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Review of measures to decrease nitrate pollution of drinking water sources

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SUMMARY

Sufficient safe drinking water is vital for human health, public welfare and an important driver of a healthy economy. This drinking water is extracted from groundwater (aquifers) or surface waters, and in many countries purified before consumption. About 2 billion people in the world lack sufficient safe drinking water, mostly in Africa and Asia. In the European Union about 65 million people are exposed to drinking water resources which quality cannot be guaranteed. Further, many drinking water resources run the risks of pollution by nitrates and pesticides, resulting from the intensification of agricultural production. In response, drinking water authorities have taken a range of measures around their drinking water resources to reduce the pressures from pollution, and have invested in various purification steps, or in the closure of wells when contamination was unacceptably high. In addition, various policy measures have been implemented as a blanket in the European Union from the early 1990s onwards to decrease the pollution of drinking water resources with nitrates and pesticides. The current view is that not all measures are equally effective, and that the protection of drinking water resources has to be improved.

The overall objective of the EU-project FAIRWAY is '*to review current approaches and measures for protection of drinking water resources against pollution caused by pesticides and nitrate from agriculture in the EU and elsewhere, and to identify and further develop innovative measures and governance approaches, together with relevant local, regional and national actors*'.

The project runs for four years, from June 2017 to June 2021, and combines literature reviews, stakeholder interviews and engagement, 13 study sites across the EU-28 where measures are tested, analyses of governance approaches and upscaling activities.

The current report deals with a review and assessment of measures to decrease nitrate pollution of drinking water resources. The work builds on insights and results gathered in EU-wide and global projects and studies. It provides an overview and assessment of the effectiveness and efficiency of measures aimed at decreasing nitrate pollution of drinking water reservoirs. This report is deliverable D4.1 of FAIRWAY (Review of measures to decrease nitrate leaching). It complements the related deliverable D4.2 (Review of measures to decrease pesticides leaching).

Chapter 1 describes the background and objectives of the review. Various reviews on measures aimed at decreasing nitrate leaching have been published already, but either these reviews focussed on single measures or were rather qualitative and descriptive in nature. The novel aspect of this review is that the accessible literature has been screened for experimental data related to the effectiveness of most measures to reduce nitrate pollution of groundwater and surface waters, in a coherent and quantitative manner, using statistical analyses.

Chapter 2 presents the review methodology. Two surveys were conducted. Firstly, a survey of practical guidelines and measures, also at the case study sites, and earlier inventory reports yield gross lists of some 40 measures. All these measures were uniformly and concisely described and are to be found in Annexes 1 and 2 of this report. Secondly, a survey of published literature was conducted to identify papers that reported experimental results on the effectiveness of measures to decrease nitrate leaching, using the ISI-Web of Science and Google Scholar from 1980 to 2017. The reviews were conducted by different review teams covering different geographical regions using an approved protocol. Results were stored in a database and analysed statistically.

Chapter 3 provides background information about the sources of nitrate nitrogen in agriculture and about the processes and factors that contribute to the pollution of groundwater and surface waters with nitrates. The nitrogen cycling has been characterised as a leaky cycle and at the same time is complex. Main sources are animal manures and synthetic fertilizers, but also residues and wastes, and the mineralization of soil organic matter following land use change can be sources regionally. Estimates suggest that some 60% of the amounts of nitrogen entering the aquatic system

originates from diffuse agricultural sources in EU-28, which is about 6 Tg (1 Tg is 1 million ton is 10^{12} g), and equivalent to 60% of the N fertilizer use in EU-28.

Chapter 4 presents background information about agricultural systems and land use in EU-28 and about management factors that influence nitrogen use in agriculture. The nitrogen input-output balance is a synthetic manner for summarizing N use at farm level but also at regional and national levels. The chapters also discusses the difficulties of optimizing N fertilization due to site and temporal variations in N demands by growing crops.

Chapter 5 presents information about the hydrological cycle and about the pathways of N transfers from land to groundwater and surface waters. The potential risks of runoff and leaching of nitrate and nitrogen to surface waters is determined by a combination of pedo-climatic factors and the amounts of nitrate and nitrogen in the top soil. Important pedo-climatic factors are: (i) rainfall amount and distribution, especially heavy rainfall events, and (ii) water infiltration rate into the soil. The latter is determined by slope, soil texture, soil structure, soil depth to underlying rock, vegetation cover, snow and frost and freeze-thaw cycles, and the presence of terraces, tree-lines, buffer zones, riparian zones, which all contribute to intercepting overland flows. Soils with a high nitrate leaching vulnerability have a high infiltration rate and a high hydrological conductivity, such as coarse-sandy soils and shallow soils overlying karst formations.

Chapter 6 provides an overview of measures aimed at decreasing nitrate losses from agriculture to groundwater and surface waters. The mean cost-effectiveness of most measures roughly ranged from 1 to 5 euro per kg N, but the uncertainty in the cost-effectiveness is large, and some measure had higher costs. At farm level, the cost of the measures ranged from a net gain to a cost of more than a few thousands euro per year. The rational and effectiveness of 11 key measures have been discussed in some further detail, also as basis for a further quantitative analysis in Chapter 7.

Chapter 7 presents results of the quantitative analyses of the effectiveness of measures that have been tested in the field experimentally, using statistical analyses. A total of 84 papers with 228 experimental comparisons have been examined and utilized for statistical analyses; these papers report experimental data related to measures aimed at decreasing nitrate leaching losses. Most measures were on average effective, but some measures turn out to be not effective than others. Effective measures were (i) N input control, (ii) adjustment of crop type and/or crop rotation, (iii) growth of cover crops, (iv) minimum tillage and surface mulching, and (v) nitrification inhibitors. Somewhat surprising, fertilizer type and time and method of application turned out to be not effective. These initial results need further underpinning. Moreover, the effective measures do show a wide variation; the 95% confidence interval of the mean response ratio was often very large, which is probably related to site-specific variations in socio-economic and environmental conditions.

Chapter 8 discusses briefly the implications of the findings, also in relation to recent meta-analyses studies. Our findings largely confirm the observations of most earlier reports, but some meta-analysis studies provide also additional and different results. The differences will be examined further and reported together with an analysis of ‘most promising measures’.

Chapter 9 list the most important conclusions of this review. The variability in the effectiveness of measures to decrease nitrate leaching losses across site is possibly one of the reasons for the widespread existence of groundwater and surface water monitoring stations with nitrate concentrations that exceed 50 mg/L, despite the implementation of series of measures during the last 2 to 3 decades. It demands for farm-specific packages of measures. This report and the forthcoming report on most promising measures will be an important scientific building block for the further development of innovative measures and governance approaches for a more effective drinking water protection, together with local, regional and national actors.

1. INTRODUCTION

Water is a fundamental human need. Humans require at least 20 to 50 liters of clean, safe water a day for drinking, cooking, and simply keeping themselves clean. Sufficient safe drinking water is vital for public welfare and an important driver of a healthy economy. According to the World Health Organization, safe drinking-water is water that "does not represent any significant risk to health" (WHO, 2017). About 2 billion people in the world lack sufficient safe drinking water. About 1 million people are estimated to die annually as a result of unsafe drinking-water (WHO, 2018). Both, access to and the quality of drinking water are important. Protecting human health from adverse effects of unsafe drinking water is a top global priority of the United Nations Sustainable Development Goals (UN, 2018).

The search for pure drinking water began in prehistoric times. Ancient civilizations established themselves around water sources. Farming and the development of settlements lead to the beginning of the problem– how to get drinkable water for humans and cattle and how to manage the waste they produce. The availability of water in large quantities has been considered an essential part of human civilizations. The importance of good quality drinking water has been known for years, but the importance of proper sanitation was not understood until the 19th century, while standards for water quality appeared only in the early 1900s. Only gradually, people recognized that their senses alone were not accurate judges of water quality (Baker, 2012; Juuti et al., 2007).

The health effects of nitrate (NO_3^-) and nitrite (NO_2^-) in drinking water have long been debated (L'Hirondel, 2001; Bryan and Van Grinsven, 2013). The 1958 WHO International Standards for Drinking-water stated that the ingestion of water containing nitrates in excess of 50–100 mg/l (as nitrate) may give rise to methaemoglobinaemia in infants under 1 year of age (Schullehner et al. 2018). In the 1963 International Standards, this value was lowered to 45 mg/l (as nitrate), which was retained in the 1971 International Standards. The current guideline values are 50 mg/l for nitrate ion and 3 mg/l for nitrite; they are meant to protect against methaemoglobinaemia in bottle-fed infants (WHO, 2017).

