A broad-scale spatial analysis of the environmental benefits of fertiliser closed periods implemented under the Nitrates Directive in Europe

Tzilivakis, J.*, Warner, D.J., Green, A. and Lewis, K.A.

* Corresponding author: J.Tzilivakis@herts.ac.uk

Agriculture and Environment Research Unit (AERU), School of Life and Medical Sciences, University of Hertfordshire, United Kingdom. AL10 9AB.

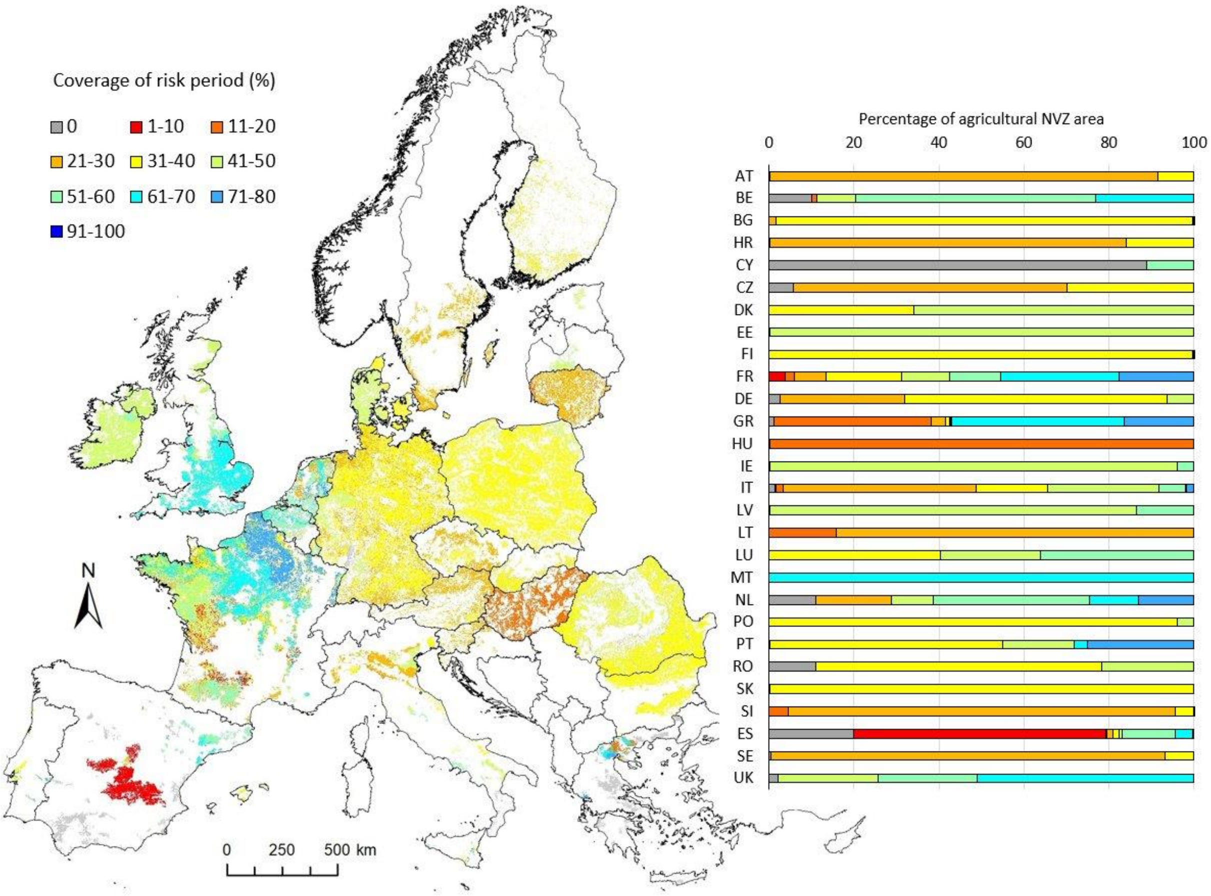
Abstract

Nutrient pollution from agriculture has been an ongoing challenge for decades, contributing to numerous negative environmental impacts. In the European Union policies have been developed to address nutrient pollution, including Nitrate Action Programmes under Council Directive 91/676/EEC. Although Member States report on progress on implementation, there have been few studies that explore how measures have been implemented; the environmental implications of any differences; and how they vary spatially on a European scale. This study aims to address this gap with respect to fertiliser closed periods (1155 different closed periods across 69 Nitrate Action Programmes). This included the development of an approach that can be applied using readily available spatial data. Each closed period was scored for its coverage of risk periods for losses of nitrate; organic material; nitrous oxide and ammonia. Closed periods were then matched to relevant combinations of spatial data for each environmental zone and fertiliser type. The scores for each combination were used to create maps and calculate spatial statistics. The results show that in addition to nitrate, closed periods also reduce the risk of organic material run-off, emissions of nitrous oxide and to a lesser extent ammonia. However, risk reduction is spatially variable across all the impacts and the scope for synergy is also variable (e.g. nitrate loss does not always correlate with nitrous oxide or ammonia risk reduction). Regions in the Atlantic, Lustanian and some areas within the Mediterranean zones appear to provide the greatest combined risk reduction, with other zones, especially in eastern Europe, having a lower combined risk reduction (due to a combination of different risk periods coupled with lower coverage of individual risks). The spatial analysis within this study is relatively simple; is based on a snapshot of closed periods during 2019-2020; and only explores one measure. However, it does provide some useful data and insights that could support policy development in the future. This includes scope for Member States and regions to learn from others where greater coverage of risk periods has been achieved; and highlighting how a more holistic perspective can be taken to the environmental management of nutrients. As we strive towards developing sustainable production systems, farmers and policy makers need to take a more integrated approach to incorporate additional environmental objectives; which increases the complexity of the challenge. Consequently, the demand for pragmatic approaches that take a more holistic approach is likely to increase in the future.

Keywords: agriculture; ammonia; closed periods; nitrate; nitrous oxide; organic material.

Graphical abstract

Spatial variability in the combined coverage of risk periods for nitrate loss, organic material, nitrous oxide and ammonia due to fertiliser closed periods in Europe



Highlights

- A novel spatial analysis of the environmental impacts of fertiliser closed periods in Europe is developed and applied.
- Risk reduction and scope for synergy varies spatially for losses of nitrate, organic material, nitrous oxide and ammonia.
- Regions in the Atlantic, Lustanian and some Mediterranean zones appear to provide the greatest combined risk reduction.

1.0. Introduction

The issue of nutrient pollution from agriculture has been an ongoing challenge for decades (Collins and McGonigle, 2008; de Vries *et al*., 2011; Sharma, 2020; Van der Voet *et al*., 1996; Van Grinsven *et al*., 2015). In particular, the use of nitrogen (N) fertilisers can result in losses of nitrate (NO_3^-) to surface and groundwater (contributing to poor water quality and eutrophication) (Schröder *et al*., 2004), and emissions of nitrous oxide (N_2O) (Rees *et al*., 2013) and ammonia (NH_3) to the atmosphere (contributing to climate change and poor air quality) (Skjøth and Hertel, 2013). Many of the processes are well understood, but their management in the context of commercial production is often one of trying to strike a balance between competing objectives, especially economic production versus environmental protection. It also involves finding solutions that reduce environmental burdens overall and do not simply export or displace impacts elsewhere and/or swap one pollutant for another (e.g. reducing NO_3^- leaching at the expense of increasing NH_3 emissions). Consequently, there is a need to take a more holistic and integrated perspective to the environmental management of nutrients, however this can further complicate decision-making processes at both the farm and policy levels due to the need to account for multiple objectives.

In the European Union (EU), policies have been developed that aim to address nutrient pollution from agriculture. Council Directive 91/676/EEC (the Nitrates Directive) (EC, 1991) aims to reduce water pollution caused by nitrates used in agriculture; reducing nitrate pollution is an integral part of Directive 2000/60/EC (the Water Framework Directive - WFD) (EC, 2000); and Directive 98/83/EC (the Drinking Water Directive) requires that nitrate does not exceed 50 mg NO_3^- per litre in drinking water (EC, 1998). Additionally, Directive 2016/2284 (the National Emission Ceilings Directive - NECD) (EC, 2016) sets national emission reduction commitments for five key air pollutants including NH_3. The original NECD (EC, 2001) largely laid out emissions targets for air pollutants, however, the latest amendment (EC, 2016) contains obligations to introduce measures to reduce NH_3 emissions. There are also policies which have indirect effects on nutrient pollution by aiming to protect ecosystems (including from the deleterious effects of nutrient pollution), such as Directives 2009/147/EC and 92/43/EEC, better known as the Birds and Habitats Directives respectively (EC, 2009, 1992). Finally, there was a commitment under the Seventh Environmental Action Programme (EC, 2013) to ensure that the nutrient cycle (nitrogen and phosphorus) is managed in a more sustainable and resource-efficient way.

The development of Nitrate Action Programmes (NAPs) (under Article 5 of the Nitrates Directive) by Member States is a key mechanism for implementing measures to reduce nutrient pollution. Annexes II and III of the Nitrates Directive outline the minimum measures to be included in NAPs, but Member States have scope to tailor and build upon these to account for national and regional circumstances. The Nitrates Directive is not a blanket set of prescriptions and NAPs can vary from one Member State or region to another. Consequently, there is scope for differences in NAPs across the EU. The European Commission (EC) commissioned a research project in 2019-20 to create an inventory of NAP measures and identify differences in approaches between Member States and regions (Tzilivakis *et al*., 2020). This work identified that there were 80 different NAPs across the 28 Member States (note this work was undertaken prior to the UK leaving the EU), with regional NAPs in Belgium (2), Finland (2), France (12), Greece (7), Italy (18), Spain (14) and the UK (4). One of the most common and key measures implemented in the NAPs are fertiliser closed periods. Tzilivakis *et al*. (2020) identified that this measure has been implemented in 69 NAPs. It is anticipated that the remaining 11 NAPs (9 in Spain) may have this measure, but this could not be confirmed from the documentation compiled for the inventory. This study explores the benefits of closed periods in further detail, extending the work undertaken by Tzilivakis *et al*. (2020) to include a broad spatial analysis.

Closed periods are specific times of the year when the application of inorganic and/or organic fertilisers are prohibited, with the objective of reducing the loss of NO_3^- via leaching and run-off. There are periods of the year when the potential for N loss (particularly leaching) is enhanced should they correspond to periods when soils contain significant quantities of available (soluble) N. Generally these occur when inputs of water (e.g. precipitation) exceed the levels that can be retained due to the water holding capacity of the soil or lost through evapotranspiration (ET); although in some cases periods when soils (most notably clay soils) are cracked allowing rapid water movement may also be relevant (Alterra *et al.*, 2011). Consequently, times of the year when heavy rainfall is expected, temperatures are low, crop growth is limited and/or soils are left bare (limiting ET), are particularly vulnerable to both leaching losses and the generation of overland flow (run-off losses). In most cases, the winter months are likely to be the main risk period, since in northern Europe (for example) this is when rainfall is high and growth is limited. The situation is a little more complicated in Mediterranean areas since in rain-fed systems winter is likely to be the main period of crop growth, and precipitation very limited in summer; however, these are also areas in which there is a lot of irrigated agriculture. Nevertheless, prohibiting the application of N fertilisers during the most sensitive periods (based on an evaluation of climatic factors) will aid in avoiding N losses.

Closed periods also have the potential to have other environmental benefits and these will vary spatially (e.g. due to different climatic conditions). Prohibiting the application of organic fertilisers at times when overland flow is most likely reduces the likelihood of organic materials (containing and pathogenic organisms and substances with a high Biochemical Oxygen Demand (BOD)) being washed into surface waters or leached into groundwater (where many pathogens can remain reasonably stable) (Pandey *et al.*, 2014). The application of N containing fertilisers at times when soil conditions may be prone to waterlogging may result in increased denitrification and emissions of N_2O. Consequently, measures which prohibit the application of fertilisers at times when such conditions are most likely to occur have the potential to limit N_2O emissions (Butterbach-Bahl *et al*., 2013; Machefert *et al*., 2002 & 2004; Veraart *et al*., 2011). Similarly, prohibiting the application of fertilisers (especially surface applied high N organic fertilisers) during times and conditions that favour NH_3 emissions, for example higher temperatures (Holly *et al*., 2017; Gilbert *et al*., 2006; Webb *et al*., 2010), will help reduce these emissions.

The implementation of closed periods is highly variable between NAPs, in terms of different closed periods for different fertilisers, crops, conditions, etc., ranging from a single closed period for all fertilisers (e.g. Malta) to multiple closed period dates depending on, for example, fertiliser type and crop (e.g. 109 different closed periods in Nouvelle Aquitaine, France); with 1155 different closed periods across 69 NAPs. Closed period dates vary based on a combination of one or more different parameters. Figure 1 summarises the parameters used in each of the 69 NAPs and shows that land use/crop and fertiliser type are the most common parameters used to vary closed periods, followed by region, and then soil type; all of which will vary spatially.

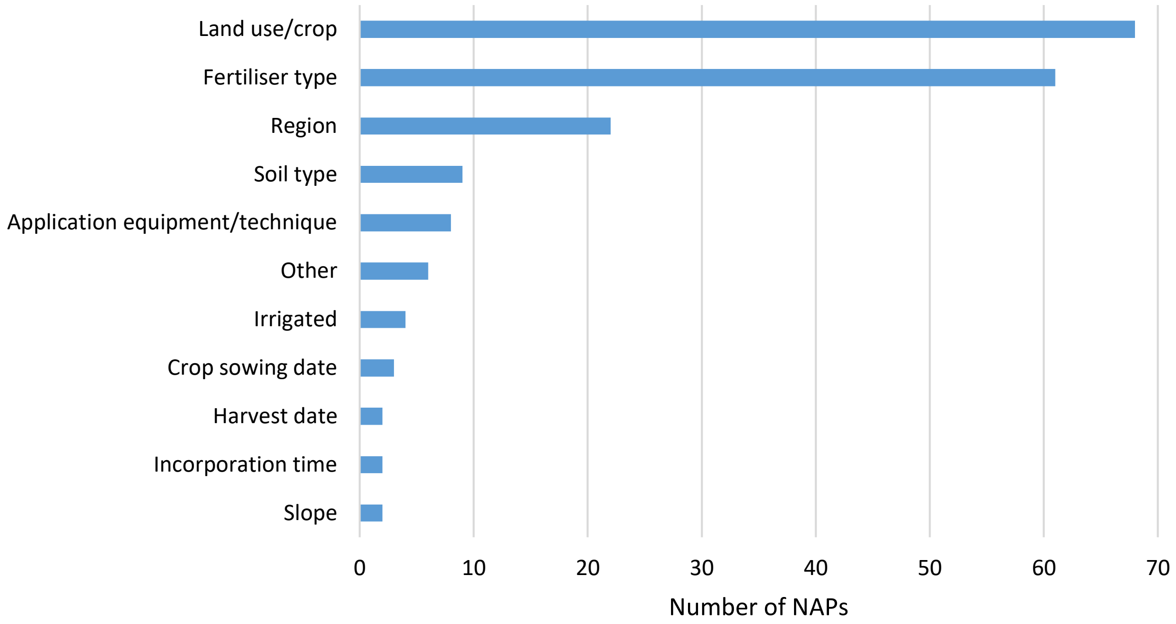


Figure 1: Parameters used to vary closed periods

There have been many previous studies that have attempted to assess the environmental effects and impacts of measures within the Nitrates Directive. All are, unavoidably, a snapshot of the measures at the time of the study, and they range from those that focus on the implementation of either specific or all measures within the Nitrates Directive within a specific Member State; through to specific or all measures within two or more Member States (e.g. D' Haene *et al.*, 2014; Monteny, 2001; Van Grinsven *et al.*, 2012 & 2016; Velthof *et al.*, 2014). However, although Member States report on progress on implementation of Nitrates Directive to the EC, there have been few (if any) independent studies that explore how measures have been implemented within each Member State or region on a full European scale (hence why the EC commissioned this study). For example, Gault *et al.* (2015) examined the details of the implementation of closed periods (in terms of closed period dates) for six Member States, but they did not examine the environmental implications of any differences and/or how they vary spatially. Tzilivakis *et al.* (2020) attempted to address this gap and this study has extended this work with of aim of assessing the implementation of closed periods across Europe and their potential environmental benefits in further detail including a spatial analysis.

