).
- Further research and modelling will be required especially to tackle BMP longevity and maintenance issues.
- A future step should assess the potential for software tools, perhaps a web-based tool which would be a user-friendly interface to a BMP matrix, similar to the EPA/Teagasc funded SloWaterZ project's Riparian Measures Selection Tool.

7. References

Bateman, A., van der Horst, D., Boardman, D., Kansal, A., & Carliell-Marquet, C. (2011). Closing the phosphorus loop in England: the spatio-temporal balance of phosphorus capture from manure versus crop demand for fertiliser. *Resources, Conservation and Recycling*, *55*(12), 1146-1153.

Boumans, L. and Fraters, D. (2017) Actualisering van de trendmodellering van gemeten nitraatconcentraties bij landbouwbedrijven Landelijk Meetnet effecten Mestbeleid, RIVM Rapport 2016-0211 Rijksinstituut voor Volksgezondheid en Milieu, Netherlands.

schippeColeman, K., Jenkinson, D.S., Crocker, G.J., Grace, P.R., Klír, J., Körschens, M., Poulton, P.R., Richter, D.D., 1997. Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. *Geoderma* 81, 29–44. https://doi.org/10.1016/S0016-7061(97)00079-7

Collins, A.L., Zhang, Y.S., Winter, M., Inman, A., Jones, J.I., Johnes, P.J., Cleasby, W., Vrain, E., Lovett, A. and Noble, L. (2016). Tackling agricultural diffuse pollution: what might uptake of farmer-preferred measures deliver for emissions to water and air? *Science of the Total Environment*, *547*, 269-281.

Collins, A. L., Price, J. N., Zhang, Y., Gooday, R., Naden, P. S., & Skirvin, D. (2018). Assessing the potential impacts of a revised set of on-farm nutrient and sediment 'basic' control measures for reducing agricultural diffuse pollution across England. *Science of the Total Environment*, *621*, 1499-1511.

COST 869: Schoumans et al. (2011), Alterra-Report 2141

Environment Agency (2019) Catchment Sensitive Farming Evaluation Report – Water Quality, Phases 1 to 4 (2006-2018). Natural England publication, June 2019. 54pp

Jebari, A., Pereyra-Goday, F., Kumar, A., Collins, A.L., Rivero, M.J. and McAuliffe, G.A. (2024) Feasibility of mitigation measures for agricultural greenhouse gas emissions in the UK. A systematic review. *Agronomy for Sustainable Development*, 44, 2 (2024). https://doi.org/10.1007/s13593-023-00938-0

Kleinman, P. J. A., Osmond, D. L., Christianson, L. E., Flaten, D. N., Ippolito, J. A., Jarvie, H. P., Kaye, J. P., King, K. W., Leytem, A. B., McGrath, J. M., Nelson, N. O., Shober, A. L., Smith, D. R., Staver, K. W., & Sharpley, A. N. (2022). Addressing conservation practice limitations and trade-offs for reducing phosphorus loss from agricultural fields. *Agricultural & Environmental Letters,* 7, e20084.

Lintern, A., McPhillips, L., Winfrey, B., Duncan, J. and Grady, C. (2020) Best Management Practices for Diffuse Nutrient Pollution: Wicked Problems Across Urban and Agricultural Watersheds. *Environmental Science & Technology* 54.15 (2020): 9159-9174.

Newell Price, J. P., Harris, D., Taylor, M., Williams, J. R., Anthony, S. G., Duethmann, D., Gooday, R. D., Lord, E. I., Chambers, B. J., Chadwick, D. R. and Misselbrook, T. H. (2011). An inventory of mitigation methods and guide to their effects on diffuse water pollution, greenhouse gas emissions and ammonia emissions from agriculture. *Prepared as part of Defra Project WQ0106*, 162.

Oenema et al. (2018) *Review of Measures to decrease nitrate pollution of drinking water sources,* Fairway Report D4.1, European Union's Horizon 2020 Grant Agreement No. 727984

RIVM (2021) Dutch National Water Quality Monitoring Network - Waterkwaliteit 2021. https://www.rivm.nl/landelijk-meetnet-effecten-mestbeleid/onderzoeksresultaten/waterkwaliteit-2021

Rothwell, S. A., Forber, K. J., Withers, P. J. A. & Lyon, C. (2023) *Wye Rephokus Report 2: Lancaster University.*

Schoumans, O.F., Chardon, W.J., Bechmann, M.E., Gascuel-Odoux, C., Hofman, G., Kronvang, B., Rubæk, G.H., Ulén, B. and Dorioz, J.M. (2014) Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: A review. Science of The Total Environment 468-469, 1255-1266.