Nitrate in groundwater and surface waters originates primarily from nitrogen fertilizers and manure storage and spreading operations, and from sewage waste and septic systems, The global amounts of nitrate-nitrogen lost from sewage and septic systems to groundwater and rivers greatly differ between countries; averages range from 1 to 6 kg of nitrogen per person per year (Van Drecht et al., 2009). Global losses from fertilizers and manures are a factor 2 to 4 larger (Beusen et al., 2016). Nitrogen that is not taken up from soil by plants may be lost to surface waters and groundwater as nitrate via surface runoff and leaching (Burt et al., 1993). This makes the nitrogen unavailable to crops and increases the nitrate concentration in groundwater and surface waters (Sutton et al., 2011).

The pollution of groundwater and surface waters with nitrate has shifted in scale from local in the past to regional and continental dimensions currently (Burt et al., 1993). Mean nitrate concentrations in groundwater have remained relatively stable in Member States of the European Union (EU) since 1992, although there is wide variation at the scale of individual groundwater bodies. Approximately 13 % of the stations across EU in 2009, exceeded the 50 mg/l limit (EC, 2014). Pristine lakes and rivers have a nitrate concentration of about 0.1 mg NO_3^- N per liter. The mean nitrate concentration in European rivers ranged between 0.5 and 5.0 mg N per liter in 2012, suggesting a 5 to 50 times increase relative to background concentration levels (EEA, 2015). However, the average nitrate concentration in European rivers reduced 0.5 mg NO3-N per liter during the period 1992 to 2012, as a result of various measures.

The European Union (EU) has developed a series of directives, guidelines and policies over the last decades to decrease the pollution of drinking water sources by nitrates from agriculture, industry and households. The requirements of the EU Drinking Water Directive set an overall minimum quality for drinking water within the EU. The EU Water Framework Directive, the Groundwater Directive, and the Nitrates Directive require Member States to protect drinking water resources against nitrate pollution in order to ensure production of safe drinking water.

The aforementioned directives have as yet not achieved a consistent level of implementation and effectiveness across all Member States. As a consequence, limits for nitrate (50 mg/l) are still exceeded in some areas with vulnerable water resources. Diffuse pollution of nitrogen from agriculture is the main obstacle to meeting the Drinking Water Directive targets for nitrate and nitrite.

Various measures and good agricultural practices have been developed and implemented in practice at farm level in the EU. These measures and practices have been successful in some regions but not in all (Dalgaard et al., 2014). There is a huge diversity within the EU in farming systems, climate, geomorphology, hydrology, soils, education level of farmers, quality of extension services, and type of water supplies, which means that site-specific measures and good practices are required to decrease nitrate pollution of drinking water resources. Coherent site-specific packages of measures are needed. However, the critical success factors that determine the effectiveness of these measures on a site by site basis are not well-known. It has been recognized in several studies and working groups that environmental directives and the Common Agricultural Policy should be better integrated when focusing on the protection of drinking water resources. The possibility of an integrated risk assessment and risk management by using Water Safety Plans, which was recently included in the Drinking Water Directive, is generally welcomed as a vehicle to become more flexible and proactive. In general, there is a growing consensus that good water governance is an essential prerequisite for water management since multiple actors may contribute to pollution.

There are several excellent reviews about nitrates from agriculture in groundwater and surface waters and about measures to reduce the loss of nitrate from agriculture (e.g., Addiscott et al., 1991; Burt et al., 1993; Goulding, 2000; Kirchmann et al. 2002; Mosier et al., 2004; Osterburg et al., 2007; Hatfield and Follett, 2008; Sutton et al., 2011; Cost869, 2011). Most of our current understanding of the mechanisms of nitrate losses from agriculture and of the measures to reduce these losses has been established in 1950s to 2000s, and much of the experimental testing of measures to reduce losses has been conducted in that period. Thereafter, simulation took over much to the scientific studies on nitrate losses from agriculture (e.g., Thomassen et al., 1991). This does not mean that no testing has been done during the last 2 or 3 decades, but that the experimental testing was often done in function of model calibration and validation. As a result, there are a large number of simulation models that are able to estimate the effects of measures to reduce nitrate leaching, as function of climate, soil, hydrology, and agricultural management conditions (Table 1).

Most of these models have only been applied to the region for which they were developed. The models differ from each other with respect to:

- The aim for which they were developed (academic research, water management tool, policy advise)
- The spatial scale on which they are applied
- The type of output they can produce (nitrate fluxes and/or concentrations; groundwater and/or surface waters)
- The type of process descriptions that are implemented and the temporal simulation scale

Table 1 lists a number of simulation models for the field scale and the regional scale estimation of nitrate losses. All the models listed are able to calculated nitrogen losses from the root zone, but not all the field scale models consider transport routes to groundwater and / or surface waters. Most of the field scale models have a strong focus on the organic matter and nitrogen cycle in the root zone and how these are influenced by agricultural management.

Table 1 Overview of simulation models used to estimate nitrate leaching at the field scale and/or the regional scale.

Models	Country of origin	Model ability to calculate output				References
		Leaching flux to groundwater	Concentration of NO3 in groundwater	Leaching flux to surface water	Concentration of NO3 in surface water	
Field scale, detailed process descriptions						
ANIMO	NL	+	+	+		Groenendijk et al, 2005
ARMOSA	IT	+				Perego et al, 2012
CANDY	GE	+				Franko et al, 1995
CoupModel (successor of SOILN)	SE	+	+			Jansson & Karlberg
DAISY	DK	+				Abrahamsen & Hansen, 2002
DNDC	USA	+		+		Li et al, 2006
Daycent	USA	+	+	+		https://www2.nrel.colostate.edu/projects/daycent/
DRAINMOD-N	USA	+	+	+		Brevé, et al, 1997
EPIC	USA	+				Williams et al, 1989
HERMES	GE	+		+		Kersebaum, 2007
HYDRUS-1D	USA	+	+			Šimůnek et al, 2008
LEACHM-N	USA	+				Wagenet & Hutson, 1989
NLES	DK	+		+		Kristensen, et al 2008.
PASTIS	FR	+				Garnier et al 2001
SIMWASER-/STOTRASIM	AT	+				Feichtinger, 1998
WAVE	BE	+				Vanclooster et al., 1996
Catchment scale, distributed models						
GEPIC (EPIC based)	Int	+				Liu et al, 2007
HYPE	SE	+		+		Strömqvist, J.,2012
INCA-N	GB	+		+	+	Wade et al, 2002
Danish National N-model (DAISY linked)	DK	+	+	+		Højberg et al., 2017
GROWA-DENUZ/WEKU	GE	+	+	+		Wendland et al, 2009
MITERRA-Europe	NL	+		+		Velthof et al., 2009
STONE (ANIMO-link)	NL	+	+	+		Wolf et al, 2003
SWAT	Int	+		+	+	Arnold et al, 2012

Despite the implementation of a range of policy measures since the early 1990s, the nitrate problems still persist across EU-28, although less severe than in the 1990s-2000s (EEA, 2015). There are various reasons for explaining why policy measures have been less effective than initially thought (e.g. Sutton et al., 2011). A main reason is that nitrogen is a key input in agriculture for crop and animal productivity, and that the nitrogen cycle is a leaky cycle. Another possible reason is that measure to reduce nitrate losses from agriculture to water bodies are perhaps less effective (quantitatively) than initially thought, and/or less effective in practice than in experimental conditions.

The overall objective of the FAIRWAY project is to review current approaches and measures for protection of drinking water resources against pollution caused by nitrate and pesticides from agriculture in the EU, and to identify and further develop innovative measures and governance approaches for a more effective drinking water protection (https://www.fairway-project.eu/). The project started in June 2017 and will last till June 2021. FAIRWAY has 8 work packages and 13 case-study sites in 11 countries across the EU. Work package 4 has the objective to review and assess measures and practices aimed at preventing and decreasing nitrate and pesticides pollution of drinking water.