The objectives of this paper were to:

1. Develop an approach that utilises open source data to determine the potential spatial variability in environmental benefits of closed periods implemented through the 69 NAPs across Europe (in place during 2019/20).
2. Determine spatial variability of the benefits of closed periods with respect to nitrate (NO_3^-) leaching and run-off using (1).
3. Determine spatial variability of the benefits of closed periods with respect to organic material run-off, nitrous oxide (N_2O) and ammonia (NH_3) emissions using (1).[1]
4. Identify locations where closed periods appear to have the greatest potential to provide multiple environmental benefits.

[1] With respect to the third objective, the purpose was to determine the potential additional benefits provided by closed periods (that are designed to reduce nitrate loss); and not to assess their effectiveness for these impacts. It should be acknowledged that there are other measures in place that specifically target these impacts, such as NECD (EC, 2016) for ammonia, but it is not the objective of this study to determine the effectiveness of these measures.

2.0. Methods

2.1. Introduction and overview

A key challenge for the first objective was to find a pragmatic approach that can be applied across Europe using data that is readily available (i.e. open source). Given these criteria, a sophisticated modelling approach was not feasible, as this would require exploring real scenarios where, for example, the amounts of fertiliser applied on a field by field basis are known for specific locations/catchments (which would be a massive undertaking on a European scale). Thus, a simpler risk-based approach has been developed and applied. This involves matching some of the key parameters used to vary closed periods (see Figure 1) with pertinent spatial data (e.g. CORINE data (Copernicus, 2018) for crop/land use) to determine their spatial distribution, which was then coupled with spatial data on risk periods for the different impacts. The overall process consists of three main stages (see Figure 2).

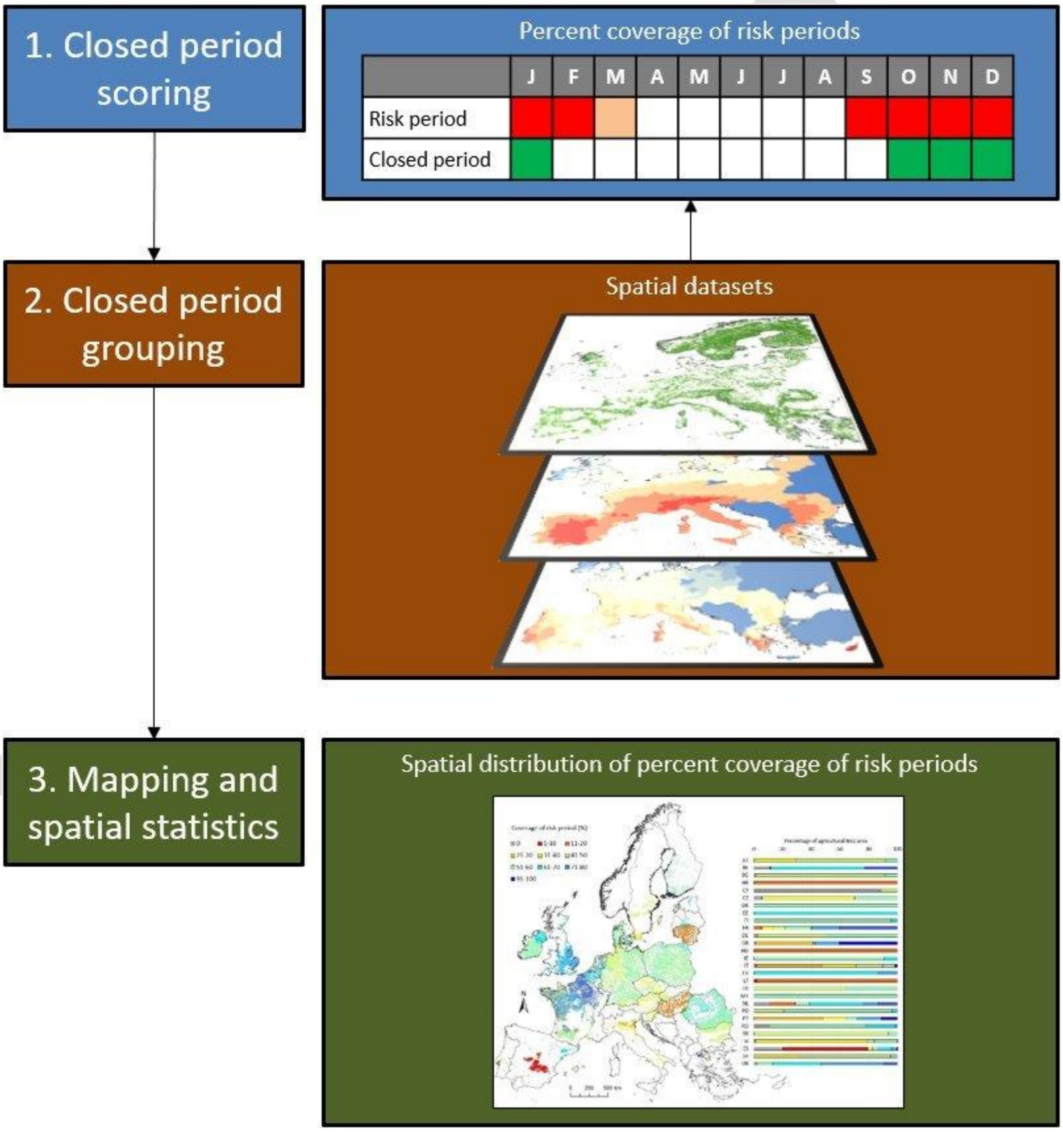


Figure 2: Method flowchart

Firstly, each of the 1155 closed periods across all the NAPs was scored for its coverage of risk periods for leaching and run-off of NO_3^-; run-off of organic material (pathogens and substances with high BOD); and gaseous emissions of N_2O and NH_3. Secondly, closed periods were matched, and grouped together where necessary, to readily available spatial datasets for each environmental zone and each fertiliser type. Thirdly, the risk period coverage scores for the closed periods for each combination of spatial data were transposed into a Geographical Information Systems (GIS) format to create maps and calculate spatial statistics (which are the main outputs of the analysis).

2.2. Closed period scoring

Scoring closed periods for leaching (NO_3^-) and run-off (NO_3^-; and organic material) drew upon the work of Alterra *et al*. (2011) which defined the main risk periods for 12 environmental zones (see Figure 3, note the Anatolian zone is excluded from the analysis as it outside Europe). Tables 1 and 2 show the risk periods for NO_3^- leaching and run-off respectively for these zones (based on Alterra *et al*., 2011). The risk periods for run-off shown in Table 2 have also been used for assessing the risk of run-off of pathogens and substances with high BOD.

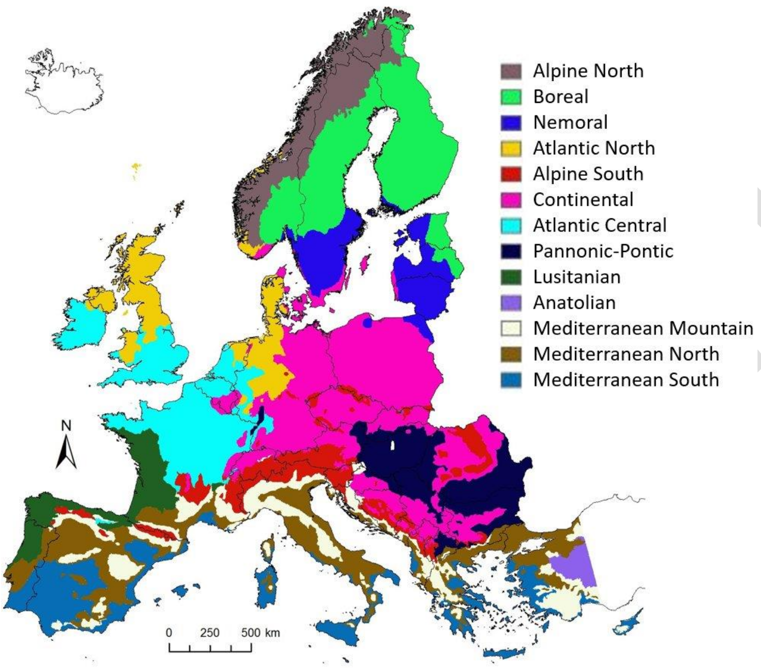


Figure 3: Environmental zones
(Derived from Alterra *et al*., 2011)

Table 1: Leaching risk periods for environmental zones

Zone	Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Alpine North	All crops	1	1	0	0	0	0	0.5	1	1	1	1	1
Alpine South	All crops	1	1	0	0	0	0	0	0.5	1	1	1	1
Atlantic Central	All crops	1	0	0	0	0	0	0	0.5	1	1	1	1
Atlantic North	All crops	1	1	0	0	0	0	0	0.5	1	1	1	1
Boreal	All crops	1	1	0	0	0	0	0.5	1	1	1	1	1
Continental	Arable	1	0	0	0	0	0	0	1	1	1	1	1
Continental	Grass	1	0	0	0	0	0	0	0.5	1	1	1	1
Lusitanian	All crops	1	0	0	0	0	0	0	0.5	1	1	1	1
Mediterranean Mountain	All crops	1	0	0	0	0	0	0	0.5	1	1	1	1
Mediterranean North	Arable - early summer	1	0	0	0	0	0	0	0	1	1	1	1
Mediterranean North	Arable - late summer	0	0	0	0	1	1	1	0	0	0	0	0
Mediterranean North	Non-irrigated grass/perm crops	1	0	0	0	0	0	0	0	0	0	1	1
Mediterranean South	Arable - early summer	1	0	0	0	0	0	0	0	0.5	1	1	1
Mediterranean South	Arable - late summer	0	0	0	0	1	1	1	0	0	0	0	0
Mediterranean South	Non-irrigated grass/perm crops	1	0	0	0	0	0	0	0	0.5	0.5	1	1
Nemoral	All crops	1	1	0	0	0	0	0	0.5	1	1	1	1
Pannonic-Pontic	Arable	1	0	0	0	0	0	0	1	1	1	1	1
Pannonic-Pontic	Grass	1	0	0	0	0	0	0	0.5	1	1	1	1

Key: 0 = low; 0.5 = medium; 1 = high

Table 2: Run-off risk periods for environmental zones

Zone	Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Alpine North	All crops	1	1	0.5	0	0	0	0	0	1	1	1	1
Alpine South	All crops	1	1	0.5	0	0	0	0	0	1	1	1	1
Atlantic Central	All crops	1	0.5	0	0	0	0	0	0	1	1	1	1
Atlantic North	All crops	1	1	0.5	0	0	0	0	0	1	1	1	1
Boreal	All crops	1	1	0.5	0	0	0	0	1	1	1	1	1
Continental	Arable	1	0.5	0	0	0	0	0	1	1	1	1	1
Continental	Grass	1	0.5	0	0	0	0	0	0	1	1	1	1
Lusitanian	All crops	1	0.5	0	0	0	0	0	0	1	1	1	1
Mediterranean Mountain	All crops	1	0.5	0	0	0	0	0	0	1	1	1	1
Mediterranean North	Arable - early summer	1	0.5	0	0	0	0	0	0	1	1	1	1
Mediterranean North	Arable - late summer	0	0	0	0	1	1	1	0	0	0	0	0
Mediterranean North	Non-irrigated grass/perm crops	1	0.5	0	0	0	0	0	0	0	0	1	1
Mediterranean South	Arable - early summer	1	0.5	0	0	0	0	0	0	0	1	1	1
Mediterranean South	Arable - late summer	0	0	0	0	1	1	1	0	0	0	0	0
Mediterranean South	Non-irrigated grass/perm crops	1	0.5	0	0	0	0	0	0	0	0	1	1
Nemoral	All crops	1	1	0.5	0	0	0	0	0	1	1	1	1
Pannonic-Pontic	Arable	1	0.5	0	0	0	0	0	1	1	1	1	1
Pannonic-Pontic	Grass	1	0.5	0	0	0	0	0	0	1	1	1	1

Key: 0 = low; 0.5 = medium; 1 = high

A similar approach was developed for gaseous losses (i.e. N_2O and NH_3) that takes account of the key processes involved (denitrification for N_2O and volatilisation for NH_3) and the effect of climatic parameters (associated with the environmental zones) on these processes. With respect to N_2O emissions via denitrification, firstly it is important to note that it is a microbial process (Machefert *et al*., 2002), so at low soil temperatures activity ceases, before proceeding more rapidly with a corresponding increase in temperature (Veraart *et al*., 2011). Secondly, since the process reduces NO_3^- in the absence of oxygen to NO, N_2O and N_2, anaerobic soil conditions are necessary (Butterbach-Bahl *et al*., 2013; Machefert *et al*., 2002). Machefert *et al*. (2002; 2004) cite soil moisture of 55-100% water filled pore space. Cool or dry soils supress denitrification, thus the risk periods account for mean monthly rainfall and temperature (see Table 3). Where rainfall is below 50 mm or temperatures exceed 10°C the risk declines due to increased evapotranspiration rates and drier soil conditions. An exception is where monthly rainfall is >75mm. Denitrification can occur at warmer soil temperatures due to the high levels of precipitation maintaining a suitable water filled pore space. The two risk scores are multiplied to give an overall risk factor. This was normalised onto a scale of 0 to 1 (low to high risk). With respect to NH_3 emissions via volatilisation, the risk increases in response to mean monthly temperature (Table 3) (Holly *et al*., 2017; Gilbert *et al*., 2006; Webb *et al*., 2010). The risk periods for N_2O and NH_3 have been calculated for each month for each environmental zone using the risk factors in Table 3, resulting in Tables 4 and 5.

Table 3: Climatic risk factors for N_2O and NH_3 emissions

Mean monthly rainfall (mm)	**N_2O risk score**	**Mean monthly temperature range (°C)**	**N_2O risk score**	**Mean monthly temperature range (°C)**	**NH_3 risk score**
<=50	0	<=2	0	<=2	0
>50 – 60	0.25	>2 – 5	0.2	>2 – 10	0.25
>60 – 75	0.5	>5 – 10	0.35	>10 – 15	>10 – 15
>75 – 100	0.75	>10	0	>15 – 25	0.75
>100	1			>15	1

Table 4: N_2O risk periods for environmental zones

Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Alpine North	0	0	0	0	0.5	0.75	0.5	0.5	1	0	0	0
Alpine South	0	0	0	0.5	1	0.5	0.5	0.5	0.5	0.75	0	0
Atlantic Central	0.5	0.25	0.5	0.25	0	0	0	0	0	0	0.75	0.5
Atlantic North	0	0	0.25	0.5	0.5	0	0	0	0	0.75	0.5	0.5
Boreal	0	0	0	0	0	0	0	0	0.5	0.25	0	0
Continental	0	0	0	0	0	0	0	0.25	0.5	0.25	0	0
Lusitanian	0	0	0	0	0	0	0	0	0		0	0
Mediterranean Mountain	0	0	0	0	0	0	0	0	0	0.25	0	0
Mediterranean North	0.5	0.5	0.25	0	0	0	0	0	0	0	0	0.75
Mediterranean South	0.5	0	0	0	0	0	0	0	0	0	0	0
Nemoral	0	0	0	0	0	0	0	0	0.25	0.25	0	0
Pannonic-Pontic	0	0	0	0	0	0	0	0	0	0	0	0

Key: 0 = low; 0.5 = medium; 1 = high

Table 5: NH_3 risk periods for environmental zones

Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Alpine North	0	0	0	0	0.25	0.25	0.5	0.5	0.25	0	0	0
Alpine South	0	0	0	0.25	0.25	0.5	0.5	0.5	0.5	0.25	0	0
Atlantic Central	0.25	0.25	0.25	0.25	0.5	0.5	0.75	0.75	0.5	0.5	0.25	0.25
Atlantic North	0	0	0.25	0.25	0.25	0.5	0.5	0.5	0.5	0.25	0.25	0.25
Boreal	0	0	0	0	0.25	0.5	0.5	0.5	0.25	0.25	0	0
Continental	0	0	0	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0	0
Lusitanian	0	0	0	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0	0
Mediterranean Mountain	0	0	0	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0	0
Mediterranean North	0.25	0.25	0.25	0.5	0.75	0.75	0.75	0.75	0.75	0.5	0.25	0.25
Mediterranean South	0.25	0.5	0.5	0.5	0.75	0.75	1	1	0.75	0.75	0.5	0.5
Nemoral	0	0	0	0.25	0.5	0.5	0.75	0.75	0.5	0.25	0	0
Pannonic-Pontic	0	0	0.25	0.5	0.75	0.75	0.75	0.75	0.75	0.5	0.25	0

Key: 0 = low; 0.5 = medium; 1 = high

Each closed period within each NAP was scored for coverage of the risk periods shown in Tables 1, 2, 4 and 5. This is done by summing up the risk scores the closed period covers (to the nearest half month) and expressing this as a percentage of the maximum. For example, if there is a closed period of 15 July to 15 November in the Alpine North zone, this would score 3.75 (0.25 (Jul) + 1 (Aug) + 1 (Sep) + 1 (Oct) + 0.5(Nov)) out of a maximum of 7.5, and thus attains a coverage score of 50% for leaching risk.