Scott, A., Cassidy, R., Arnscheidt, J., Rogers, D. and Jordan, P. (2023) Quantifying nutrient and sediment erosion at riverbank cattle access points using fine-scale geo-spatial data. *Ecological Indicators* 155, 111067.

Schipper, P., Renaud, L., Boekel, E.v., 2019. Bronnenanalyse nutriënten stroomgebied Maas. Rapport 2931, Wageningen Environmental Research, Wageningen.

Stutter, M., Baggaley, N., & Wang, C. (2021a). The utility of spatial data to delineate river riparian functions and management zones: A review. *Science of the Total Environment*, *757*, 143982.

Stutter, M., Costa, F.B. and Ó hUallacháin, D. (2021b) The interactions of site-specific factors on riparian buffer effectiveness across multiple pollutants: A review. *Science of The Total Environment* 798, 149238.

Tanner C.C., Tomer, M.D., Goeller, B.C., Matheson F.E., (2023a) Diverse solutions for Mitigation of Diffuse Contaminant Losses: Which goes where for what. In: *Diverse solutions for efficient land, water and nutrient use.* (Eds C.L Christensen, D.J.Horne and R.Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 35. Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand. 5 pp.

Tanner, C.C., Tomer, M.D. and Goeller, B.C. (2023b) A framework for applying interceptive mitigations for diffuse agricultural pollution. *New Zealand Journal of Agricultural Research*, 1-22.

Thomas, I., Bruen, M., Mockler, E., Werner, C., Mellander, P.-E., Reaney, S., Rymszewicz, A., McGrath, G., Eder, E., Wade, A., Collins, A. and Arheimer, B. (2021) Research 396: Catchment Models and Management Tools for Diffuse Contaminants (Sediment, Phosphorus and Pesticides): *DiffuseTools Project*, p. 64, Environmental Protection Agency.

USDA ARS (2006) *Best Management Practices to Minimize Agricultural Phosphorus Impacts on Water Quality* ARS-163.

Velthof, G., Oudendag, D.A. and Oenema, O. (2007) Development and application of the integrated nitrogen model MITERRA-EUROPE; Task 1 Service contract "Integrated measures in agriculture to reduce ammonia emissions", *Contract Number 070501/2005/422822/MAR/C1*, p. 100, ALTERRA, Wageningen UR.

Velthof, G. L., Oudendag, D., Witzke, H. P., Asman, W. A. H., Klimont, Z., & Oenema, O. (2009). Integrated assessment of nitrogen losses from agriculture in EU-27 using MITERRA-EUROPE. *Journal of Environmental Quality*, *38*(2), 402-417.

Wilkinson, M., Quinn, P.F., Benson, I., Welton, P. and Kerr, P. (2010) Runoff management: mitigation measures for disconnecting flow pathways in the Belford Burn catchment to reduce flood risk. *Proceedings of the British Hydrological Society International Symposium*. Newcastle University.

Zak D., Stutter, M., Jensen, H.S., Egemose, S., Carstensen, M.V., Audet, J., Strand, J.A., Feuerbach, P., Hoffmann, C.C., Christen, B., Hille, S., Knudsen, M., Stockan, J., Watson, H., Heckrath, G., Kronvang, B. (2019). An assessment of the multifunctionality of integrated buffer zones in Northwestern Europe. *Journal of Environmental Quality*, *48*(2), 362-375.

Zhang, Y., Collins, A. L., Johnes, P. J. and Jones, J. I. (2017). "Projected impacts of increased uptake of source control mitigation measures on agricultural diffuse pollution emissions to water and air." *Land Use Policy*, *62*, 185-201.

Zhang, Y., Griffith, B., Granger, S., Sint, H. and Collins, A.L. (2022) Tackling unintended consequences of grazing livestock farming: Multi-scale assessment of co-benefits and trade-offs for water pollution mitigation scenarios. Journal of Cleaner Production 336, 130449.