The current report deals with a review and assessment of measures and practices to decrease nitrate pollution of drinking water. The work builds on insights and results gathered in EU-wide and global projects and studies. It provides an overview and assessment of the effectiveness and efficiency of measures and practices aimed at decreasing nitrate pollution of drinking water reservoirs. The first chapters provide a qualitative overview of sources and factors that contribute to nitrate pollution of groundwater and surface waters, as a basis for understanding the measures aimed at decreasing nitrate pollution. Chapters 6 and 7 then provide qualitative and quantitative analyses of the effectiveness of the measures that have been tested in the field experimentally, using statistical analyses. This report is deliverable D4.1 of FAIRWAY (Review report on effective nitrate leaching mitigation measures and practices). It complements the related deliverable D4.2 (Review report on effective pesticides leaching mitigation measures and practices).

The novel aspect of this study is that the accessible literature has been screened for experimental data related to the effectiveness and efficiency of basically all measures to reduce nitrate pollution of groundwater and surface waters, in a coherent and quantitative manner, using statistical analyses. The current report provides an overview of the measures and practices and overall statistical results, while the forthcoming report “Most promising measures to decrease nitrate pollution” (FAIRWAY deliverable 4.3) and accompanying scientific papers will present the results of an in-depth meta-analysis.

2. REVIEW METHODOLOGY

This chapter presents a brief overview of the process and procedures related to the execution of the review. A total of 16 institutions across EU-28 have been involved in the review process, including, Aarhus University, ADAS, Agri-Food & Biosciences Institute, Aristotle University of Thessaloniki, BGRM, CLM, Coimbra Polytechnic Agri. School, GEUS, ICPA, Kmetijsko gozdarski zavod Maribor, LWK (Chamber of Agriculture), SEGES, Thünen Institute, University of Ljubljani, University of Lincoln, Wageningen Research, and Wageningen University.

2.1 LITERATURE REVIEW PROCEDURES

Measures to prevent and reduce the risk of surface runoff and leaching can be categorized according to the *source-pathway-receptor* concept, i.e. there are (i) source-based measures, (ii) pathway-based measures, and (iii) receptor or effects-based measures. Examples of source-based measures are appropriated storage of animal manures and fertilizers, balanced fertilization, and prohibition periods for and restrictions on the application of manures and fertilizers. Examples of pathway-based measures are irrigation measures, drainage, buffer strips, green covers, terracing. Examples of receptor or effects-based measures are dredging and, creation of riparian zones, etc.

The review presented in this report focusses mainly on source-based measures and pathway-based measures. At the start, a protocol was written and discussed by all partners involved in the review. The purpose of the protocol was 'to provide guidance for a uniform, effective and efficient literature review and assessment of measures aimed at decreasing pollution of drinking water resources by nitrates'. Two types of reviews were made (i) a qualitative review of measures, practices and factors that affect nitrate pollution of groundwater and surface waters, and (ii) a quantitative review of the effectiveness and efficiency of measures, based on experimental studies in the field.

The qualitative review focussed on the processes and factors that control the pollution of groundwater and surface waters with nitrates from agricultural sources. The results of this review are presented in Chapters 3 to 6. This review yielded also a so called 'longlist' of possible measures to reduce nitrate pollution of groundwater and surface waters. The measures of the longlist were characterized using a common format (Table 2). The longlist of measures are derived from literature review and are presented in Annexes 1 and 2 of this report.

Next, a systematic search was performed through online databases, and a local/expert based search was done throughout Europe. The aim of the local search was to find high quality studies which are not easily accessible through online databases, but which contain valuable data. The criteria used for this search were; (1) well documented (peer reviewed or reports), (2) the article/report should provide the results of one or more experiments to decrease nitrate leaching to groundwater/surface waters, (3) the article/report should present quantitative data of results and statistics to enable a meta-analysis. For the online systematic search online databases were used; CAB-Abstract/Ovid and Web of Science. Query criteria used:

```
(nitrate and (leaching or drain* or "surface water" or groundwater or "ground
water" or runof*) and (mitigat* or measure)  and (effect* or reduct* or
decreas*) and(treatment or "field trial" or experiment))
```

Other options involved excluding of the key "model*" and including the key word "agricult*". The final search yielded 496 results