2.3. Closed period grouping

To facilitate spatial comparisons of closed periods with respect their potential impact, the 1155 closed periods needed to be categorised into common groups. There were two parts to this process, grouping based on (i) the type of fertiliser; and (ii) spatial parameters.

2.3.1. Type of fertiliser

As shown in Figure 1, the type of fertiliser is a key parameter that is used to vary closed periods (in 61 NAPs). Closed periods tend to vary based on either the N content and/or type of N in fertilisers, to account for both the quantity and mobility of N. There are variable classifications of fertiliser types across the 61 NAPs, but they broadly fall into three types: (I) mineral/inorganic fertilisers; (II) high N organic fertilisers; and (III) all other (lower N) organic fertilisers. Types I and II present a higher risk for NO_3^- leaching and run-off and N_2O emissions; and Types II and III present a higher risk for NH_3 emissions and run-off of organic material (pathogens and BOD) (AHDB, 2021; Chambers et al., 1999; Misselbrook et al., 2005; Peyton et al., 2016; Smith et al., 2001). To account for this, the closed periods have been scored for different groups of fertiliser types that are of most relevance for each of the impact categories (Table 6). In the case of NO_3^- leaching, NO_3^- run-off, N_2O and NH_3 emissions, the contribution of different fertiliser types to the overall risk has been weighted to reflect those fertiliser types which present the greatest risk. For these four N loss pathways, mineral/inorganic fertilisers and high readily available N organic fertilisers are considered to present a greater risk compared to all other organic fertiliser types, and thus have a higher weight. The weighting of each fertiliser type accounts for the Readily Available N (RAN) content of each fertiliser type (AHDB, 2021) and the ratio of this RAN (ammonium N and ureic acid N) as a proportion of the total N content (i.e. the N released in the current crop growth cycle). For example, the median RAN value for high N manures (>30% RAN; e.g. broiler manure and cattle slurry) is 50% (AHDB, 2021). For low available N manures (e.g. old or fresh cattle farmyard manure) the RAN is 15 to 20%. High N manures have three times the RAN of low N manures, which means N that is potentially available to environmental loss if it is not utilised by the growing crop. For example, if the manure is applied during autumn or winter. Weightings of three and one are given to high and low N fertilisers respectively.

For NH_3 emissions all organic fertilisers are considered to present a greater risk compared to solid mineral/inorganic fertilisers (note: in Europe solid ammonium nitrate fertilisers is the dominant form of N applied in Europe rather than solid urea fertilisers; Isherwood, 2009). The risk of NH_3 volatilisation from inorganic fertiliser is reduced when, for example, applied in a dry granular pellet ammonium form as opposed to a liquid urea based product (Black *et al*., 1985; Chambers and Dampney, 2009; Forrestal *et al*., 2016; Misselbrook *et al*., 2004). The dry granular pellet formulation is used here. The risk and weightings attributed to organic manures and respective manure type is based on the % total ammoniacal N (TAN), i.e. the N in a readily volatilisable form for the given risk period (EEA, 2016; Forrestal *et al*., 2016; Sommer *et al*., 2019; Tao and Ukwuani, 2015) and the overall RAN content of the manure (AHDB, 2021).

Table 6: Fertiliser groups for each impact category

Group ID	Fertiliser	Weight	Impact category
1	Mineral/inorganic fertilisers and high N organic fertilisers	3	NO_3^- leaching NO_3^- run-off N_2O emissions
2	All other organic fertilisers	1	NO_3^- leaching NO_3^- run-off N_2O emissions
3	All organic fertilisers	1	Organic run-off
4	Mineral/inorganic fertiliser	1	NH_3 emissions
5	All organic fertilisers (including high N organic fertilisers)	3	NH_3 emissions

2.3.2. Spatial parameters

Closed periods needed to be grouped, using pertinent spatial data, to be able to spatially plot the coverage scores calculated. As shown in Figure 1, land use/crop, region and soil type are common parameters that are used to differentiate closed periods. These can all be related to spatial data that is readily available for Europe and combined with the environmental zones that have been used for the different risk periods (Tables 1, 2, 4 & 5). Table 7 lists the spatial data that has been utilised.

Table 7: Spatial data

Parameter	Dataset	Reference
Land use/crop	CORINE 2018 land use data. The land uses defined closed periods for each NAP have been matched up to one or more of the CORINE land uses. This has been overlaid with the NVZ area (see Figure 4) to show where the land uses/crops occur within NVZs.	Copernicus (2018)
Region	In some instances, administrative regions (usually NUTS regions) are used to define areas where some closed periods apply.	Eurostat (2021)
Soil type	Dominant surface textural class: The soil types defined in each MSs closed periods variants will be matched up to one of the dominant texture classes.	JRC (2021a&b)
Environmental zones	The environmental zones (see Figure 3 and Tables 1, 2, 4 & 5) used to define risk periods for different impacts	Alterra *et al*. (2011)

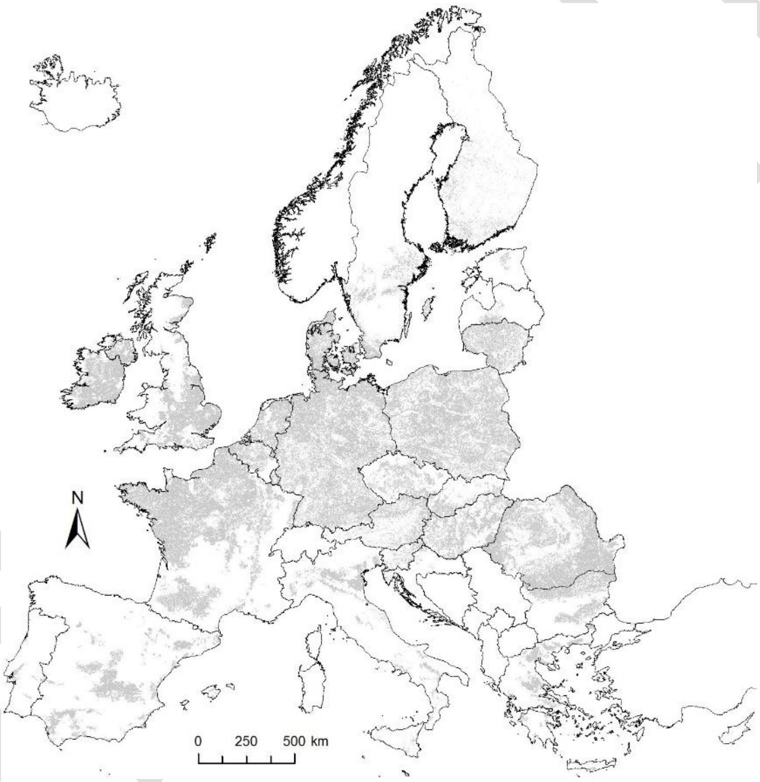


Figure 4: Agricultural NVZ area

ArcGIS® (ESRI, 2021) was used to overlay each of these spatial datasets to spatially plot unique combinations into which each of the closed periods within a NAP were allocated. Table S1 (in the supplementary material) shows the spatial parameters that applied to each NAP and the number of combinations that exist. Where a unique combination contains more than one closed period the coverage scores for those closed periods were averaged. For example, in Nouvelle Aquitaine in France, there are 59 closed periods for Group 1 fertilisers which have been classed into 4 crop groups: Arable (51 closed periods for 5 crop types); Fruit and vines (2 closed periods for 1 crop type); Grass (4 closed periods for 2 crop types); and Other (2 closed periods for 1 crop type).

2.4. Maps and spatial statistics

The coverage scores for each closed period within each NAP were transposed to the pertinent unique spatial combination (Table S1) for each fertiliser type (Table 6). A GIS raster was created for each unique spatial combination and these were then combined to derive a map of the coverage of risk periods for each NAP. Where regional NAPs exist, these were then further combined to create a raster for each Member State. The raster for each Member State is presented in one map for the whole of Europe using the same key. This key classifies the score attained for each closed period into one of ten categories (1-10; 11-20; 21-30; 31-40; 41-50; 51-60; 61-70; 71-80; 81-90; 91-100). Spatial statistics were then generated to determine the proportion of the agricultural NVZ area (Figure 4) within each Member State that falls into each of these 10 categories.

To reflect the relative risk posed by different fertiliser types in relation to the different impacts, the outputs for the different fertiliser groups (where applicable) have been weighted (see Table 6) when combining them. For leaching, run-off, and N_2O the results for Group 1 fertiliser have been given a weighting 3 times that of Group 2; and for NH_3, Group 4 fertiliser have a been given a weighting 3 times that of Group 5. In theory, there is scope to vary these weights where, for example, more specific details about the fertiliser types are known (e.g. amounts of RAN). However, this would only be applicable for more localised analyses and thus this is not relevant for the broad scale spatial analysis undertaken in this study.

Finally, a combined map and set of spatial statistics were created to highlight those areas where there is the highest potential for multiple benefits (in terms of coverage of risk periods for multiple impacts). This has been done by combining the results of the impacts on NO_3^-leaching; NO_3^-run-off; organic run-off; N_2O and NH_3 with an equal weighting (i.e. each makes up 20% of the total combined score; see Equation 1). In theory, the impacts could be given different weights (e.g. to represent the significance and/or political priorities of the different impacts), but in this instance they have been weighted equally to aid transparency.

$$Total\ impact = \sum\big((L \times 0.2) + (R \times 0.2) + (O \times 0.2) + (N \times 0.2) + (A \times 0.2)\big) \quad \text{[Equation 1]}$$

Where:

L = NO_3^- leaching
R = NO_3^- run-off
O = Organic run-off
N = N_2O emissions
A = NH_3 emissions

3.0. Results

Figures 5 to 9 show the maps and charts for NO_3^- leaching; NO_3^- run-off; organic material run-off ;N_2O emissions; and NH_3 emissions. Figure 10 shows the combined map and chart for all impacts. Intermediate maps for different fertiliser groups (see Table 6) are also available in the supplementary material.