Appendix 1 Longlist of measures to reduce nitrate leaching to groundwater under different local conditions

codes	value		Characterisation N-pollution						
limited / not effectiveness	1	groundwater level	deep (>2m) focus on sandy soils				shallow (<1m); peat (sandy)		drained (clay)
low effectiveness	2	ditches	no ditches				ditches		ditches
moderate	3	Land use	perm. grass		arable		perm. grass	arable	all
effective	4	Landscape	flat	hilly	flat	hilly			
highly effectiveness	5	actual N losses (nitrate groundwater)	high	high	very high	very high	low - moderate	moderate - high	moderate
		actual N losses (N surface water)	low - moderate N losses by high rainfall events	moderate - high N losses by high rainfall events	moderate - high N losses by high rainfall events	(very) high N losses by high rainfall events	N losses often low - moderate	N losses moderate to high	N losses moderate to high
		list of measures focus on NO3-groundwater							
		field scale							
Souce limiting	**Right amount**	Lower application standards in general (currently already no derogation and 20% less N in N polluted areas)	4	4	4	4	2	2	3
		Precision application that matches the quality of the soil; Manure application in accordance with the fertilization advice; Adjusts (artificial) fertilizer application to mineralization through additional sampling; Optimizes the Ph and Ca/Mg ratio for crop production	4	4	4	4	2	2	3
	Right timing	For clay: spring manure application instead of autumn	/	/	/	/	/	/	3
		Extend closing period : 1. Shifting the spreading period of liquid manure on arable land; 2. Extending the period for spreading solid manure on grassland; 3. Later spring application of animal manure to grassland and corn)	2	2	2	2	2	2	2
		Uses manure storage facility (cellar or foil basin) with sufficient capacity to regulate the application timing							
	Right location	No N application in fields above optimum yield; balance fertilisation	1	1	2	2	1	2	2
		Uses fertigation and/or drip irrigation	/	/	1	1	/	1	1
		Row fertilization for maize and vegetables	/	/	2	2	/	2	2
	Right type	Apply different forms of manure (e.g: dilute slurry before spreading, manure separation&mixing, use of compost and organic fertilizer); apply solid manure fractions on arable land (more stable; ploughed) in stead of injected manure slurries	1	1	3	3	1	2	2
Route control	**Crop diversification**	Crop rotation, adjust crop plan, ban on certain crops	/	/	3	3	/	3	2
		Apply catch crops (maize) after 1 August; no additional N-application	/	/	4	4	/	3	3
		Switch from vegatable crops to ceraels with deep rooting (high N uptake)	/	/	3	3	/	2	2
		Convert grassland to production-oriented herb-rich grassland	2	2	/	/	2	/	/
		Cultivation of silage maize in strips milled in grassland	2	2	/	/	2	/	/
		Recycled cultivation system	/	/	5	5	/	1	1
		Impact of no-derogation: less grassland in general --> increase of arable land	1	1	1	1	1	1	1
		Extension of the age of grassland (no grazing after the first of 1 August); grassland renewal 3-5 years and no N-application after renawal	4	4	/	/	4	/	3
	Physical structure	Ploughing only in spring	/	/	2	2	/	1	2
		Minimal tillage	/	/	3	3	/	/	3
		Controlled drainage; applying underwater drainage in peat areas	/	/	/	/	/	1	1
	Soil composition	Add compost or other organic matter-enriching sources	1	1	1	1	1	1	1
		Improve soil structure by applying soil improving agents	1	1	1	1	1	1	1
		Remove N rich crop residues after harvest	/	/	4	4	/	4	4
	Treatment	Remediation of hotspots	1	1	1	1	1	1	1
		Reuse of N and P recovered from ditch dredging	/	/	/	/	1	1	1

Appendix 2 Longlist of measures to reduce N losses to surface waters under different local conditions

codes	value
limited / not effectiveness	1
low effectiveness	2
moderate effectiveness	3
effective	4
highly effectiveness	5