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(nitrate and (leaching or drain* or "surface water" or groundwater or
"ground water" or runof*) and (mitigat* or measure) and (agricult* or
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farm* or crop* or field*) and (effect* or reduct* or decreas*)
and(treatment or "field trial" or experiment) not (model*))
```

CAB-Abstract/Ovid 121 records
Web of Science 496 records

In addition, University and Institute libraries were examined in Member States of the European Union, also because a significant fraction of the research on measures to reduce nitrate leaching and surface runoff has been conducted before the 1990s and 2000s when it was still common to publish the results in reports and documents. These reports and documents quite often have not been digitalized and made available to the international scientific audience and as such are not traced by the search machines of Google Scholar and Scopus.

Data and results of reviewed reports and articles were collected in Excel spreadsheets in a uniform manner. The Excel spreadsheets were subsequently transferred to a database for statistical analyses (see section 2.1). Annex 3 presents the list of references of the studies that have been examined.

Table 2. Format for the description of measures of the so-called longlist of measures presented in the Annexes 1 and 2.

Name of the measure	Explain the measure in one sentence
Description	Brief characterization of the measure in maximal three sentences; what is (are) the <u>action(s)</u> of the land manager/farmer/citizen
Mode of action	Brief description of the <u>mechanism(s)</u> of the measure in maximal three sentences, addressing the following possible mechanisms: • Reduction / substitution of contaminant input • Modification of pollution pathway • Re-design of the system
Expected effectiveness	Decrease of pollution (concentration or load); select one answer out of five options: • High: >25% decrease in concentration/load • Moderate: 10-25% decrease in concentration/load • Low: 5-10% decrease in concentration/load • Insignificant: <5% decrease in concentration/load • Unknown
Expected implementation cost	Economic cost, in euro per ha of utilized agricultural land; select one answer out of five options: • Low: < 10 euro per ha • Moderate: 10-50 euro per ha • High: 50-100 euro per ha • Very high: >100 euro per ha • Unknown
Underpinning of the measure	Is the measure well examined, as shown by various reports; select one answer out of four options: • Yes (> 5 reports) • Partly (1-5 reports) • No (≤ 1 report) • Unknown
Applicability of the measure	Is the measure widely applicable; select one answer out of four options: • Yes (on more than 75% of the agricultural land) • Partly (on 25-75% of the agricultural land) • No (on <25% of the agricultural land) • Unknown

Name of the measure	Explain the measure in one sentence
Adoptability of the measure	Do the land managers/farmers/citizen adopt the measure easily; select one answer out of four options: • Yes (more than 75% of the addressees) • Partly (on 25-75% of the addressees) • No (on <25% of the addressees) • Unknown
Other benefits	Does the measure contribute to beneficial side-effects; select one or more answers out of four options: • Yes, decreases energy costs • Yes, decreases greenhouse gas emissions • Yes, decreases ammonia emissions • Yes, contributes to landscape diversity • No • Unknown • Other: please specify
Disadvantages (other than implementation costs and labour)	Does the measure contribute to negative side-effects: select one or more answers out of four options: • Yes, decreases crop yield • Yes, decreases crop quality • Yes, decreases soil quality and biodiversity • Yes, contributes to (more) pest and diseases • No • Unknown
References	Provide up to three key literature references

The flowchart below shows the general lay-out of the protocol of the review. Each block represents a set of questions, as described in the Excel spreadsheet and here further below:

(i) Contributor: information on person(s) who did the data collection
(ii) Reference: Two option available, 1) peer reviewed articles, and 2) book or report. This last category includes so-called 'grey literature'.
(iii) Number of measures: the number of measures described in the literature source.
(iv) Pollution type: Nitrate or pesticides or both.
(v) General information: Data about the location, land use, soil type etc. This information is used to categorize and specify the results (and effectiveness of the measure).
(vi) Control treatment: Describe the characteristics of the reference or control situation. This information is essential for estimating the effectiveness and efficiency of the measure(s).
(vii) Measure: Describe briefly the characteristics of the tested measure.
(viii) Effectiveness: Describe the test results, in terms of reduced leaching and/or loading of the pollutant.
(ix) Economic cost: Describe the operational (running) economic cost of the tested measure, in euro per ha per year, compared to the control (reference) treatment.

In the review, common definitions were used, as follows:

Measure: an agro-management technique, or a change in an agro-management technique, applied at field, farm, landscape and/or water basin levels. A measure often involves a plan or action to achieve a particular purpose. Measures may relate to (changes in) crop types, rotations, cover crops, soil tillage and cultivation, fertilization, irrigation, drainage, pest and disease management, weed management, harvesting, machines and trafficking, landscape management, etc.

Effectiveness: The extent to which the objectives have been achieved, i.e., the extent to which the pollution of drinking water resources by nitrates and pesticides have decreased. The effectiveness can be expressed in different units; here we propose to use the decrease in pollutant concentration (mg/l, or µg/l) or pollutant load (kg/ha/year or g/ha/yr), depending on the results available in the literature source.[1]

Efficiency: The extent to which the desired effects are achieved per unit of cost. The term refers also to "cost effectiveness", which is expressed as ratio of the effect achieved and the costs required (e.g. mg nitrate per litre per euro or µg pesticides per litre per euro).

Applicability: Applicability is the extent to which a measure can be implemented in practice (without the special provisions that can be made during a research or experiment). Applicability is expressed in the percentage of the area where the measure can be implemented in practice without much difficulty.

Willingness (or adaptability): the extent to which stakeholders implement the measures without additional incentives and, if necessary, maintain the extra facilities that have to be taken. Willingness is expressed in the percentage of stakeholders who implemented the measure(s) without external incentives.