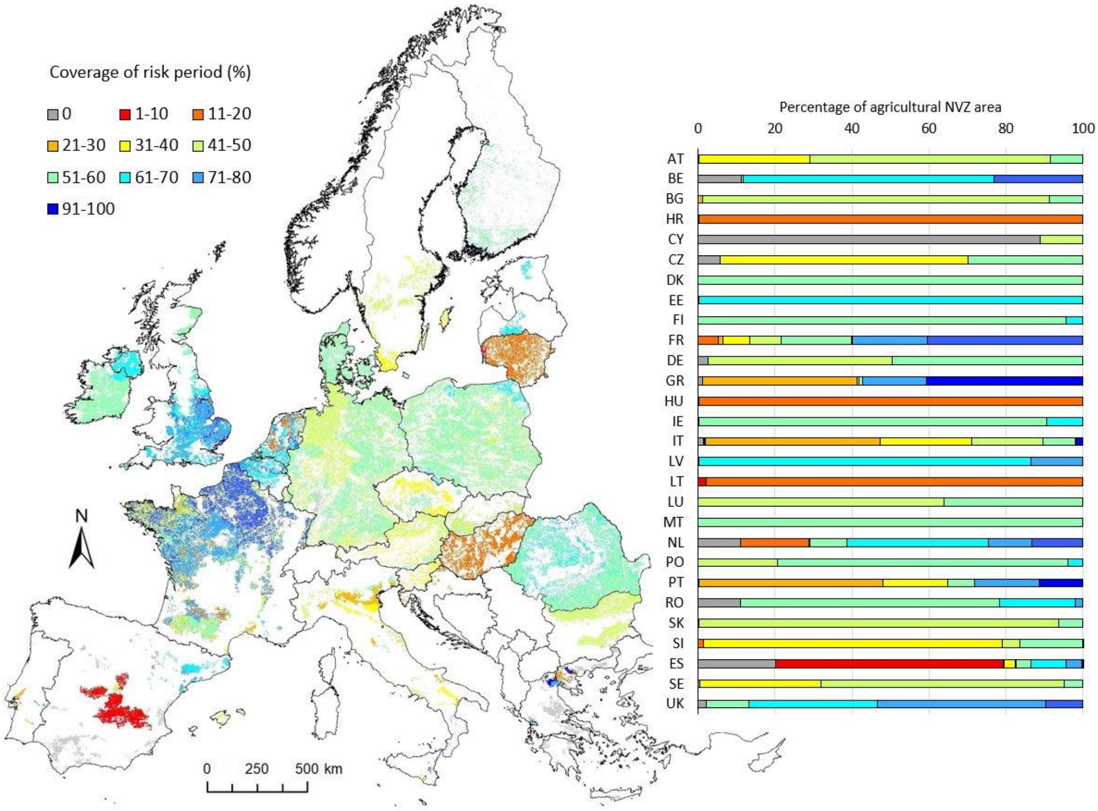


Figure 5: NO_3^- Leaching

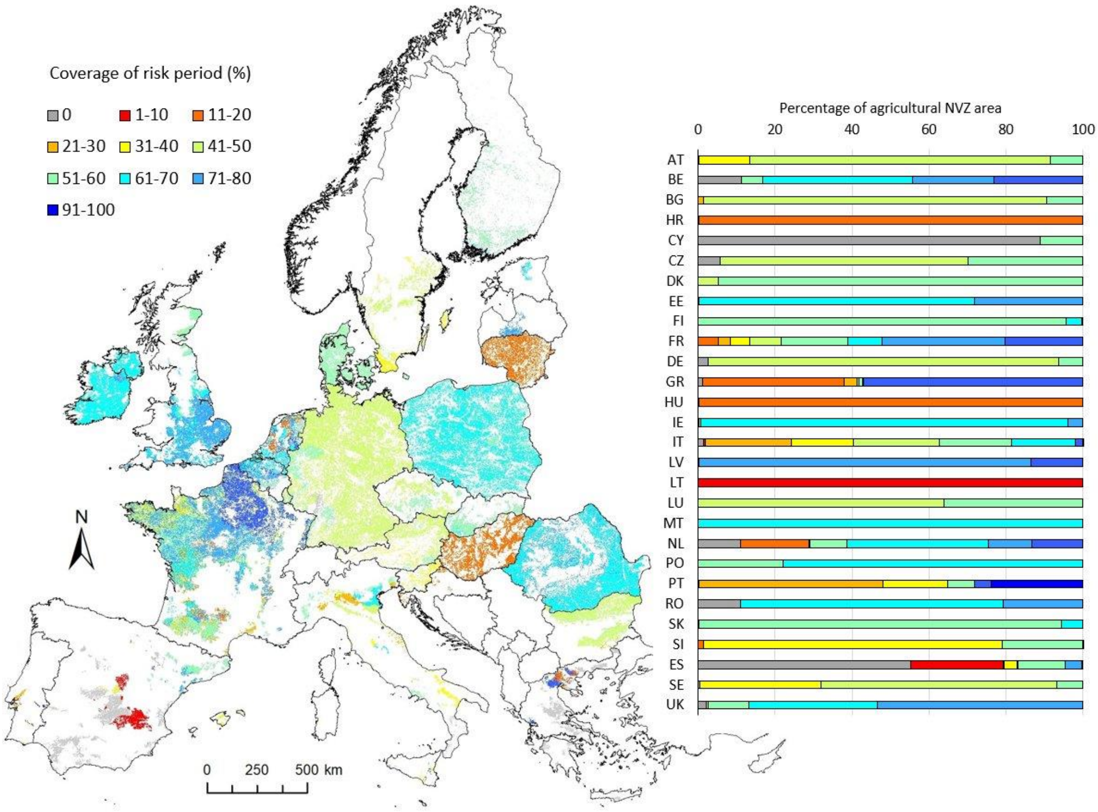


Figure 6: NO_3^- Run-off

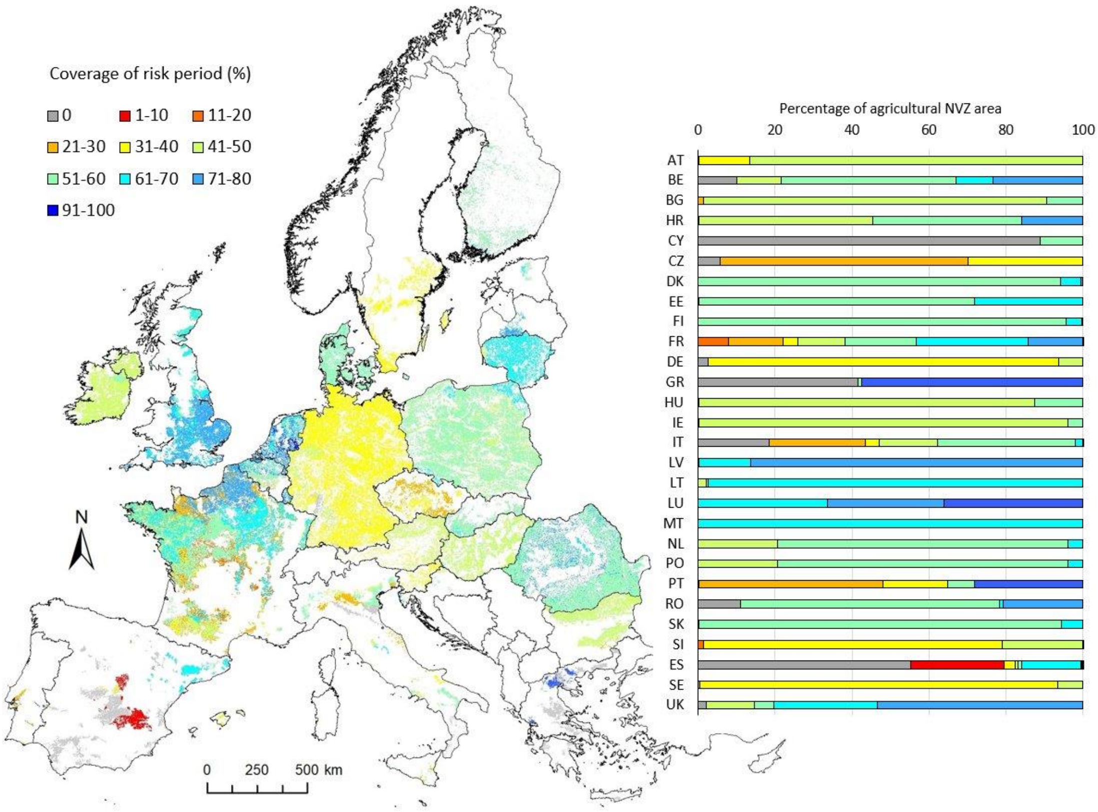


Figure 7: Organic run-off

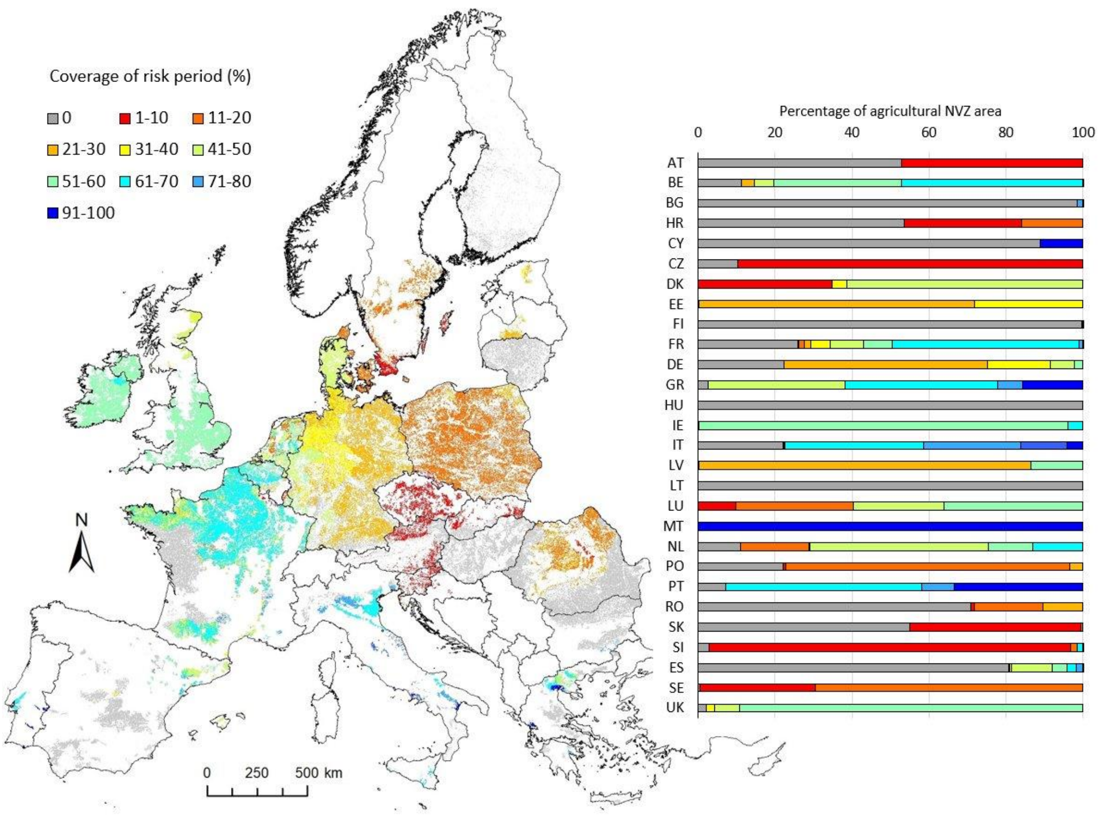


Figure 8: N_2O emissions

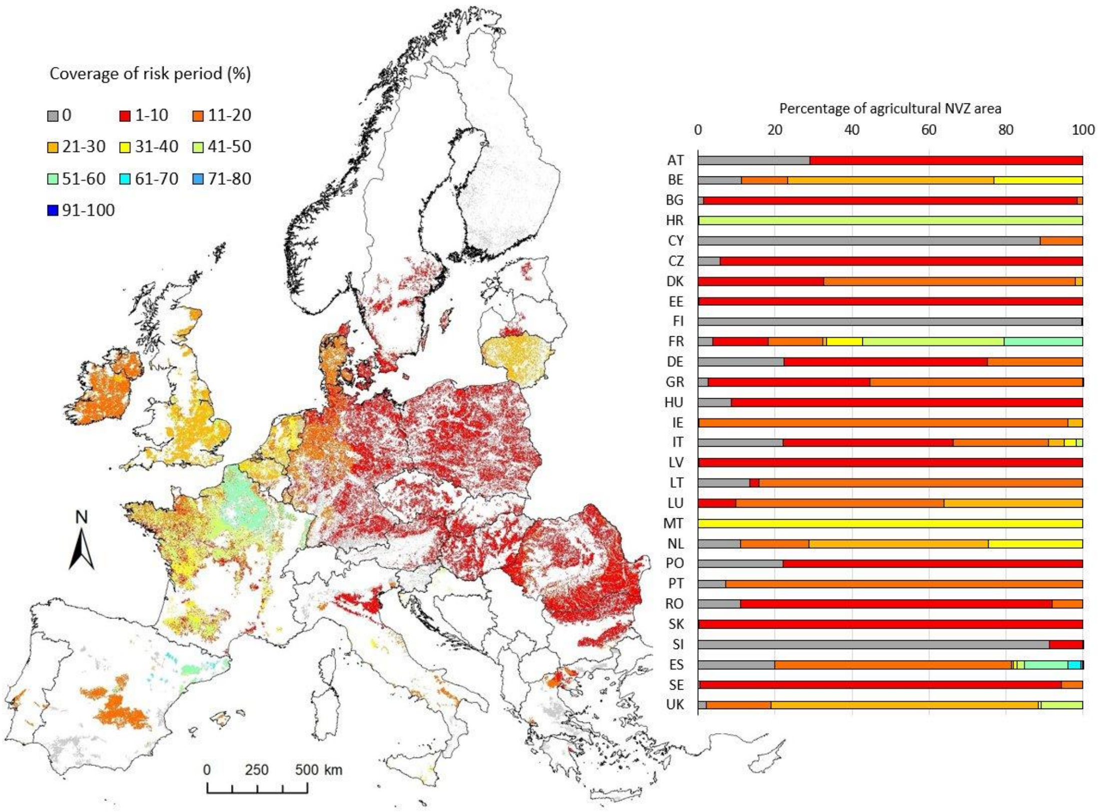


Figure 9: NH_3 emissions

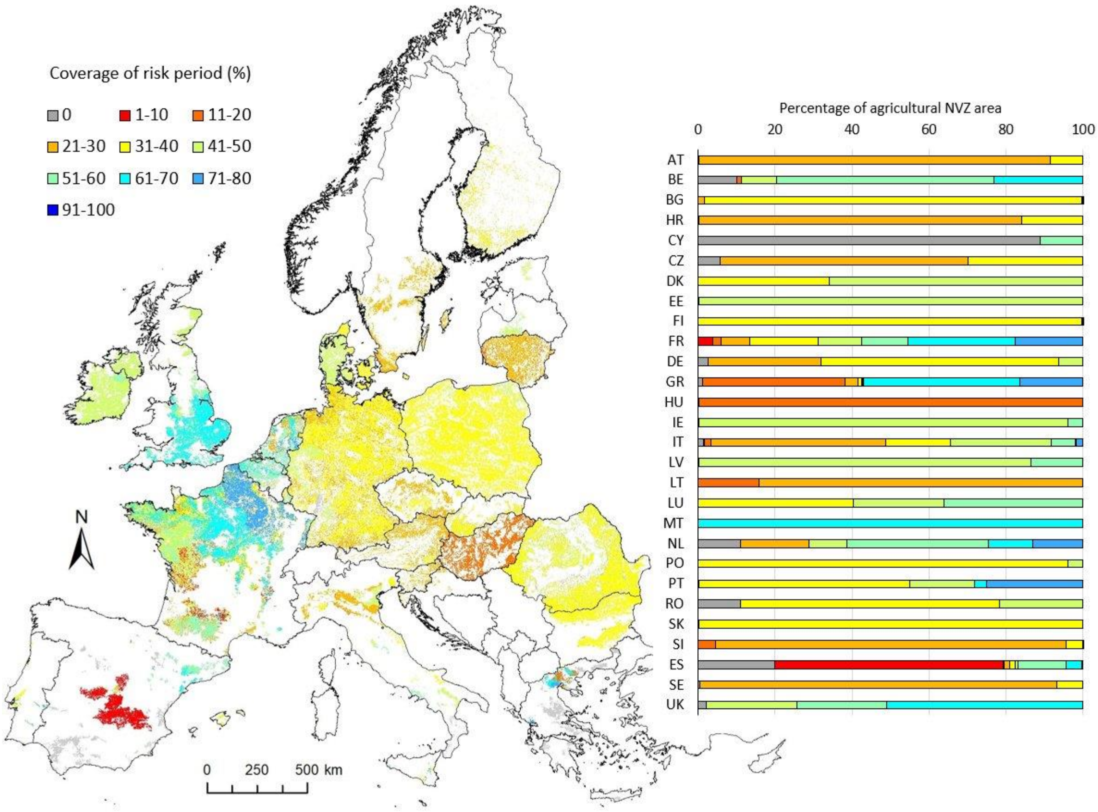


Figure 10: Combined impact

Reducing the risk of NO_3^- loss via leaching is a key objective of closed periods, by avoiding the presence of large amounts of available N during periods when there is a higher risk of this process occurring (see

Table 1). Figure 5 shows that 7 Member States have more than 50% of their agricultural NVZ area with more than 61% coverage of leaching risk periods (Belgium, France, the Netherlands, and the UK, which have a relatively large agricultural NVZ area; and Estonia, Greece and Latvia, which have a relatively small agricultural NVZ area). Examples of closed periods with a high coverage of risk periods (within Member States and regions) include:

- In Belgium, in Flanders, closed periods on arable land between Aug/Sep and Feb score 95% for Group 1 fertilisers; and in Wallonia closed periods between 16 Sep and 15 Feb score 75-80% and 73% for arable and grassland respectively.
- In France, Normandy, Ile de France, Hauts-de-France, and Grand Est have 10 to 12 closed periods for a range of arable crops for mineral fertiliser which score 90-100%; 10 closed periods for high N organic fertiliser which score 60-100%; and 7 closed periods for low N organic fertiliser that attain 9-100% coverage.
- In Greece, Thessaloniki Plain - Pella - Imathia and Strymon Basin have closed periods for Group 1 fertilisers between 1 Nov and 31 Jan which score 30-55% and 55-100% for arable and other crops respectively; and 55-100% for Group 2 fertilisers used on other crops.
- In the Netherlands, closed periods for grassland between 16 Sep and 31 Jan score 69-82% and 54-91% for Group 1 and 2 fertilisers respectively.
- In Spain, in Aragón, closed periods for vines, olives and fruit crops between Oct and Feb/Mar score 73-100% for both Group 1 and 2 fertilisers. In Cataluña, closed periods for olives between Aug and Feb score 88-100% and 33-50% for Group 1 and 2 fertilisers respectively; closed periods for rice between Jun and Feb score 67% and 83% for Groups 1 and 2 fertilisers respectively; and closed periods between Jul/Aug/Nov and Jan/Feb score 85-92% and 44-58% for Group 1 and 2 fertilisers respectively.
- In the UK, in England closed periods on arable land between Sep and Jan score 69-82% and 62-82% for Group 1 and 2 fertilisers respectively; and closed periods on grassland between Sep/Oct and Dec/Jan score 62-73% and 54-73% for Groups 1 and 2 fertilisers respectively.

Generally, there is greater coverage of risk periods for Group 1 than Group 2 fertilisers. However, for Denmark, Luxembourg the Netherlands, and Sweden (and Croatia, Hungary and Lithuania, which have no closed periods for Group 1), coverage is greater for Group 2 fertilisers.

Reducing the risk of the loss of NO_3^- via run-off is also a key objective of closed periods and tends to echo the findings for NO_3^- leaching, albeit there are some slight differences which relate back to slight differences in the start and end of the risk periods for leaching and run-off (e.g. in the Alpine North region a higher risk in March and a lower risk in July and August for run-off compared to leaching; see Tables 1 and 2). Figure 6 shows that 11 Member States have more than 50% of their agricultural NVZ area with more than 61% coverage of run-off risk periods. This includes Belgium, France, Ireland, the Netherlands, Poland, Romania, and the UK, which have a relatively large agricultural NVZ area; and Estonia, Greece, Latvia and Malta, which have a relatively small agricultural NVZ area. Examples of closed periods with higher coverage of risk periods (within Member States and regions) include:

- In Belgium, in Flanders, closed periods on arable land between Aug/Sep and Feb score 95-100% for Group 1 fertilisers; and in Wallonia closed periods between 16 Sep and 15 Feb score 73-86% and 73% for arable land and grassland respectively.
- In France, Ile de France, Hauts-de-France, and Grand Est have 10 to 12 closed periods for a range of arable crops for mineral fertiliser which score 90-100%; 10 closed periods for high N organic fertiliser which score 50-100%; and 7 closed periods for low N organic fertiliser that attain 90-100% coverage.
- In Greece, Thessaloniki Plain - Pella – Imathia and Strymon Basin have closed periods for Group 1 fertilisers between 1 Nov and 31 Jan which score 27-55% and 55-86% for arable and other crops respectively; and 55-86% for Group 2 fertilisers used on other crops.
- In Latvia, closed periods between Sep/Oct and March on grassland score 77-91% and 57-64% for Group 1 and 2 fertilisers respectively, and on arable land score 62-73% for Group 1 and 2 fertilisers.

- In the Netherlands, closed periods for grassland between 16 Sep and 31 Jan score 69-82% and 54-92% for Group 1 and 2 fertilisers respectively.
- In Portugal, closed periods for grassland and tree crops between Nov and Feb score 55-100% and 55-86% for Group 1 and 2 fertilisers respectively.
- In the UK, in England and Wales, closed periods between Sep and Jan score 69-82% and 62-73 for arable and grassland respectively for Group 1 fertilisers only.

Generally, there is greater coverage of risk periods for Group 1 than Group 2 fertilisers. However, for Denmark, Luxembourg, the Netherlands (and Sweden; and Croatia, Hungary and Lithuania, which have no closed periods for Group 1), coverage is greater for Group 2 fertilisers.