Characterisation N-pollution							
groundwater level	deep (>2m) focus on sandy soils				shallow (<1m); peat (sandy)		drained (clay)
ditches	no ditches				ditches		ditches
Land use	perm. grass		arable		perm. grass	arable	all
Landscape	flat	hilly	flat	hilly			
actual N losses (nitrate groundwater)	high	high	very high	very high	low - moderate	moderate - high	moderate
actual N losses (N surface water)	low - moderate N losses by high rainfall events	moderate - high N losses by high rainfall events	moderate - high N losses by high rainfall events	(very) high N losses by high rainfall events	N losses often low - moderate	N losses moderate to high	N losses moderate to high

list of measures focus N runoff/erosion

field scale

Souce limiting	**Right amount**	Lower application standards in general	1	2	1	2	4	4	4
		Precision application that matches the quality of the soil; Manure application in accordance with the fertilization advice; Adjusts (artificial) fertilizer application to mineralization through additional sampling; Optimizes the Ph and Ca/Mg ratio for crop production	1	2	1	2	3	3	3
	Right timing	For clay: spring manure application instead of autumn	/	/	/	/	/	/	4
		Extend closing period : 1. Shifting the spreading period of liquid manure on arable land; 2. Extending the period for spreading solid manure on grassland; 3. Later spring application of animal manure to grassland and corn)	1	2	2	2	3	4	4
		Uses manure storage facility (cellar or foil basin) with sufficient capacity to regulate the application timing							
	Right location	No N application in fields above optimum yield; balance fertilisation	/	/	1	1	/	3	2
		Uses fertigation and/or drip irrigation	/	/	1	1	/	1	1
		Row fertilization for maize and vegetables	/	/	1	1	/	2	2
	Right type	Apply different forms of manure (e.g: dilute slurry before spreading, manure separation&mixing, use of compost and organic fertilizer); apply solid manure fractions on arable land (more stable; ploughed) in stead of injected manure slurries	3	3	3	3	3	3	3
Route control	**Crop diversification**	Crop rotation, adjust crop plan, ban on certain crops	/	/	3	3	/	3	2
		Apply catch crops (maize) after 1 August; no additional N-application	/	/	4	4	/	4	4
		Switch from vegatable crops to ceraels with deep rooting (high N uptake)	/	/	2	2	/	3	3
		Convert grassland to production-oriented herb-rich grassland	2	2	/	/	2	/	/
		Cultivation of silage maize in strips milled in grassland	1	1	/	/	1	/	/
		Recycled cultivation system	/	/	2	2	/	2	2
		Impact of no-derogation: less grassland in general	1	1	1	1	1	1	1
		Extension of the age of grassland (no grazing after the first of 1 August); grassland renewal 3-5 years and n-application after renawal	1	2	/	/	3	/	/
	Physical structure	Ploughing only in spring	/	/	2	2	/	3	3
		Minimal tillage	/	/	2	2	/	/	3
		Countour ploughing	/	/	/	2	/	/	/
		Increase water infiltration (grassland often is already okay)	1	1	2	2	1	2	2
		Raised plot areas at the field edges, low ridges along the field; allow ponding of in-field excess of water	1	2	1	2	1	3	3
		Apply cover crops (grass) to reduce erosion and runoff	/	/	2	2	/	4	4
		Conditions and usage standards for ploughed grassland on sandy and loess soil (no manure application on ploughed grassland)	/	/	1	1	/	2	2
		Prevent soil compaction by adjusting wheel load	/	/	2	2	/	2	2
		Level depressions in field (to raise wet areas)	/	/	/	/	/	/	/
		Grass buffer strips, unfertilized strips along watercourses	1	1	2	2	3	4	4
		Controlled drainage; applying underwater drainage in peat areas	/	/	1	1	/	3	3
	Soil composition	Add compost or other organic matter-enriching sources	1	1	1	1	1	1	1
		Improve soil structure by applying soil improving agents	1	1	1	1	1	1	1
		Remove N rich crop residues after harvest	/	/	1	1	/	2	2
	Treatment	Grassed waterways to regulate water during extreme rainfall events	/	/	1	2	/	2	2
		Reactive barriers to increase retention (swamp filters, iron-coated drains, sludge collection in ditches, etc.)	1	2	2	3	3	5	5
		Remediation of hotspots	3	3	3	3	3	3	3
		Nature-friendly edge management and dredging of ditches	1	1	1	1	2	2	1
		Reuse of N and P recovered from ditch dredging	/	/	/	/	1	1	1
		Dredging pump for effective ditch dredging	1	1	1	1	1	1	1