The literature review was divided among the FAIRWAY partners involved, according to regions. Five regions have been distinguished, as follows:
Central EU: Czech, Slovakia, Hungary, Romania, Bulgaria, Slovenia, Croatia, Bosnia, Serbia
Central – northern EU: Poland, Germany, Austria, Switzerland, Baltic States
Mediterranean: Andorra, Portugal, Spain, Italy, Greece,
Scandinavia: Denmark, Norway, Sweden, Finland, Iceland
Western Europe: Ireland, United Kingdom, Netherlands, Belgium, France
The world outside EU: America, Australia, Asia

2.1. Quantitative analysis of the effect size of measures

The results discussed in this report are based on literature study and statistical analyses. There are roughly three approaches to express the effects of measures.

The first approach applied in this report through simple response ratios, which is the nitrate leaching loss from a treatment measure divided by the nitrate leaching loss of the reference treatment (control treatment), according to

$$RR = Y_T/Y_C$$

where RR is the response ratio (dimensionless; or percentage), Y_T is the measured result (expressed in terms of nitrate concentration in groundwater or surface waters, or in terms of soil mineral N, or N surplus) of the treatment measure, and Y_C is the measured result of the reference treatment or control treatment. The latter is usually current practice or conventional practice. The ratio may vary from 0 to more than 1; a value smaller than 1 indicates that the treatment measure decreases the nitrate leaching loss relative to the reference treatment. A ratio of 1 means no effect.

[1] Effectiveness is also interpreted in terms of bridging the gap between actual concentration (or load) and target concentration (or load). However, here we prefer the first mentioned notation and units, also to allow a uniform statistical analysis

Instead of a relative comparison of nitrate leaching loss, the response ratio was sometimes derived from a comparison of nitrate concentration in waterbodies or from the amounts of soil mineral N in the soil between treatments, depending on the availability of the data in the reviewed publications.

A second approach is to express the effectiveness in terms of relative effects, i.e., the ratio of the treatment measures, corrected for the reference treatment, and the reference treatment according to

$$ES = \frac{Y_T - Y_C}{Y_C} = \frac{Y_T}{Y_C} - 1$$

where *ES* is the effect size (dimensionless; or percentage). In case a treatment measure does not result in a (significant) different outcome than the reference treatment, then $ES = 0$. For $Y_T > Y_C$ this results in $ES > 0$, and vice-versa.

A third approach is the one used in most meta-analyses studies; the means and standard deviations of the effects are determined based on ln-transformed ratio's (following the protocol of Hedges et al (1999) as given by

$$L = \ln\left[\frac{Y_T}{Y_C}\right]$$

Once the ln-transformed average ratio (and standard deviation) are known, it can be back-transformed to obtain the average effect size according to

$$ES_{avg} = \exp\left[L_{avg}\right] - 1$$

Similarly the confidence interval for *ES* can be determined by back-transforming the confidence interval limits for *L*. The reported average *ES* is significant when the available confidence interval (based on standard deviation) does not include the value zero. Formal meta-analysis studies often are based on the ln-transformed approach, whereas single studies and some reviews mostly consider the effect size or the response ratio RR=Y_T/Y_C.

In this report, we estimated and used RR (see chapter 7), because it is the most straightforward expression of the response of a measure. The data as collected through the structured data review from the Excel sheets was processed in the statistical software programme R, following a careful check of all data manually, so as to obtain a good quality and uniform database. Main focus during the processing was on homogenizing units of measurement and setting the right reference treatment. This was done to optimize the calculation of the response ratio for each treatment in each study.

The collected data was divided in categories based on the already identified measures in the shortlist. For each category of measures the reference was defined and this was applied to all individual treatments, in this way the uniformity between studies was optimized.

As general analysis the response ratios for each study within a category were combined and a summery effect ratio was calculated for each measure. In the case of input control there was a clear relation between effectiveness and amount of reduction, so a linear regression was applied to study the relation. However further analysis of co variables and the fitting of a random effect model will be done as next step in this research to identify the most promising measure included in the database.

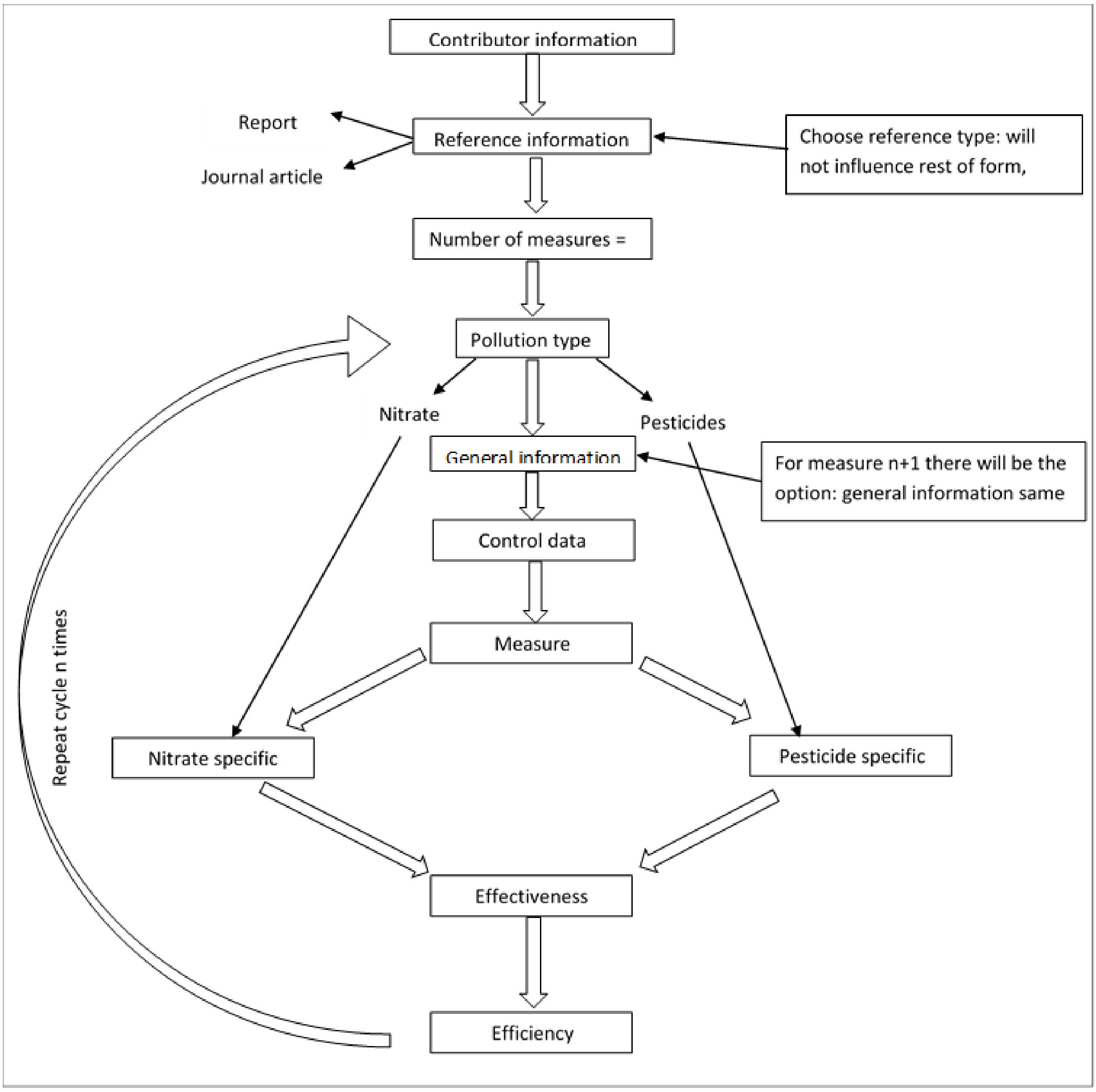

Figure 1. Flowchart of the quantitative literature review of measures to reduce nitrate leaching (this report) and measures to review pesticide leaching (reported in the related report by Commelin et al., 2018).

3. THE NITROGEN CYCLE AND NITROGEN TRANSFORMATION PROCESSES

This chapter presents a brief overview of the global nitrogen cycle and of the nitrogen transformation processes. Nitrogen cycling and transformations are influenced by a range of processes and factors, which in the end influence both the production and transport of nitrate and thereby the pollution of groundwater and surface waters by nitrates. Nitrogen cycling is strongly associated with carbon cycling and with the cycling of water and other nutrients. Figure 2 presents an illustration of the nitrogen cycle of soil-plant systems. It shows how nitrate (NO_3^-) leaching is connected to a range of nitrogen pools and transformation processes, which ultimately affect the magnitude of nitrate leaching. In addition, N leaching losses may occur via dissolved organic N (DON), and also as ammonium (NH_4^+) in sandy and volcanic soils (Addiscott et al., 1991; Burt et al., 1993; Hatfield and Follett, 2008).

Understanding the sources, pools and transformation processes, as well as the factors that influence the sources, pools and transformation processes is needed for evaluating the effectiveness of measures to decrease nitrate leaching.

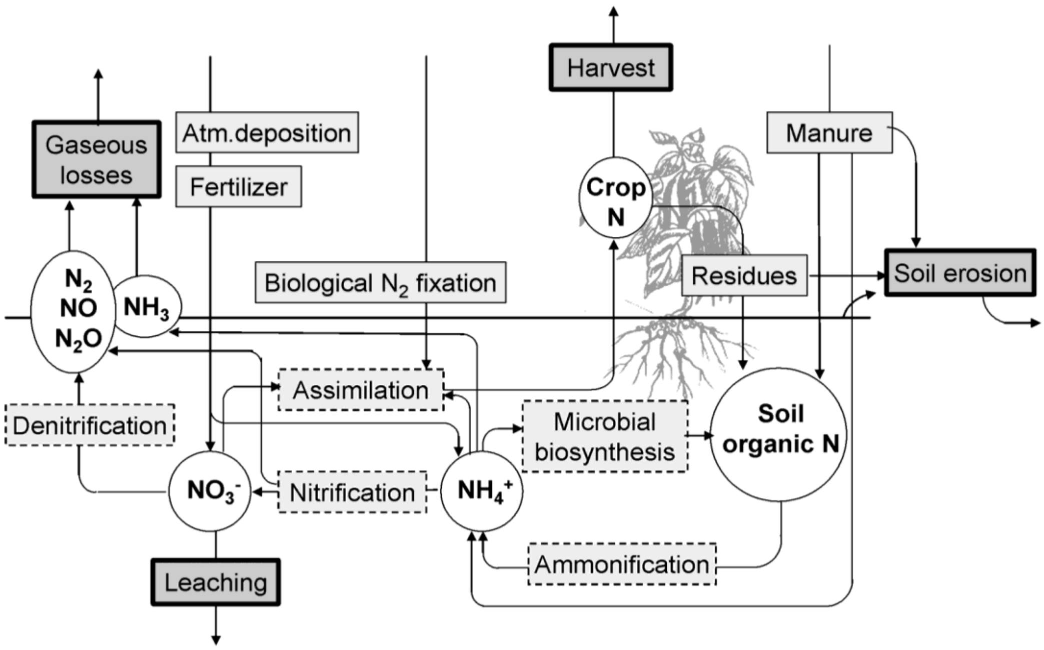

Figure 2. Nitrogen cycle in soil-plant systems. Circles indicate pools, boxes with dashed lines are processes, light-grey boxes with solid lines are inputs, and dark-grey boxes with bold lines represent outputs (Source: Bouwman et al., 2009).

3.1 NITROGEN CYCLING AND TRANSFORMATION PROCESSES