Reducing the risk of run-off of organic material (containing pathogens and substances with a high BOD) is a potential secondary benefit of closed periods. There are some similarities to the results of NO_3^- run-off but also some differences, especially where Member States have closed periods for organic fertilisers only and/or where the closed periods for organic fertilisers are significantly different to those for inorganic fertiliser. Figure 7 shows that 6 Member States have more than 50% of their agricultural NVZ area with more than 61% coverage of run-off risk periods. This includes Lithuania, Luxembourg, and the UK, which have a relatively large agricultural NVZ area; and Greece, Latvia and Malta, which have a relatively small agricultural NVZ area. Examples of closed periods with higher coverage of risk periods include:

- In Belgium, in Flanders, closed periods between Aug/Sep and Feb score 36-100% and 36-95% on arable and grassland respectively; and in Wallonia closed periods between 16 Sep and 15 Feb score 23-86% and 27-73% for arable land and grassland respectively.
- In France, Ile de France and Normandy have 12 to 17 closed periods respectively for a range of arable crops which score 0-100%.
- In Greece, Thessaloniki Plain - Pella – Imathia and Strymon Basin have closed periods between 1 Nov and 31 Jan score 55% and 86% for arable and other crops respectively.
- In Latvia, closed periods between Sep/Oct and March score 62-73% and 57-65% for arable and grassland respectively.
- In Luxembourg, closed periods between Aug/Oct and Feb/March score 57-100% and 50-81% for arable and grassland respectively.
- In Malta, a closed period between 15 Oct and 15 March on all agricultural land scores 63%.
- In Portugal, closed periods for grassland and tree crops between Nov and Feb score 55-86%.
- In the UK, in England and Wales, closed periods between Aug/Sep and Dec/Jan score 46-61% and 53-61 for arable and grassland respectively.

Reducing the risk of N_2O emissions is also a potential secondary benefit of closed periods. Coverage of risk periods tends to be lower compared for NO_3^- leaching, but there are a few instances where it is higher. Figure 8 shows that 4 Member States have more than 50% of their agricultural NVZ area with more than 61% coverage of N_2O risk periods. This includes France, which has a relatively large agricultural NVZ area; and Greece, Italy, and Portugal, which have a relatively small agricultural NVZ area. Examples of closed periods with higher coverage of risk periods (within Member States and regions) include:

- In Greece, closed periods between 15 Oct and 1 Feb for arable, grassland and permanent crops for inorganic fertilisers score 100% in Argolid Plain; 50-100% in Kopaida Plain and Pineiós Basin – Ilia; and 0-63% in Plain of Arta – Preveza, Strymon Basin and Thessaloniki Plain - Pella – Imathia; and 0-100% for liquid manures on sandy soils in Kopaida Plain and Pineiós Basin – Ilia.
- In Italy, in Abruzzo closed periods between Oct and Feb for all crops score 88-100% and 0-88% for Group 1 and 2 fertilisers respectively; in Apulia closed periods between Nov/Dec and Feb for all crops score 69-100% and 75-100% for Group 1 and 2 fertilisers respectively; in Basilicata closed periods between Nov/Dec/Jan and Feb for all crops score 0-100% for Group 1 and 2 fertilisers; in Campania closed periods between Nov/Dec and Jan/Feb for all crops score 0-100% for Group 1

and 2 fertilisers; in Marche closed periods between Nov and Feb score 0-75% and 0-81% for grassland and all other crops respectively for Group 1 and 2 fertilisers; in Molise closed periods between Nov/Dec and Jan/Feb score 0-88% for all crops for Group 1 fertilisers and 0-59% and 0-88% for grassland and all other crops respectively for Group 2 fertilisers; in Tuscany closed periods between Nov/Dec and Feb score 0-88% for all crops for Group 1 and 2 fertilisers; and in Umbria closed periods between Oct and Feb score 88-100% for all crops for Group 1 and 2 fertilisers.

- In Malta, a closed period between 15 Oct and 15 March on all agricultural land scores 100% for Group 1 and 2 fertilisers.
- In Portugal, closed periods between Nov and Feb score 0-100% for Group 1 and 2 fertilisers.

Generally, there is greater coverage of risk periods for Group 1 than Group 2 fertilisers. However, for Denmark, Luxembourg, and the UK (and Croatia, which has no closed periods for Group 1), coverage is greater for Group 2 fertilisers.

Reducing the risk of NH_3 emissions is also a potential secondary benefit of closed periods, but to a much lesser extent than N_2O emissions. This is not unexpected given the differences in the risk periods (see Tables 4 and 5). Figure 9 shows that the coverage of risk periods is much lower for all Member States compared to NO_3^- leaching, run-off, and N_2O emissions. Three Member States have more than 50% of their agricultural NVZ area with more than 31% coverage of NH_3 risk periods. This includes France, which has a relatively large agricultural NVZ area; and Croatia and Malta, which have a relatively small agricultural NVZ area. Examples of closed periods where the coverage of NH_3 risk periods would considered relatively high (within Member States and regions) include:

- In France, Ile de France, Hauts-de-France, and Grand Est have 10 to 12 closed periods for a range of arable crops for mineral fertiliser which score 60-100%; 10 closed periods for high N organic fertiliser which score 20-100%; and 7 closed periods for low N organic fertiliser that score 10-100%.
- In Spain, in Aragon there are 18 closed periods for a range of arable crops at different times of the year which score 22-85% and 9-87% for Group 1 and 2 fertilisers respectively; in Cataluña there are 18 closed at different times of the year which score 35-100%, 0-100%, 42-90%, 70-81%, and 27-90% for arable, grass, olive, rice and tree (excluding olives) crops respectively for Group 2 fertilisers.

Generally, there is greater coverage of risk periods for Group 4 fertilisers (than Group 5). However, for Denmark, Luxembourg, the Netherlands, Spain, and Sweden (and Croatia, Hungary and Lithuania, which have no closed periods for Group 4), coverage is greater for Group 5 fertilisers.

Finally, the combined impact (Figure 10) shows that closed periods in the Atlantic, Lustanian and some areas within the Mediterranean zones appear to provide the greatest combined risk reduction. Five Member States have more than 50% of their agricultural NVZ area with more than 51% coverage of risk periods. This includes Belgium, France, the Netherlands, and the UK, which have a relatively large agricultural NVZ area; and Malta which has relatively small agricultural NVZ area. In Belgium, France the Netherlands and the UK, closed periods provide relatively high (60-100%) coverage of NO_3^- leaching and run-off and organic run-off; France, Belgium and some regions in the Netherlands have moderate to high (61-70%) coverage of N_2O risk periods; and some regions in France have a moderate (51-60%) coverage of NH_3 risk periods, notably Grand Est, Hauts-de-France and Ile de France. In other zones, especially in eastern Europe, the combined coverage of risk periods is lower. This is due to a combination of slightly different risk periods in these zones, coupled with lower coverage of individual risks by the closed periods. For example, Poland and Romania have 61-70% coverage of risk periods for NO_3^- run-off, but lower coverage for NO_3^- leaching, organic run-off, N_2O and NH_3 emissions (e.g. 70% of the Romanian agricultural NVZ area has zero coverage of N_2O risk periods, largely corresponding with the Pannonic-Pontic zone).

4.0. Discussion

4.1. Introduction

Fertiliser closed periods are one of approximately 70 measures that have been implemented across Europe as part of action programme measures under the Nitrates Directive; and they have been implemented in at least 69 of the 80 NAPs that exist (Tzilivakis *et al*., 2020). Understanding the spatial variability and any additional environmental benefits of closed periods could provide some useful insights for both analysis of existing policy measures and the development of future policies, especially more integrated approaches to tackle multiple environmental issues. The objectives of this study were to firstly develop a pragmatic technique, using readily available data, to spatially analyse the benefits of closed periods for NO_3^- leaching and run-off, emissions of N_2O and NH_3, and run-off of organic material (containing pathogens and substances with a high BOD) at a European scale; and secondly to apply that technique and explore the findings. The following sections explore these objectives in reverse, by firstly exploring the results of the analysis and then reflecting on the performance of the technique used.

4.2. Spatial variability in the environmental benefits of closed periods

There are number of areas within different Member States that have a relatively high coverage of risk periods. These areas tend to be where closed periods cover the highest risk periods and apply to crops that are widely grown (examples have been highlighted in Section 3). There are also a few Member States and regions where coverage of risk periods is relatively low across many of the impact categories. Firstly, there are some areas which do not have closed periods as a measure within the NAP; this includes some regions in Spain and Greece. It should be noted that this may be due a lack of information on the NAP that was collated for the inventory of NAP measures on which this analysis is based (Tzilivakis *et al*., 2020). Secondly, some Member States only have closed periods for organic fertilisers, this includes Croatia, Lithuania, and Hungary. This results in a lower coverage of risk periods especially for NO_3^- leaching, NO_3^- run-off and N_2O emissions, where closed periods for inorganic fertilisers (with high readily available N) are of more importance.

The analysis has shown that risk reduction is spatially variable across all the impact categories and the scope for synergy is also variable. For example, it cannot be assumed that high coverage of risk periods for nitrate loss will always correlate with high coverage N_2O and NH_3 risk periods. It will depend on the specific combination of climatic, soil and agronomic factors within each region. However, there are examples across Europe where closed periods are resulting in risk reduction across all the impact categories. In some instances, such as some regions in France, this is often where closed periods are highly tailored for specific circumstances (e.g. crop and fertiliser types). This is likely to be the case for other factors that could not be plotted spatially (e.g. different application techniques or land management options). Each Member State takes account of their regional circumstances to determine how measures, such as closed periods, are implemented. However, there may be scope for them to utilise analyses (such as that presented herein) to further refine closed periods so that multiple impacts are addressed; especially where regional circumstances are similar.

4.3. Wider perspectives

Firstly, it is important to note that closed periods are just one measure amongst a suite of measures that have been implemented as part of the NAP in each Member State/region and there are other measures in place for other impacts, such as measures within the NECD (EC, 2016) for ammonia emissions. Thus, it is important not to use the analysis undertaken in this study to judge the environmental performance of the NAP or Member State (the purpose is to simply highlight the potential spatial variability that arises from different closed periods under different regional circumstances).

Table S2 (in the supplementary material) lists 18 other NAP measures related to fertiliser applications and land management (extracted from Tzilivakis *et al*., 2020) that have the potential to influence the impacts covered in this study. This includes measures that prohibit the application of fertilisers when soil and climate conditions (1), topography (2) and land uses (3) present an increased risk of run-off and leaching; field and farm limits for fertiliser applications (4-7); periods of time (usually each side of closed periods) when there are limits for fertiliser applications (9); buffer distances between fertiliser applications and surface and groundwater sources (10-13); prohibition of specific fertilisers (14); restrictions or requirements on application techniques and incorporation of fertilisers (15 & 16); and restrictions and requirements for the cultivation and management of land cover (17 & 18). Field limits on application amounts at specific times (9) has the most overlap with closed periods, in that it restricts the amount of fertiliser that can be applied during the same risk periods examined within this study. It is a practical trade-off to allow fertiliser application to occur (rather than prohibition) but at a level that lowers the risk of loss. There is scope to assess this measure using the same approach used within this study, with perhaps a reduced score for the coverage of risk periods. However, assessing the other measures is likely to require different, and possibly more sophisticated, approaches and/or would be difficult to assess in a robust way for a similar spatial analysis. For example, the benefit of field limits (6) will be highly dependent on the details of those limits for specific crops; and assessing the benefits of buffer distances (10-13) would need to account for the spatial distribution of water bodies in relation to application areas, topographical, geological, and hydrological properties to determine risk.

There are also numerous other measures within the NAPs which will also contribute towards reducing environmental impacts, but which are not directly associated with fertiliser applications. This includes fertiliser planning and nutrient balancing; fertiliser storage, including measures controlling temporary field heaps for organic manures; and measures for livestock, such as controls on grazing periods.

Finally, there may be scope to extend this approach to other impacts such as loss of phosphorus (P). The application of inorganic fertilisers (that contain P) or organic fertilisers, elevates the soil's P content, such that periods in which there is an increased chance of overland flow generation, carry with them an increased risk of fine sediment transport, and therefore the transport of the P that tends to be associated with those sediments (Deasy *et al.*, 2010). Consequently, prohibiting those applications may be beneficial in this respect. The circumstances and conditions that increase the risk of P loss can be complicated (e.g. Jordan *et al*., 2012) and most NAPs do not have controls on P application; only 5 have farm or field limits on P application (Tzilivakis *et al*., 2020) (note: this is in respect to measures within the Nitrate Directive; some Member States have other regulations controlling the use of P). Thus, it has not been included as an impact category within this study, but the approach could be extended to account for P loss risk factors.

4.4. Reflections on the approach

Firstly, it is important to acknowledge that the analysis is a snapshot of the measures that were in place in 2019-20. Also, information for some NAPs was lacking detail, either because of little detail in the source documentation and/or due to language translation difficulties. This is a challenge that exists for any study examining NAP measures, thus is not necessarily a limitation specifically associated with this study. It is also important to acknowledge that the spatial analysis only relates to those areas that have been defined as NVZs in each Member State and/or region. There will be other measures that apply to agricultural land outside of NVZs that may also impact on NO_3^- leaching and run-off; organic material run-off, and emissions of N_2O and NH_3. This should be taken into consideration for all Member States, but especially those where only a small proportion of the agricultural area has been defined as an NVZ (e.g. Croatia, Greece, or Italy).

A key issue to consider for this study is the effect of a potential mismatch in the detail of the closed periods and the spatial datasets they can be correlated with (see Section 2.3.2). For example, some Member States/regions have closed periods for quite specific circumstances, such as specific crops and fertilisers, and these closed periods may only be for short duration. However, spatial data (on a European scale) is not available for such specific circumstances; thus the score obtained for these closed periods (which will be low due to their short duration) will be used when calculating the average score for a group of closed periods that are then associated with spatial data. Consequently, this could have the effect of lowering the average score for this group without accounting for the relative proportion (spatially) within that group. For example, in Germany, the closed periods have been scored for grassland and arable areas, however the arable area included different closed periods for perennial fodder crops, vegetables, strawberries, berry-fruit, intercrops, winter rape, fodder crops, winter barley, and other arable crops. The scores (for NO_3^- leaching for inorganic fertiliser in the Atlantic North zone) for each of the crops range from 30% for strawberries and berry-fruit to 61% for winter barley and rape and 77% for perennial fodder crops and other arable crops. These values are averaged with an equal weight resulting in an average of 54% for arable land. It is likely there is, for example, a greater area of winter barley and rape than strawberries, thus the 30% value for strawberries results in a lower average for all arable crops than perhaps it should. Similarly, some Member States/regions have closed periods that vary with application technique, and as above these get averaged as there is no spatial combination to represent them. Where techniques are used that reduce the risk of run-off, the closed periods may be shorter, but as these are not accounted for spatially, this could also result in the lowering of the score for the group in which they are included in the average. For example, in Estonia, the closed periods for liquid manures start on 20 Sep if they are broadcast, 1 Nov if incorporated after 48 hours, and 1 Dec if they are incorporated within 48 hours (with all the closed periods ending on 20 March). As the area of land subject to these application techniques is unknown the scores for these closed periods are averaged (they score 40%, 53% and 73% respectively, for NO_3^- leaching in the Boreal zone). These issues could be addressed in the future if reliable European scale datasets covering these aspects become readily available. This would not only facilitate a higher resolution spatial analysis but could also be used to refine the definition of risk periods (e.g. by accounting for application techniques when defining risks).

It is also important to acknowledge that this analysis only accounts for the potential risk of leaching and run-off of NO_3^-; run-off of organic material; and gaseous emissions of N_2O and NH_3. It does not quantify the losses and/or provide any insights into the effectiveness of closed period compared to other measures. A more sophisticated and site-specific approach would be required to do this, in which real scenarios (using farm or field level data on fertiliser applications and practices) in specific locations are explored and/modelled, ideally coupled with monitoring data to ground truth findings. However, such an approach is not feasible on a European scale.

Finally, it is important to acknowledge that there may be different priorities in different Member States/regions with respect to specific NO_3^- loss pathways, which may have influenced the measures implemented (i.e. the agricultural practices or fertiliser types targeted by the measures). For example, leaching into groundwater may be more of an issue in some Member States than run-off into surface water and vice-versa. These priorities have not been explored within this study; however, they should be taken into consideration when interpreting and/or comparing the findings for any specific locations.

5.0. Conclusions

Reducing the loss of nutrients from agricultural land and addressing water quality issues have been an ongoing challenge for decades. This is now coupled with the need to reduce emissions of greenhouse gases (e.g. N_2O), and NH_3. Closed periods implemented under the Nitrates Directive aim to reduce the presence of NO_3^- at time when there is the greatest risk for it to be lost via leaching and/or run-off. This study has shown that in some instances these closed periods also reduce the risk of organic material run-off, emissions of N_2O and to a lesser extent emissions NH_3. However, there is significant spatial variation in the risk reduction for all impacts and thus the scope for synergy is also variable (i.e. NO_3^- loss risk reduction does not always correlate with N_2O and NH_3 risk reduction).

The broad spatial analysis developed and applied within this study although relatively simple has provided some useful data and potential insights that could support policy development in the future. For example, those Member States and regions which have highly tailored closed periods appear to provide higher coverage of risk periods. There may be scope for other Member States and regions to learn from this approach to see how their own closed periods could be adapted. Similarly, there may be scope to explore how closed periods can be better used to tackle N_2O and NH_3 emissions, by exploring where closed periods in similar zones have resulted in higher coverage of risk periods (e.g. such as in Italy and Greece for coverage of N_2O risk periods). Although the approach has some limitations (outlined in Section 4.4), generally it is considered that the approach has worked well and achieved the objective of developing a pragmatic approach that can be applied across Europe using data that is readily available. Additionally, there may be scope to refine the approach with more up to date information and more detailed and higher resolution spatial data in the future.

Finally, it is important to acknowledge that closed periods are just one measure (albeit a key measure) that have been implemented under the Nitrates Directive, thus there are many others that will also help reduce the risk of NO_3^- loss and may also offer other benefits (and in some instances burdens) with respect to other environmental impacts, but these have not been assessed in this study. Also, the closed periods that have been implemented within each Member State and region have been developed with the objective of not only reducing NO_3^- loss, but also as measures that can be pragmatically implemented within the context of commercial agriculture, thus a balance needed to be struck with respect to the closed period dates and ensuring the economic viability of different production systems. As we strive towards developing sustainable production systems, farmers and policy makers need to take a more integrated and holistic approach to the environmental management of nutrients. This requires the incorporation of additional environmental objectives and thus increases the complexity of the challenge. Consequently, the demand for pragmatic approaches that take a more holistic approach (such as those explored in this study) is likely to increase in the future to support the development of sustainable agricultural production systems.

Credit author statement

John Tzilivakis: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing - Review & Editing, Visualization, Project administration, Funding acquisition Douglas J. Warner: Methodology, Validation, Investigation, Writing - Original Draft, Writing - Review & Editing, Funding acquisition Andy Green: Investigation, Data Curation, Writing - Original Draft, Funding acquisition Kathy A. Lewis: Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper is based on work originally undertaken for a project funded by the European Commission (Ref. ENV.D.1/SER/2018/0017). The Commissions support is gratefully acknowledged. The opinions expressed herein are those of the authors and not necessarily those of the funding body.

References

AHDB, 2021. Nutrient Management Guide (RB209). Section 2 Organic materials. Agriculture and Horticulture Development Board (AHDB). https://ahdb.org.uk/knowledge-library/rb209-section-2-organic-materials (accessed: 14 June 2021).

Alterra, PRI, NEIKER Tecnalia, ITP, JTI, 2011. Recommendations for establishing Action Programmes under Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Contract Number N° 07 0307/2010/580551/ETU/B1. DLO-Alterra, Wageningen, Netherlands; DLO-Plant Research International (PRI), Wageningen, Netherlands; NEIKER, Derio, Spain; Institute of Technology and Life Sciences (ITP), Warsaw, Poland;

and Swedish Institute of Agricultural and Environmental Engineering (JTI), Uppsala, Sweden. https://publications.europa.eu/en/publication-detail/-/publication/e1d06bc3-58c4-43a3-b2bc-6ad6d53d7953/language-en (accessed: 14 June 2021).

Black, A.S., Sherlock, R.R., Smith, N.P., Cameron, K.C., Goh, K.M. 1985. Effects of form of nitrogen, season, and urea application rate on ammonia volatilisation from pastures. New Zealand Journal of Agricultural Research 28(4), 469-474. https://doi.org/10.1080/00288233.1985.10417992.

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., Zechmeister-Boltenstern, S., 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Philosophical Transactions of the Royal Society B: Biological Sciences 368(1621), 20130122. https://doi.org/10.1098/rstb.2013.0122.

Chambers, B., Dampney, P., 2009. Nitrogen efficiency and ammonia emissions from urea-based and ammonium nitrate fertilisers. International Fertiliser Society Proceedings 657, 1-20. ISSN1466-1314.

Chambers, B.J., Lord, E.I., Nicholson, F.A., Smith, K. A., 1999. Predicting nitrogen availability and losses following application of organic manures to arable land: MANNER. Soil Use and Management, 15(3), 137-143. https://doi.org/10.1111/j.1475-2743.1999.tb00079.x.

Collins, A.L., McGonigle, D.F., 2008. Monitoring and modelling diffuse pollution from agriculture for policy support: UK and European experience. Environmental Science & Policy 11(2), 97-101. https://doi.org/10.1016/j.envsci.2008.01.001.

Copernicus (2018) CORINE Land Cover: CLC 2018. European Union Copernicus Programme. https://land.copernicus.eu/pan-european/corine-land-cover/clc2018 (accessed: 14 June 2021).

D' Haene, K., Salomez, J., De Neve, S., De Waele, J., Hofman, G., 2014. Environmental performance of nitrogen fertiliser limits imposed by the EU Nitrates Directive. Agriculture, Ecosystems & Environment 192, 67-79. https://doi.org/10.1016/j.agee.2014.03.049.

Deasy, C., Quinton, J.N., Silgram, M., Stoate, C., Jackson, R., Stevens, C.J., Bailey, A.P., 2010. Mitigation Options for Phosphorus and Sediment (MOPS): reducing pollution in run-off from arable fields. The Environmentalist 108, 12-17.

de Vries, W., Leip, A., Reinds, G.J., Kros, J., Lesschen, J.P., Bouwman, A.F., 2011. Comparison of land nitrogen budgets for European agriculture by various modeling approaches. Environmental Pollution 159(11), 3254-3268. https://doi.org/10.1016/j.envpol.2011.03.038.

EC, 1991. Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. European Commission (EC). Official Journal L 375, 31/12/1991 P. 0001 – 0008.

EC, 1992. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. European Commission (EC). Official Journal L 206, 22/7/1992 P. 0007 – 0050.

EC, 1998. Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption. European Commission (EC). Official Journal L 330, 05/12/1998 P. 0032 – 0054.

EC, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. European Commission (EC). Official Journal L 327, 22/12/2000 P. 0001 – 0072.

EC, 2001. *Directive* 2001/81/EC of the European Parliament and of the Council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants. European Commission (EC). Official Journal L 309, 27/11/2001 P. 0022 – 0030.

EC, 2009. Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds. European Commission (EC). Official Journal L 20, 26/1/2010 P. 0007 – 0025.

EC, 2013. Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet'. Official Journal L 354, 28/12/2013 P. 0171 – 0200.

EC, 2016. Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive

2003/35/EC and repealing Directive 2001/81/EC. European Commission (EC). Official Journal L 344, 17/12/2016 P. 0001 – 0031.

EEA, 2016. *EMEP*/EEA Air Pollutant Emission Inventory Guidebook 2016 - Technical Guidance to Prepare National Emission Inventories. European Environment Agency (EEA) Report No 21/2016.

ESRI, 2021. ArcGIS Desktop. Version 10.6. ESRI. https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview (accessed: 14 June 2021).

Eurostat, 2021. Administrative Units. Statistical Units. NUTS. Eurostat. https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/nuts (accessed: 14 June 2021).

Forrestal, P.J., Harty, M., Carolan, R., Lanigan, G.J., Watson, C.J., Laughlin, R.J., Richards, K.G., 2016. Ammonia emissions from urea, stabilized urea and calcium ammonium nitrate: insights into loss abatement in temperate grassland. Soil Use and Management 32(S1), 92-100. https://doi.org/10.1111/sum.12232.

Gault, J., Guillet, J., Guerber, F., Hubert, C., Paulin, F., Soulié, M.C., 2015. Analysis of implementation of the Nitrates Directive by other Member States of the European Union. Germany, Belgium (Flanders), Denmark, Spain (Catalonia), Ireland, the Netherlands. Ministry of Ecology, Sustainable Development and Energy No. 010012-01 and Ministry of Agriculture Agri-Food and Forestry No. 14123.

Glibert, P.M., Harrison, J., Heil, C., Seitzinger, S., 2006. Escalating worldwide use of urea–a global change contributing to coastal eutrophication. Biogeochemistry 77(3), 441-463. https://doi.org/10.1007/s10533-005-3070-5.

Holly, M.A., Larson, R.A., Powell, J. M., Ruark, M.D., Aguirre-Villegas, H., 2017. Greenhouse gas and ammonia emissions from digested and separated dairy manure during storage and after land application. Agriculture, Ecosystems & Environment 239, 410-419. https://doi.org/10.1016/j.agee.2017.02.007.

Isherwood, K.F., 2009. Fertilizer use in Western Europe: Types and amounts. In: Lal, R. (ed) Agricultural sciences Vol. II, UNESCO Encyclopedia of Life Support Systems (UNESCO-EOLSS).

Jordan, P., Melland, A.R., Mellander, P.E, Shortle, G., Wall, D., 2012. The seasonality of phosphorus transfers from land to water: Implications for trophic impacts and policy evaluation. Science of the Total Environment 434, 101-109. https://doi.org/10.1016/j.scitotenv.2011.12.070.

JRC, 2021a. Description of Raster Layers. European Soil Data Centre (ESDAC), Joint Research Centre (JRC), European Commission. https://esdac.jrc.ec.europa.eu/content/description-raster-layers (accessed: 14 June 2021).

JRC, 2021b. European Soil Database Maps. European Soil Data Centre (ESDAC), Joint Research Centre (JRC), European Commission. https://esdac.jrc.ec.europa.eu/resource-type/european-soil-database-maps (accessed: 14 June 2021).

Machefert, S.E., Dise, N.B., Goulding, K.W.T., Whitehead, P.G., 2002. Nitrous oxide emission from a range of land uses across Europe. Hydrology and Earth System Sciences Discussions 6(3), 325-338. https://doi.org/10.5194/hess-6-325-2002.

Machefert, S.E., Dise, N.B., Goulding, K.W.T., Whitehead, P.G., 2004. Nitrous oxide emissions from two riparian ecosystems: key controlling variables. Water, Air and Soil Pollution: Focus 4(2-3), 427-436. https://doi.org/10.1023/B:WAFO.0000028369.86947.9f.

Misselbrook, T.H., Nicholson, F.A., Chambers, B.J., 2005. Predicting ammonia losses following the application of livestock manure to land. Bioresource Technology, 96(2), 159-168. https://doi.org/10.1016/j.biortech.2004.05.004

Misselbrook, T.H., Sutton, M.A., Scholefield, D., 2004. A simple process-based model for estimating ammonia emissions from agricultural land after fertilizer applications. Soil Use and Management 20(4), 365-372. https://doi.org/10.1111/j.1475-2743.2004.tb00385.x.

Monteny, G.J., 2001. The EU Nitrates Directive: A European Approach to Combat Water Pollution from Agriculture. The Scientific World 1(S2), 927-935. https://doi.org/10.1100/tsw.2001.377.

Pandey, P.K., Kass, P.H., Soupir, M.L., Biswas, S., Singh, V.P., 2014. Contamination of water resources by pathogenic bacteria. AMB Express 4, 51. https://doi.org/10.1186/s13568-014-0051-x.

Peyton, D.P., Healy, M.G., Fleming, G.T.A., Grant, J., Wall, D., Morrison, L., Cormican, M., Fenton, O., 2016. Nutrient, metal and microbial loss in surface runoff following treated sludge and dairy cattle slurry application to an Irish grassland soil. Science of the Total Environment, 541, 218-229. https://doi.org/10.1016/j.scitotenv.2015.09.053.

Rees, R.M., Augustin, J., Alberti, G., Ball, B.C., Boeckx, P., Cantarel, A., Castaldi, S., Chirinda, N., Chojnicki, B., Giebels, M., Gordon, H., Grosz, B., Horvath, L., Juszczak, R., Kasimir Klemedtsson, Å., Klemedtsson, L., Medinets, S., Machon, A., Mapanda, F., Nyamangara, J., Olesen, J. E., Reay, D.S., Sanchez, L., Sanz Cobena, A., Smith, K.A., Sowerby, A., Sommer, M., Soussana, J.F., Stenberg, M., Topp, C.F.E., van Cleemput, O., Vallejo, A., Watson, C. A., Wuta, M., 2013. Nitrous oxide emissions from European agriculture – an analysis of variability and drivers of emissions from field experiments. Biogeosciences 10(4), 2671-2682. https://doi.org/10.5194/bg-10-2671-2013.

Schröder, J.J., Scholefield, D., Cabral, F., Hofman, G., 2004. The effects of nutrient losses from agriculture on ground and surface water quality: the position of science in developing indicators for regulation. Environmental Science & Policy 7(1), 15-23. https://doi.org/10.1016/j.envsci.2003.10.006.

Sharma, A., 2020. The wicked problem of diffuse nutrient pollution from agriculture. Journal of Environmental Law 32(3), 471–502. https://doi.org/10.1093/jel/eqaa017.

Skjøth C.A., Hertel O., 2013. Ammonia Emissions in Europe. In: Viana, M. (ed) Urban Air Quality in Europe. The Handbook of Environmental Chemistry, vol 26. Springer, Berlin, Heidelberg. https://doi.org/10.1007/698_2012_206.

Smith, K.A., Jackson, D.R., Pepper, T.J., 2001. Nutrient losses by surface run-off following the application of organic manures to arable land. 1. Nitrogen. Environmental Pollution, 112(1), 41-51. https://doi.org/10.1016/s0269-7491(00)00097-x.

Sommer, S.G., Hutchings, N.J., Webb, J., 2019. New emission factors for calculation of ammonia volatilization from European livestock manure management systems. Frontiers in Sustainable Food Systems 3, 101. https://doi.org/10.3389/fsufs.2019.00101.

Tao, W., Ukwuani, A.T., 2015. Coupling thermal stripping and acid absorption for ammonia recovery from dairy manure: Ammonia volatilization kinetics and effects of temperature, pH and dissolved solids content. Chemical Engineering Journal 280, 188-196. https://doi.org/10.1016/j.cej.2015.05.119.

Tzilivakis, J., Green, A., Warner, D.J., Lewis, K.A., 2020. Identification of approaches and measures in action programmes under Directive 91/676/EEC. Final report: Report prepared for Directorate-General Environment, European Commission, for project ENV.D.1/SER/2018/0017 by the Agriculture and Environment Research Unit (AERU), University of Hertfordshire, United Kingdom.

Van der Voet, E., Kleijn, R., Udo de Haes, H.A., 1996. Nitrogen pollution in the European Union - origins and proposed solutions. Environmental Conservation 23(2), 120-132. https://doi.org/10.1017/S0376892900038509.

Van Grinsven, H.J.M., Bouwman, L., Cassman, K.G., van Es, H.M., McCrackin, M.L., Beusen, A.H.W., 2015. Losses of ammonia and nitrate from agriculture and their effect on nitrogen recovery in the European Union and the United States between 1900 and 2050. Journal of Environmental Quality 44(2), 356-367. https://doi.org/10.2134/jeq2014.03.0102.

Van Grinsven, H.J.M., ten Berge, H.F.M., Dalgaard, T., Fraters, B., Durand, P., Hart, A., Hofman, G., Jacobsen, B.H., Lalor, S.T.J., Lesschen, J.P., Osterburg, B., Richards, K.G., Techen, A.-K., Vertès, F., Webb, J., Willems, W.J., 2012. Management, regulation and environmental impacts of nitrogen fertilization in northwestern Europe under the Nitrates Directive; a benchmark study. Biogeosciences 9, 5143–5160. https://doi.org/10.5194/bg-9-5143-2012.

Van Grinsven, H.J.M., Tiktak, A., Rougoor, C.W., 2016. Evaluation of the Dutch implementation of the nitrates directive, the water framework directive and the national emission ceilings directive. NJAS - Wageningen Journal of Life Sciences 78, 69-84. https://doi.org/10.1016/j.njas.2016.03.010.