Nitrogen (N) occurs in different forms and transforms from one form into the other almost endlessly (Figure 3). Molecular nitrogen (N_2) is the dominant constituent of the atmosphere and the most abundant N form on earth (Galloway et al., 2003; 2004. Only a few microorganisms have the capability to utilize (fix) N_2, converting it to organically bound N. The Haber-Bosch process converts N_2 into ammonia/ammonium (NH_3/NH_4^+) in a physical-chemical manner (Smil, 2001). The NH_3/NH_4^+ can be taken up by plants (assimilation). Following the senescence of plants and organisms, the organic-N is transformed again into NH_3/NH_4^+ (through mineralization). Autotrophic bacteria can utilize the energy contained in NH_3/NH_4^+ through nitrification. Thereby, the oxidation status increases from -3 in NH_3/NH_4^+ to +5 in nitrate (NO_3^-). The NO_3^- can be taken up by plants (assimilation) or it is denitrified to nitrous oxide (N_2O) and to di-nitrogen (N_2) in anaerobic environments through heterotrophic bacteria or it can be leached to water bodies. Molecular N (N_2) may be formed also through anaerobic ammonium oxidation (anammox; $NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O$), by chemoautotrophic bacteria (Galloway et al., 2008).

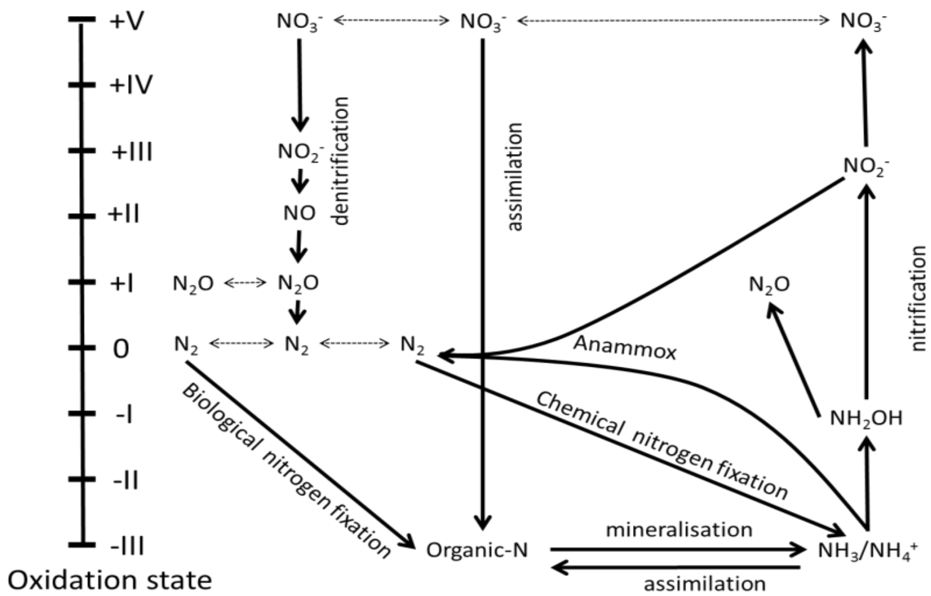

Figure 3. Processes of the N cycle and the related changes in the oxidation status of the N forms. The oxidation status (vertical axis) ranges from +5 in nitrate (NO_3^-) to +3 in nitrite (NO_2^-), to +2 in nitrogen oxide (NO), to +1 in nitrous oxide (N_2O), to 0 in di-nitrogen (N_2), and -3 in ammonia (NH_3), ammonium (NH_4^+) and amines (C-NH_2). The N forms NH_3, N_2, N_2O, NO, NO_X are gaseous at temperature at the earth surface; the N forms NO_3^- and NH_4^+ and some organic N forms (DON) are readily soluble in water. This makes N 'double mobile' (Smil, 2001).

A distinction is often made between reactive and non-reactive N. Reactive N (Nr) includes all forms of nitrogen that are biologically, photochemically, and radiatively active. Forms of nitrogen that are reactive include ammonia (NH_3), ammonium (NH_4^+), amines (and other metabolizable organically bound N), nitrous oxide (N_2O), nitrogen oxide (NO), nitrite (NO_2^-), and nitrate (NO_3^-).These forms are all involved in short-term cycling in the biosphere. Reactive forms of nitrogen support plant growth directly or indirectly and are capable of cascading through the environment and have impact through smog, acid rain, eutrophication, biodiversity loss, etc. Dominant forms of non-reactive N is N_2, which makes up about 80% of the atmosphere, and the N locked-up in deep sediments and rock. These N forms do not contribute directly to environmental impacts (Galloway et al., 2008; Sutton et al., 2011; Fowler et al., 2013).

Figure 4 presents a quantitative picture of the global N cycle. The atmosphere, sediments and terrestrial rock have the largest pools of N, but this N is largely 'non-reactive'. Large amounts of N cycle between atmosphere, terrestrial biosphere (agriculture and the urban and natural environments) and the marine biospheres (oceans, lakes). The cycling of N is related to the reactivity and mobility of the different N forms (Figure 3) and the presence of energy sources for transport. Sunlight fuels photosynthesis, the hydrological cycle (evapotranspiration) and wind and water currents (in combination with gravitational energy and internal particle energy). Natural gravity and the internal energy of particles govern the earth motion (seasonal and diurnal cycles), the physical interaction between elementary particles, including diffusion, and the physical transport of particles. The heat (energy) in the core of the earth governs tectonic uplift and volcanic activity (Smil, 2017). Humans have strongly influence the N cycle during the last few centuries, especially from the 1950s, with the help of fossil energy sources and technological developments (Smil, 2000).

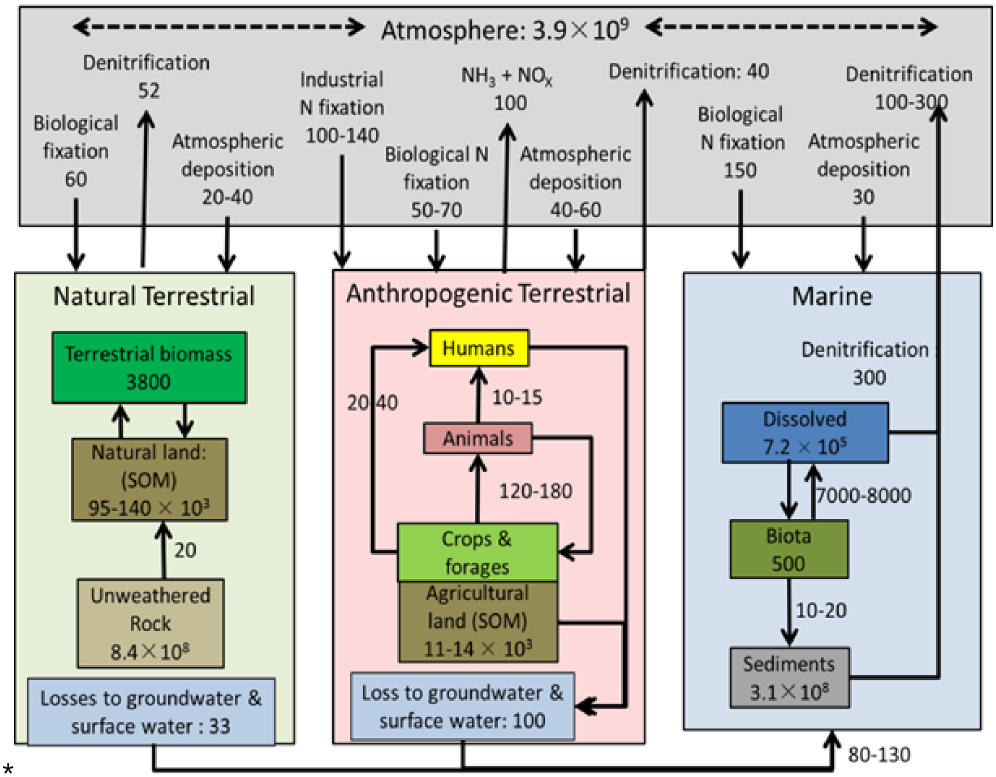

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Figure 4. Global nitrogen cycle, showing the dominant flows of N between atmosphere and the natural terrestrial area, the anthropogenic area (agricultural + industrial + urban), and the marine area. Arrows indicate the approximate size of the N flows, in Tg N per yr. Numbers in boxes refer to the size of the N pool of that compartment, in Tg N. Note that the transport of N from anthropogenic sources to the natural terrestrial and marine areas occurs mainly via the atmosphere and rivers. The magnitude of some flows are rather uncertain. Compilation of data from Smil (2001), Fowler et al (2013), Schlesinger and Bernhardt (2013).

The global N cycle is strongly influenced by anthropogenic activities. The changes in human diets towards more animal-derived protein have increased the total amount of N needed (to deliver the food of one person) to more than 100 kg per person per year in Europe (Smil 2013; Westhoek et al 2014). More than half of the food eaten by humans is produced now using N fertilizer from the Haber-Bosch process (Smil 2001; Erisman et al 2008). The industrial N_2 fixation is now as large as or larger than the biological N_2 fixation in the terrestrial system. In addition, large-scale deforestation and soil cultivation have increasingly mobilized N from the soil organic N pools, which have subsequently contributed to the increased N losses from the terrestrial system to the aquatic/marine system and to the atmosphere (Galloway et al 2008).

3.2 NITROGEN USE AND LOSSES IN AGRICULTURE

Nitrogen is needed in food and feed production in relatively large quantities for the production of amino acids (protein), nucleic acids and chlorophyll in plants. That is why farmers apply manures, composts and N fertilizers, to boost crop production. Synthetic N fertilizers became available and affordable in affluent countries from the 1950s and more recently in almost all countries (Smil, 2000). The availability of N in agriculture increased during the last 100 years also through the increased production of leguminous crops (beans, pulses, clover and alfalfa) that fix N_2 biologically, through energy combustion that increases in NOx emissions and N deposition, and through the increased production of animal manures, and residues and wastes from industries and households (Herridge et al., 2008; Davidson, 2009; Sutton et al., 2013).

The N cycle in agriculture has been characterized as a leaky N cycle, because of the many opportunities of N molecules to escape (Figure 5). Nitrogen enters agriculture either via synthetic fertilizers, biological N_2 fixation or atmospheric deposition. In addition, there is recycled N within the agricultural system, in the form of animal manure, compost, crop residues and mineralization of soil organic matter. Nitrogen leaves the system via harvested crop and animal products and via losses of various N forms to air and water (Figure 5).

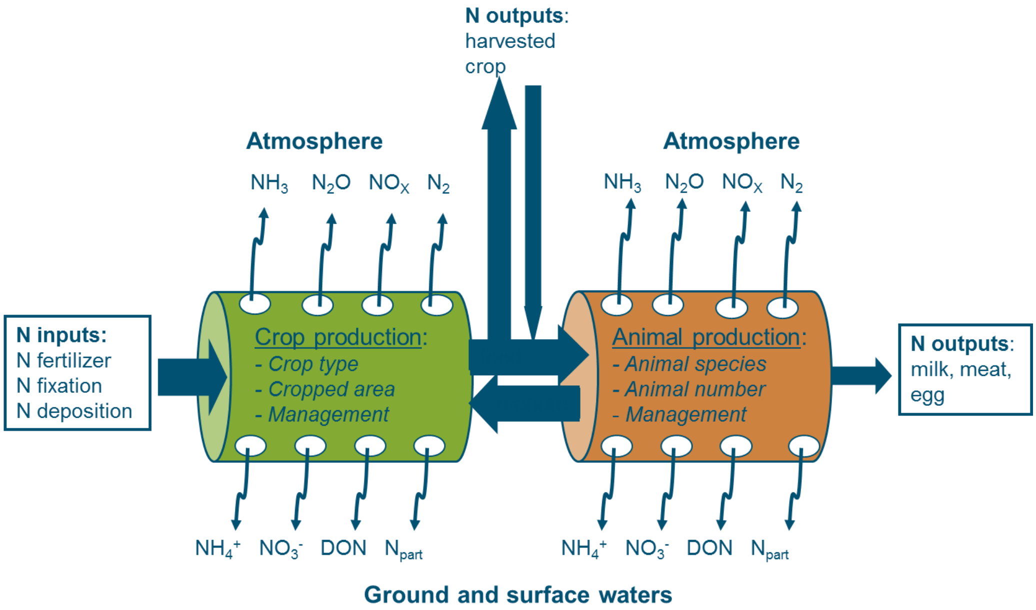