Velthof, G.L., Lesschen, J.P., Webb, J., Pietrzak, S., Miatkowski, Z., Pinto, M., Kros, J., Oenema, O., 2014. The impact of the Nitrates Directive on nitrogen emissions from agriculture in the EU-27 during 2000–2008. Science of The Total Environment 468-469, 1225-1233. https://doi.org/10.1016/j.scitotenv.2013.04.058.

Veraart, A.J., De Klein, J.J., Scheffer, M., 2011. Warming can boost denitrification disproportionately due to altered oxygen dynamics. PLoS One 6(3), e18508. https://doi.org/10.1371/journal.pone.0018508.

Webb, J., Pain, B., Bittman, S., Morgan, J., 2010. The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response—a review. Agriculture, Ecosystems & Environment 137(1-2), 39-46. https://doi.org/10.1016/j.agee.2010.01.001.

Supplementary material

Table S1: Unique combinations of spatial data within each NAP

Member State	Region	Variables (potential maximum number)	Unique combinations that exist in NVZs (potential)
Austria	-	Env zone (3); Land use (2)	6
Belgium	Flanders	Env zone (1); Land use (4)	4
	Wallonia	Env zone (2); Land use (2)	4
Bulgaria	-	Env zone (5); North/South (2); Land use (3)	18 (30)
Croatia	-	Env zone (5)	5
Cyprus	-	Env zone (2)	1 (2)
Czech Republic	-	Env zone (3); Climate region (2)	5 (6)
Denmark	-	Env zone (2); Land use (3)	6
Estonia	-	Env zone (2)	2
Finland	Mainland Finland	Env zone (3)	3
	Åland	Env zone (1); Land use (3)	2 (3)
France	Auvergne - Rhône-Alpes	Env zone (6); Land use (3)	17 (18)
	Bourgogne - Franche-Comté	Env zone (2); Land use (4)	7 (8)
	Brittany	Env zone (2); Land use (3)	6
	Centre - Val de Loire	Env zone (2); Land use (3)	6
	Grand Est	Env zone (3); Land use (3)	9
	Hauts-de-France	Env zone (2); Land use (3)	6
	Ile de France	Env zone (1); Land use (4)	4
	Normandie	Env zone (1); Land use (3)	3
	Nouvelle Aquitaine	Env zone (5); Land use (4)	14 (20)
	Occitanie	Env zone (5); Land use (3)	12 (15)
	Pays de la Loire	Env zone (2); Land use (3)	6
	Provence - Alpes-Côte d'Azur	Env zone (4); Land use (4)	12 (16)
Germany	-	Env zone (4); Land use (2)	8
Greece	Argolid Plain	Env zone (1); Land use (2); Soil type (2)	2 (4)
	Kopaida Plain	Env zone (3); Land use (2); Soil type (2)	6 (12)
	Pineiós Basin - Ilia	Env zone (3); Land use (2); Soil type (2)	3 (12)
	Plain of Arta - Preveza	Env zone (3); Land use (2)	6
	Plain of Thessaly	NA	
	Strymon Basin	Env zone (2); Land use (2)	4
	Thessaloniki Plain - Pella - Imathia	Env zone (3); Land use (2)	6
Hungary	-	Env zone (3); Land use (2)	6
Ireland	-	Env zone (2); Land use (3)	5 (6)
Italy	Abruzzo	Env zone (2); Land use (2)	4
	Apulia	Env zone (2)	2
	Basilicata	Env zone (3)	3
	Campania	Env zone (3)	2 (3)
	Emilia Romagna	Env zone (2); Land use (2)	4
	Friuli Venezia Giulia	Env zone (3); Land use (2)	6
	Lazio	Env zone (3)	2 (3)
	Liguria	Env zone (2); Land use (3)	1 (6)
	Lombardy	Env zone (3); Land use (2)	4 (6)
	Marche	Env zone (2); Land use (2)	3 (4)
	Molise	Env zone (2); Land use (2)	4
	Piedmont	Env zone (3); Land use (2)	6
	Sardinia	Env zone (3); Land use (3)	1 (9)
	Sicily	Env zone (3); Land use (3)	6 (9)
	Tuscany	Env zone (2); Land use (2)	3 (4)
	Umbria	Env zone (2)	2
	Veneto	Env zone (3); Land use (2)	4 (6)
Latvia	-	Env zone (3); Land use (2)	2 (6)
Lithuania	-	Env zone (2); Land use (2)	4
Luxembourg	-	Env zone (2); Land use (2)	4
Malta	-	Env zone (1)	1
Netherlands	-	Env zone (3); Land use (3); Soil type (3)	17 (27)
Poland	-	Env zone (3); Land use (2)	6
Portugal	-	Env zone (4); Land use (3)	8 (12)
Romania	-	Env zone (3); Land use (2)	6
Slovakia	-	Env zone (3); NVZ category (2)	6
Slovenia	-	Env zone (5); Land use (2)	10
Spain	Aragón	Env zone (4); Land use (5)	14 (20)
	Castilla La Mancha	Env zone (3)	3
	Cataluña	Env zone (4); Land use (5)	11 (20)

Member State	**Region**	**Variables (potential maximum number)**	**Unique combinations that exist in NVZs (potential)**
	Comunidad de Madrid	Env zone (3); Land use (2)	4 (6)
	Comunidad Foral de Navarra	Env zone (4); Land use (3)	3 (12)
	Islas Baleares	Env zone (1)	1
	La Rioja	Env zone (4); Land use (2)	4 (8)
	Región de Murcia	Env zone (3); Land use (4)	7 (12)
Sweden	-	Env zone (4); Land use (2); Region (3)	14 (24)
United Kingdom	England	Env zone (2); Land use (2); Soil type (2)	8
	Northern Ireland	Env zone (1); Land use (2)	2
	Scotland	Env zone (1); Land use (2); Soil type (2)	4
	Wales	Env zone (2); Land use (2); Soil type (2)	6 (8)

Table S2: Implementation of other NAP measures*

M	AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	DE	GR	HU	IE	IT	LV	LT	LU	MT	NL	PO	PT	RO	SK	SI	ES	SE	UK
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.94	1	1	1	1	1	1	1	1	1	1	0.93	0	0
2	0	1	1	0	1	1	1	1	1	0	0	0.86	1	0	0.94	1	0	1	1	1	1	0	0	1	0	0.79	1	0.25
3	0	1	0	0	1	0	1	1	0	0.08	0	0.43	1	0	0.78	0	0	1	1	1	1	1	0	0	1	0.57	0	0
4	1	1	1	1	1	1	1	1	1	1	1	0.86	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	0	1	0	0	0	0	0	1	0.5	0	0	0	1	0	0.17	0	0	0	0	0	0	0	0	0	0	0.14	0	0.75
6	1	0.5	1	1	1	1	1	1	1	0.5	0	0.57	1	1	0.83	1	0	1	1	1	1	1	1	1	1	0.93	0	1
7	1	0	0	0	0	1	0	1	1	0.42	0	0	0	0	0.61	0	0	0	0	0	1	0	0	1	1	0.14	0	0
8	1	1	1	1	1	1	1	1	1	1	1	0.86	1	1	1	1	1	1	1	1	1	1	1	1	1	0.57	1	1
9	1	1	0	0	0	1	1	0	1	1	1	0	0	0	0.06	0	0	1	0	0	0	0	0	1	1	0	0	0
10	1	1	1	1	1	1	1	1	1	1	1	0.86	1	1	1	1	1	0	1	1	1	1	1	1	0	0.93	1	0.75
11	0	0	0	0	1	0	0	1	0.5	0.08	0	0	1	0	0.06	0	0	1	1	0	0	1	0	1	0	0.57	0	0
12	1	1	1	1	1	1	1	1	1	1	1	0.86	1	1	1	1	1	1	1	1	1	1	1	1	0	0.93	1	1
13	0	0	0	0	1	0	0	1	1	0	0	0.43	1	1	0.17	0	0	1	1	0	0	1	0	1	0	0.85	0	1
14	0	0	1	1	1	0	0	0	0	0	0	0.14	0	0	0.17	1	1	0	1	0	0	0	0	0	0	0	0	0
15	1	1	0	1	1	0	1	1	1	0.08	1	0	1	1	0.72	1	1	1	1	1	1	1	1	1	1	0.5	1	1
16	1	1	1	0	1	0	0	1	1	0	1	0.43	0	0	0.56	1	1	1	0	0	1	1	0	1	0	0.43	1	0.5
17	1	1	0	0	0	0	1	1	0	1	0	0.43	0	1	0.83	1	0	0	0	1	0	1	1	1	0	0.07	1	0.5
18	1	0.5	0	0	0	0	1	0	0	1	0	0.43	0	1	0.5	0	0	1	0	1	1	0	0	0	0	0.14	0	0

Measures:

1. Climate and soil conditions that prohibit the use of fertilisers
2. Prohibition of fertilisers on sloping land
3. Land uses which prohibit fertiliser use
4. Farm limit for nitrogen from organic manures
5. Field limit for nitrogen from organic manures
6. Field limit for total nitrogen
7. Field limit for single applications
8. Closed periods when the application of fertilisers is prohibited
9. Field limit on application amounts at specific times
10. Distance between the application of inorganic fertilisers and surface water
11. Distance between the application of inorganic fertilisers and groundwater sources
12. Distance between the application of organic fertilisers and surface water
13. Distance between the application of organic fertilisers and groundwater sources
14. Fertilisers and substances that are prohibited
15. Prohibited and permitted application techniques
16. Restrictions on incorporating organic manure
17. Ground cover and land management
18. Restrictions on cultivation and tillage activities

* The numbers in Table S2 relate to where the measure has been implemented, and where MSs have regional NAPs the number is the proportion of the regions within the MS that have the measure