Figure 5. The leaky N cycle in agriculture, illustrated through the 'hole-in-the-pipe' concept. "New" N enters agriculture via N fertilizers, biological N2 fixation and atmospheric deposition. In addition, there is internal recycling of N via animal manures and crop residues. Nitrogen leaves agriculture in harvested crop and animal products, and via gaseous N losses to the atmosphere and dissolved and particulate N forms to groundwater and surface waters via leaching, overland flow and erosion (Oenema et al., 2009).

The increased availability of N in agriculture has increased the losses of N to air and water bodies (Figure 5). Emissions of N to the wider environment occur via various N forms (NH_4^+, NH_3, N_2, N_2O, NO, NO_2^-, NO_3^-), which can lead to problems related to human health and ecosystem degradation. The volatilization of ammonia (NH_3), leaching of nitrate (NO_3^-), and the emissions of di-nitrogen (N_2), nitrous oxide (N_2O) and nitrogen oxide (NO) following nitrification-denitrification reactions are the main N loss pathways from agricultural systems and food systems. Possible human health and environmental effects of this reactive N include a decrease of human health, due to NH_3 and NO_x induced formation of particle matter ($PM_{2.5}$) and smog, plant damage through NH_3 and through NO_x induced tropospheric ozone formation; a decrease of species diversity in natural areas due to deposition of NH_3 and NO_x; acidification of soils because of deposition of NH_3 and NO_x; pollution of groundwater and drinking water due to nitrate leaching; eutrophication of surface waters, leading to algal blooms and a decrease in species diversity; global warming because of emission of N_2O; and stratospheric ozone destruction due to N_2O (Sutton et al., 2011).

3.3 Nitrogen use and losses in EU-agriculture

Fertilizer N use in Europe increased rapidly between 1950 and 1990, but stabilized thereafter at a level of about 10-11 Tg per year (Figure 6; Erisman et al., 2008; Sutton et al., 2011; Sutton et al., 2013). For comparison, the use of phosphorus (P) and potassium (K) fertilizer use are also shown in Figure 6; these are the most important nutrients next to N. Global N fertilizer use has increased from about 10 Tg in 1961 to almost 110 Tg in 2012, but there are large differences between continents. Fertilizer N use in Africa is staggering at a level of about 1-2 Tg per year during the last decade, while fertilizer N use in Asia has rapidly increased during last three decades by on average 2 Tg per year (not shown). The rapid decrease in European N use around 1990 is mainly related to the political restructuring of Eastern and Central Europe at this time. The slow decrease in fertilizer use in Europe between 1990-2010 is mainly related to EU agri-environmental policy. The rapid increase in N fertilizer use between 1950s and mid-1980s, concomitant with the rapid intensification of livestock production in EU in this period are at the base of the nitrate problems in groundwater and surface waters in EU. The total amounts of N in manure produced (~10 Tg/yr) were roughly similar to the annual use of fertilizer N (~11 Tg/yr) in the EU during the last 10 years or so. In addition, there were inputs via biological N_2 fixation (about 1 Tg/yr) and atmospheric deposition (2 to 3 Tg/yr) (De Vries et al., 2011).

About 50 to 60% of the total N input to crop land via animal manure, fertilizer, biological N_2 fixation and atmospheric deposition is recovered in harvest crop in the EU. The remainder is lost from the crop land to the wider environment via ammonia volatilization, denitrification, leaching, overland flow and erosion. The losses to the environment in the EU are not well-known; the estimated total leaching losses, denitrification, and surface run-off differ by a factor of two between studies. Estimated N inputs to groundwater and surface waters range from 2.7 to 6.1 Tg in 2000 (De Vries et al., 2011).

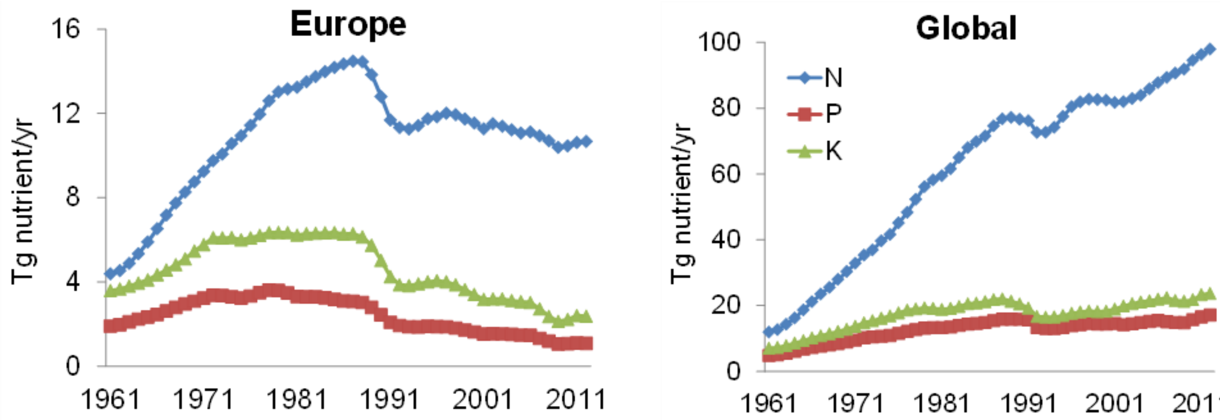


Figure 6 *Consumption of nitrogen (N), phosphorus (P), and potassium (K) fertilizers in Europe (left panel) and the world (right panel) between 1961-2012. Note the differences in Y-axis. Data source: FAOSTAT. (1 Tg = 1 million ton = 10^{12} gram)*

Figure 7 shows the spatial distribution of N losses from terrestrial systems to the aquatic system (groundwater, rivers, lakes and seas) in the EU-27 for the year 2002. The pie diagram at the right side shows the split of the various N sources for the aquatic system. The contribution from agriculture is nearly 60%. Sewage systems contribute 22%. Minor inputs are from atmospheric deposition (mainly from agriculture and industry) and natural systems. The bar diagram at the right side shows which countries contribute most N into the aquatic system. Clearly, the loss of N (nitrate, NO_3^-) originates from many different sources, which are diffusely spread across EU-27, with the exception of the sparsely populated northern parts of Scandinavia and Scotland. Within this huge spatial variability various hot spots can be found, notably in Western Europe. The estimations shown in Figure 7 have not been checked and corrected by estimations at national scales by experts from Member States.

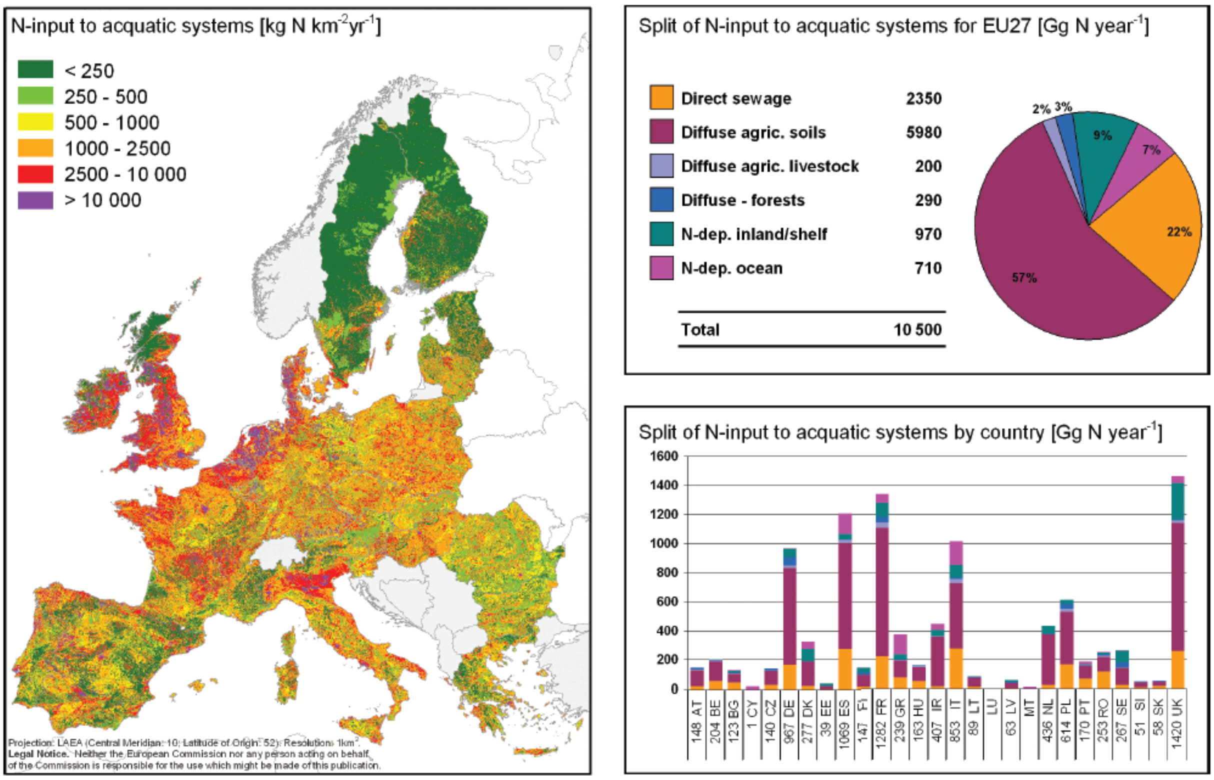


Figure 7. Spatial distribution of N losses from terrestrial systems to the aquatic system (groundwater, rivers, lakes and seas) in the EU-27 for the year 2002. The pie diagram at the right side shows the N sources and the bar diagram shows the contributions of the member states in 2002. The map, pie and bar diagrams are based on various data sources and model calculations (Leip et al., 2011).

4. AGRICULTURE IN EU-28 AND THE USE OF NITROGEN

Agriculture is a main source of nitrate pollution of the aquatic system (Figure 7, chapter 3). That is related to the facts that (i) agricultural land covers roughly 40% of the total land area of EU-28, equivalent to 174 million ha in 2013, (ii) agriculture is a large user of nitrogen (N) for producing food and feed, and (iii) on average only 50 to 60% of the applied N is taken up by the crop and withdrawn in harvested crop yield. The remainder is lost to the atmosphere via ammonia volatilization and denitrification or to lost water bodies via leaching and surface runoff. The loss of nitrate-N from agriculture to groundwater and surface waters depends on farming system, management, soil type and geomorphology, and climate. These factors define both (i) the sources of nitrate pollution and (ii) the loss pathways (e.g., downward leaching to groundwater or overland flow (surface run-off), erosion, and subsoil lateral leaching to surface waters (Leip et al., 2011).