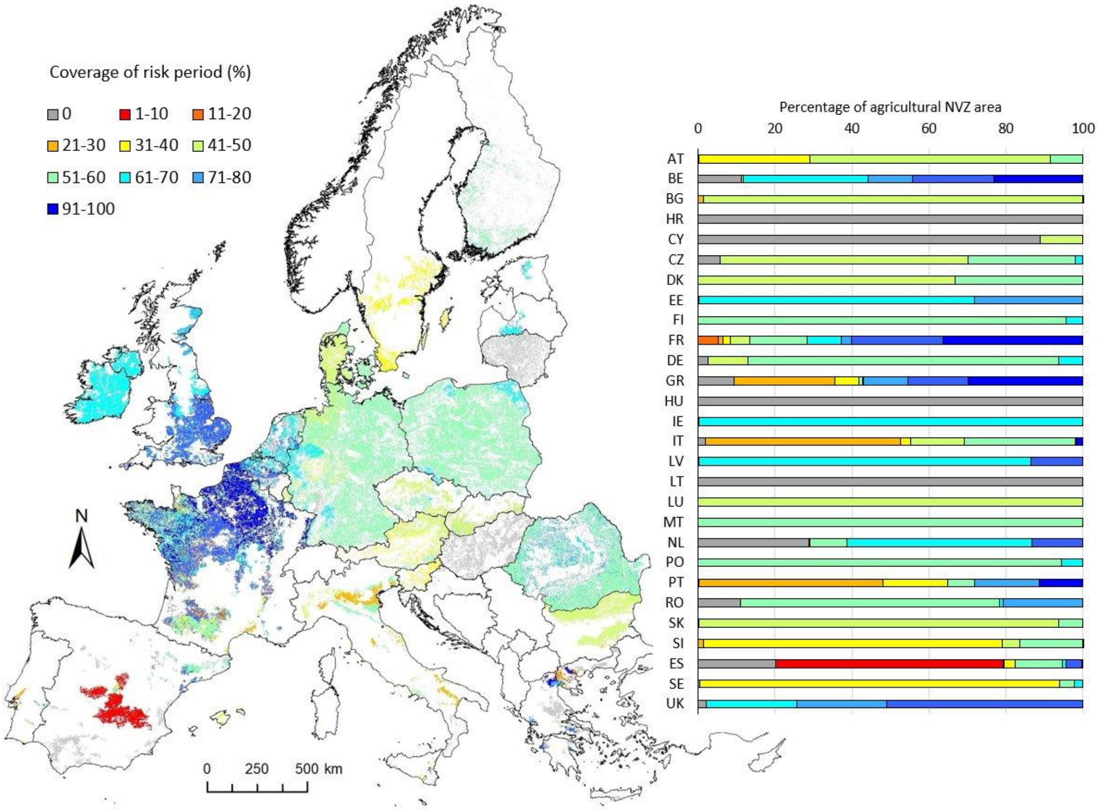


Figure S1: NO_3^- Leaching Group 1

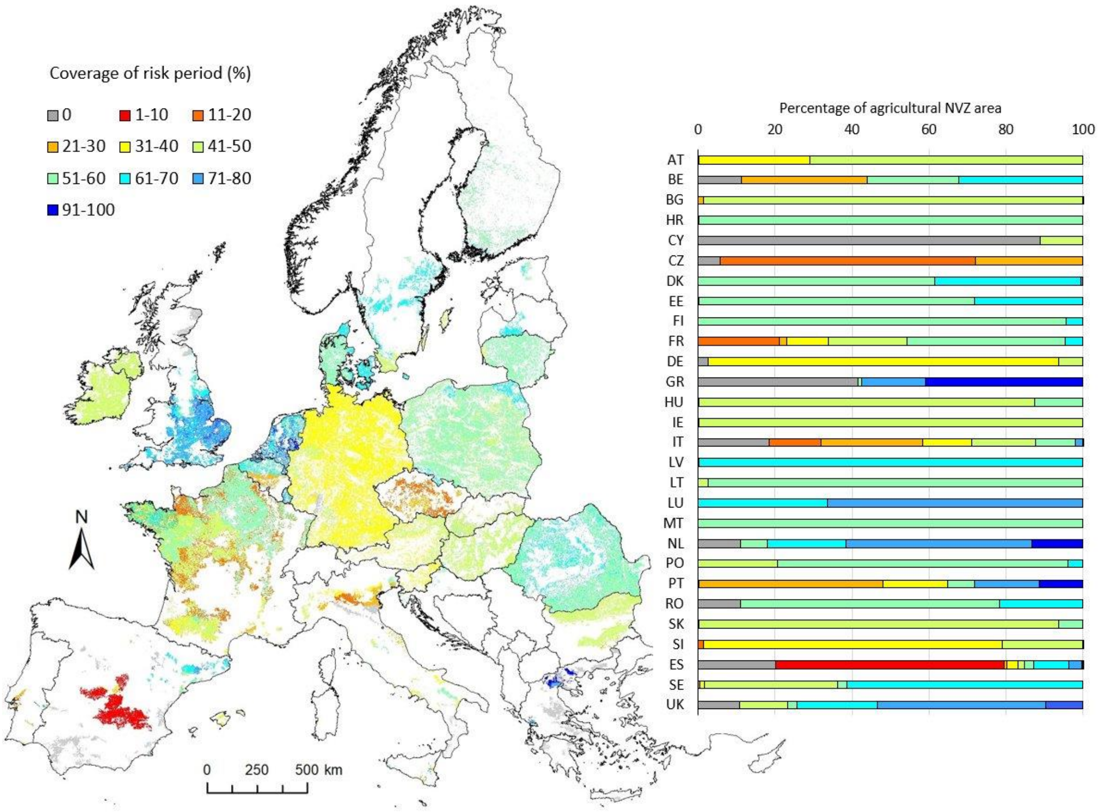


Figure S2: NO_3^- Leaching Group 2

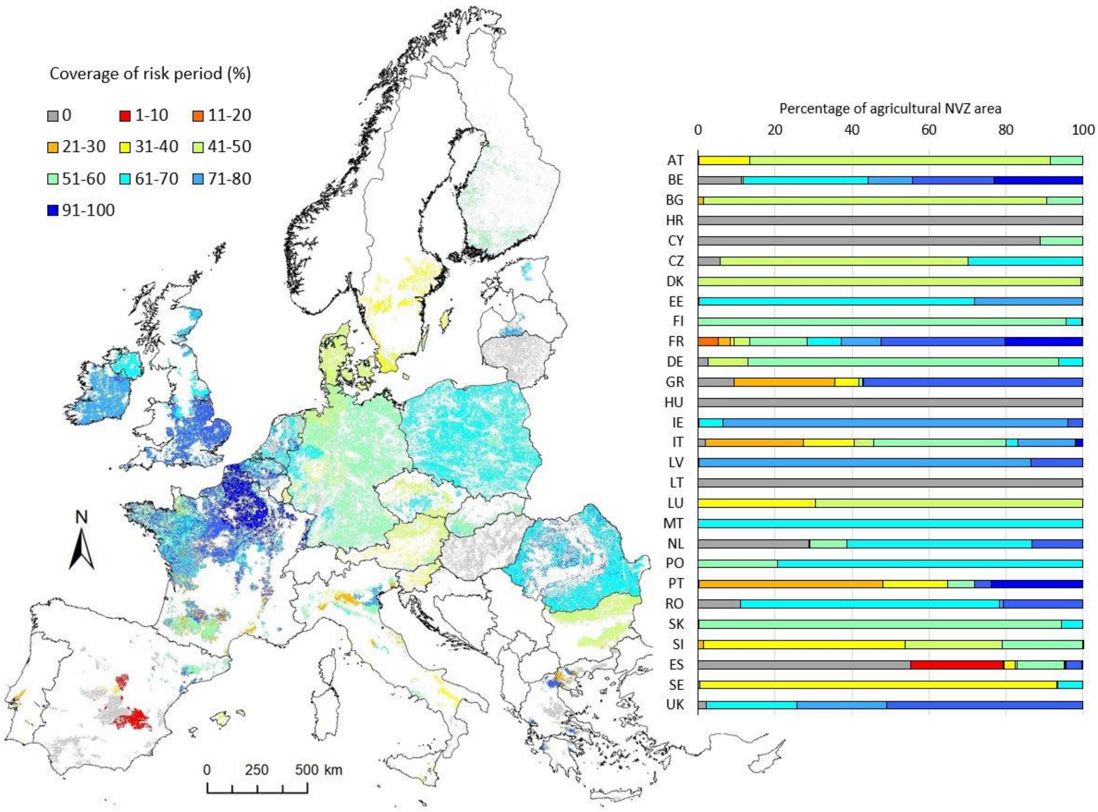


Figure S3: NO_3^- Run-off Group 1

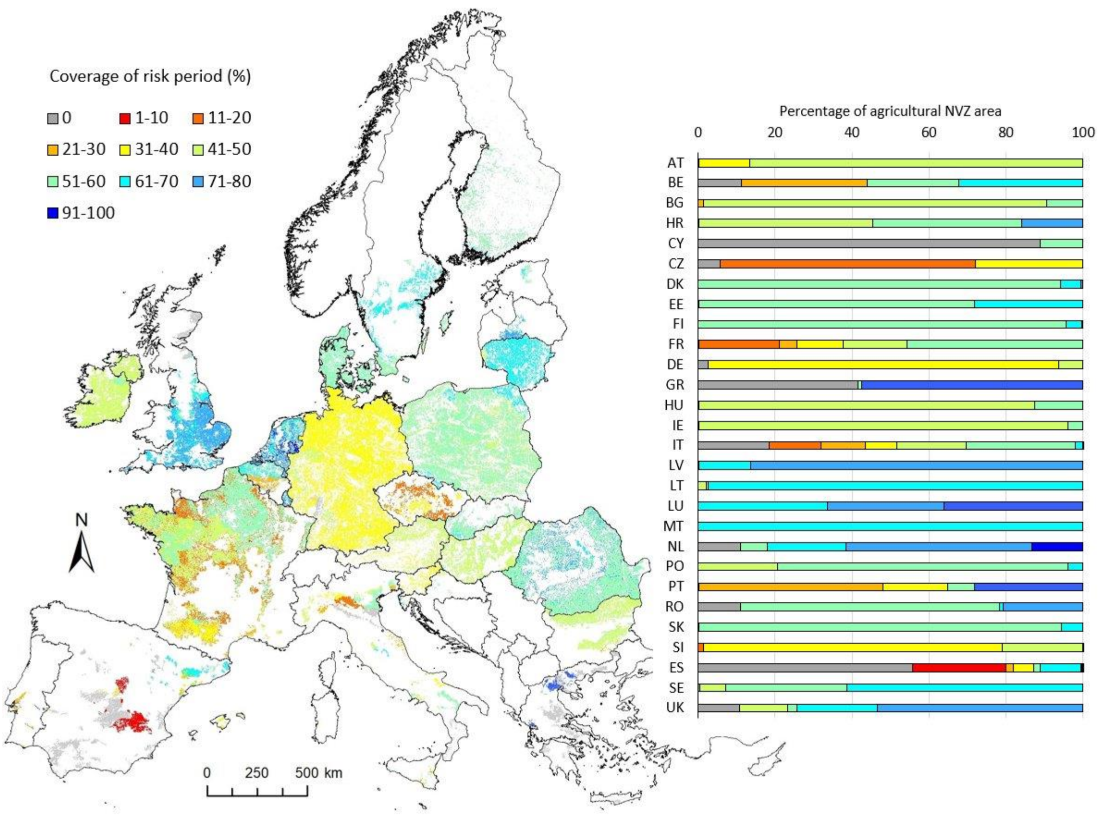


Figure S4: NO_3^- Run-off Group 2

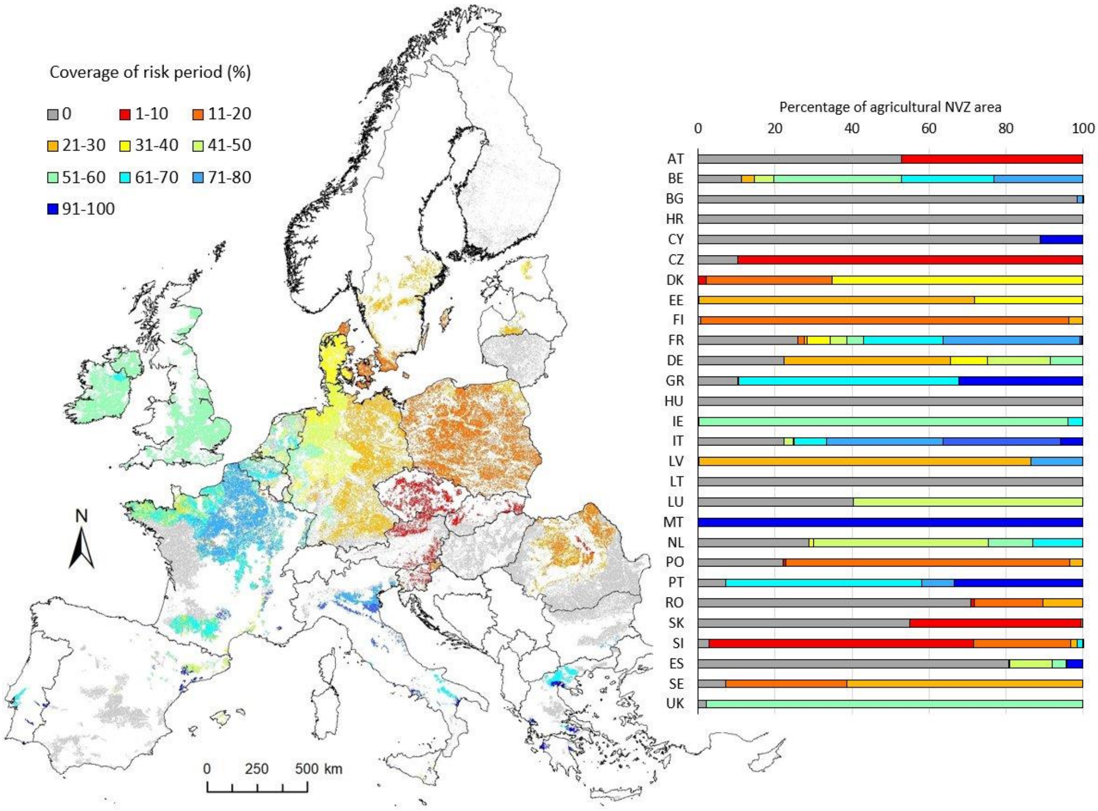


Figure S5: N_2O Emissions Group 1

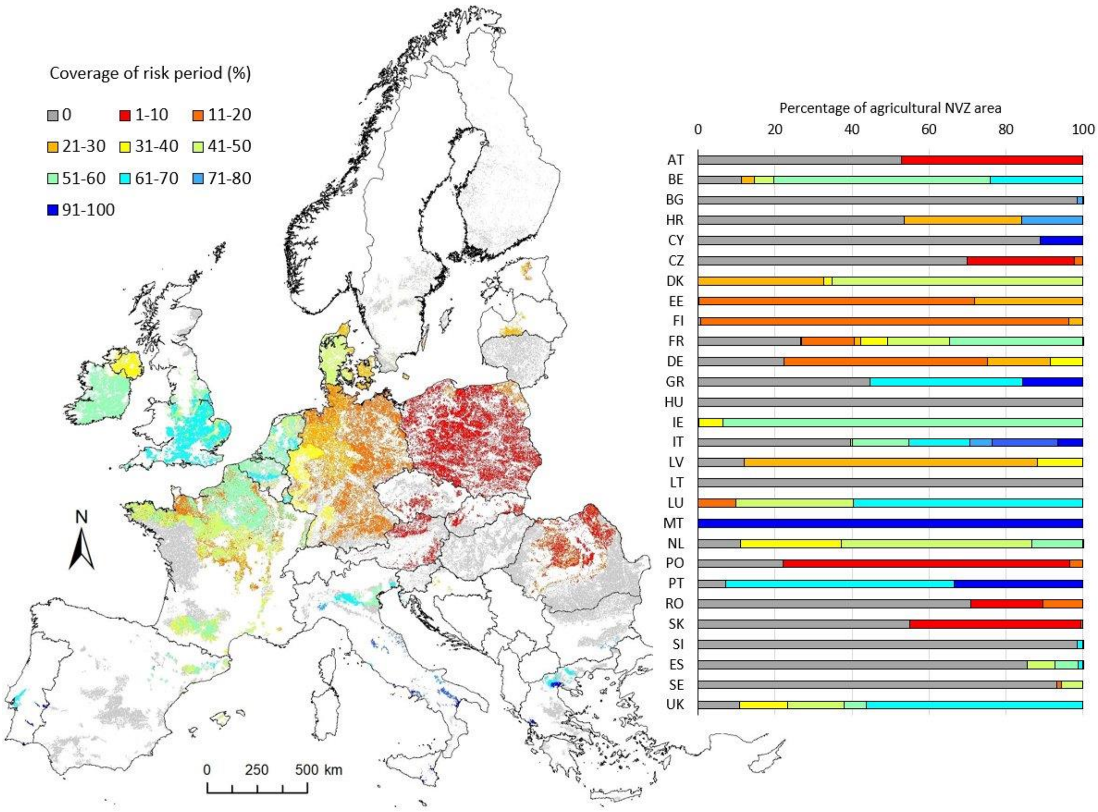


Figure S6: N_2O Emissions Group 2

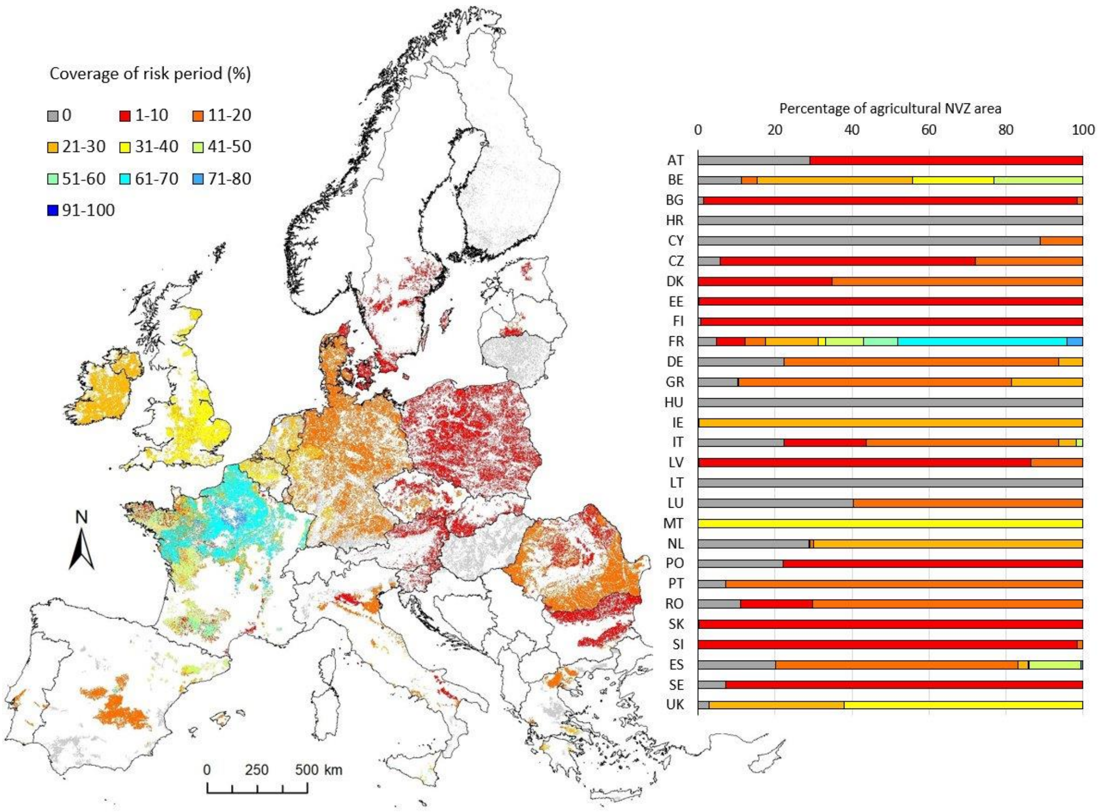


Figure S7: NH_3 Emissions Group 4

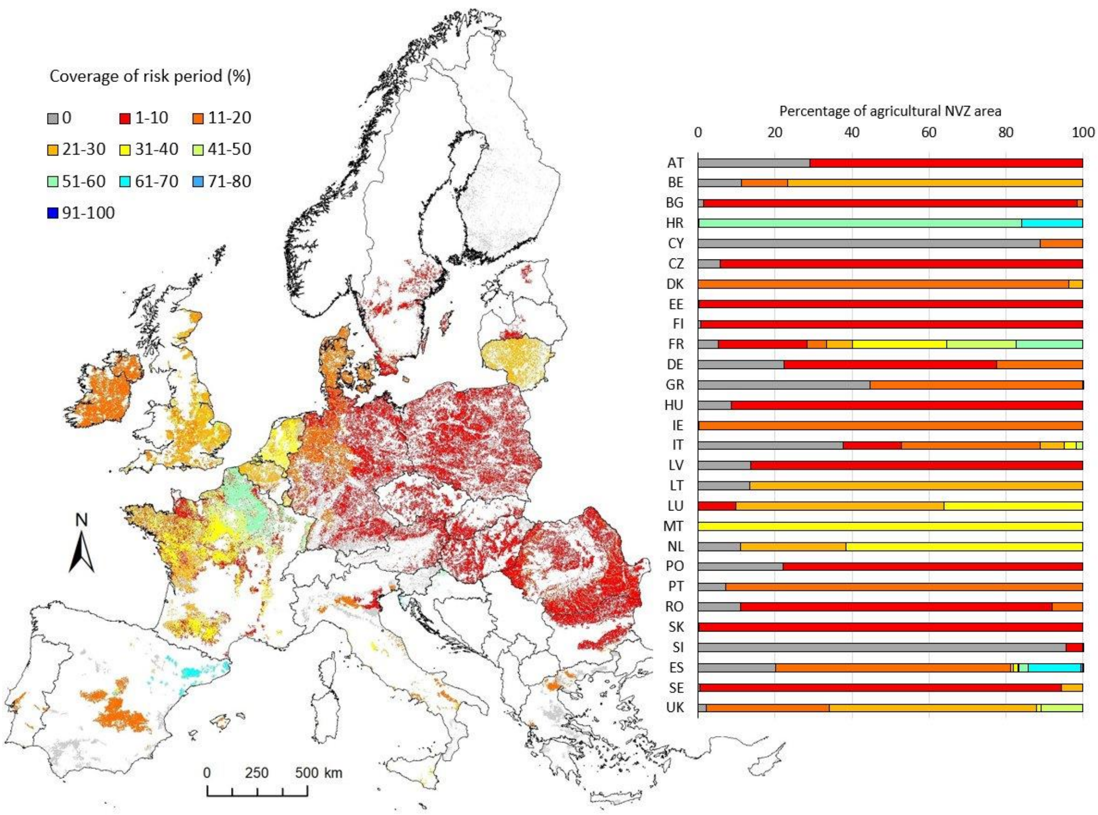


Figure S8: NH_3 Emissions Group 5