This chapter provides a brief overview of the sources of nitrate pollution in agriculture. First, a summary of farming systems and of management in EU-28 is presented, as these define the input and the utilization of nitrogen in agriculture. Secondly, an brief overview is presented of the N input-output balance, as the balance is an indicator of the potential for N pollution of water resources (Klages et al., 2018).

4.1 FARMING SYSTEMS

About 60% of the utilized agricultural area in the EU-28 in 2013 was classified as arable land, 34% as grassland and 6% as permanent cropland (orchards, vineyards). These areas are managed by some 10 million farms, which are mostly family farms. Basically, each farm is managed in a unique manner (Eurostat, 2015).

There is a huge variation in farming systems, because of differences in their resource basis, enterprise pattern, crops, animals, management and also the use of nitrogen. A first characterization is commonly made between (i) specialized crop production systems, (ii) specialized animal production systems, and (iii) mixed production systems. Eurostat (2015a) distinguishes 8 main farm types (Table 3)[2], which reflect the aforementioned three categories, and three main classes of land use.

Table 3. Agricultural holdings by farm type in EU-28 in 2013 (Eurostat, 2015a)

Code	Farm type	Number of holdings in EU-28 (millions)	Number of holdings in EU-28 (%)
1	Specialist field crops	3.20	29.6
2	Specialist horticulture	0.21	1.9
3	Specialist permanent crops	1.89	17.4
4	Specialist grazing livestock	1.86	17.1
5	Specialist granivores[1]	1.02	9.4
6	Mixed livestock	0.48	4.4
6	Mixed cropping	0.52	4.8
7	Mix crop-livestock[2]	1.50	13.8
8	Other	0.16	1.5
	Total	10.84	100.0

[1]) *Granivorous literally means ‘feeding on grains and seeds’. In practices it means farms with monogastric animals, mainly pigs and poultry, where often a significant fraction of the feed is imported.*
[2]) *Mixed crop-livestock holding have neither livestock nor crop production as dominant activity; an activity is called dominant if it provides at least two-thirds of the production of an agricultural holding.*

[2] There were 10.84 million holdings in EU-28 in 2013. A total of 1.6% had no land, 43% <2 ha, 33% 2-10 ha, 15% 10-50 ha, 3.6% 50-100 ha and 3.1% had >100 ha. The number of small farms is decreasing over time.

Anderson et al (2016) developed a farm typology for EU agriculture on the basis of:

- Specialisation: Measured as the output value from the main activity; 10 farm specialization types.
- Size: Measured as the economic size of the farms; 3 classes: <16; 16-40; >40 ESU[3]
- Intensity: Measured as the total output in Euro per ha; 3 classes: <500; 500-3000; >3000 euro/ha
- Land use: Measured as the proportion of the agricultural area covered by specific types of crops; 9 different land use types were distinguished.

The farm typology of Anderson (2006) is a useful framework for characterizing farm types, as farm size, intensity, specialization and land use are all important determinants for N use. The farm typology does however not address the level of externalization of feed use in animal production farms in sufficient detail. A large fraction of animal farms do purchase animal feed from elsewhere, which affects N inputs, N output and N surplus of the farm. The level of externalization can be defined as the percentage of the feed (in dry weight) used on the farm that is imported from elsewhere (Table 4).

Table 4. Characterization of farms in EU-28

Nr	Characteristics	Unit of characterisation
1	Specialisation	Specialization type, and output derived from the main activity, in %; The 10 dominant specialized farm types are: (i)arable farms, (ii) horticultural farms, (iii) permanent crops, (iv) dairy farms, (v) beef farms, (vi) pig farms, (vii) poultry farms, (viii) sheep and goat, (ix) mixed livestock, (x) mixed farms
2	Land use	Crop rotation and crop types, in %
3	Size	Value of output, in European Size Units (ESU), and UAA, in ha
4	Intensity	Value of output, in Euro per ha
5	Externalization	Purchased feed, in % of total feed

4.2 CHARACTERIZATION OF MANAGEMENT

The importance of individual farmer decisions on nitrogen flows and balances are large; much depends upon the skill and precision with which farmers decide on the acceptable level of risk associated with each farm operation to determine nutrient application/management regimes (Jarvis et al., 2011). Farmers have multiple roles: they are managers and risk takers. And their skills determine the level of risk they are prepared to take to achieve financial gain and/or environmental benefit. However, the majority of farmers are businessmen and women, and many are entrepreneurs, whose primary aim is to optimize their production system to the benefit of themselves and perhaps of society as well. As a result, there is a wide variation in N input and N utilization (Jarvis et al., 2011; Stoumann Jensen et al., 2011).

Management is often considered to be the most important factor for the performance of the farm and of the utilization and losses of N. Management is usually defined as ‘a set of activities to achieve objectives’. It includes a sequence (cycle) of (i) analysis of the current situation and of possible options, (ii) decision making, (iii) planning of the activities, (iv) execution, (v) monitoring,

[3] ESU is European Size Units (ESU), where 1 ESU corresponds to 1,200 Euro. It refers to the value of output from the farm less the cost of variable inputs required to produce that output, based on 3 years averages.

and (vi) verification and control of achievements. These management activities relate to different components of the farm.

Crop management includes:

(i) crop rotation aspects, i.e. crop sequence, use of cover crops and under growth, use of legumes, use of buffer zones. Crop rotations define both N input and N output in harvested crop. The crop statistics of Eurostat distinguishes 17 categories for cereals and 29 for other main crops, 40 categories for vegetables, 41 for permanent crops.

(ii) soil cultivation aspects, i.e., conventional (mouldboard) ploughing or minimum tillage or zero tillage. Soil cultivation affects the amounts of N that are released through net soil mineralization.

(iii) nutrient management, i.e., use of soil fertility analyses, organic farming, use of animal manures without low emission techniques, use of animal manures with low-emission techniques, use of fertilizers, use of GPS controlled fertilizer application. All these factors influence N input as well as N utilization at farm level

(iv) pest management, i.e., use of chemical control and/or biological control measures. This factor greatly influences crop yield and thereby the N output and the overall N balance

(v) irrigation and drainage aspects, i.e., no irrigation, sprinkler irrigation, flood irrigation, drip irrigation and/or fertigation. These factors influence both crop yield and N output as well as the nitrate leaching losses.

Livestock management includes:

(i) Animal categories, i.e., Dairy cattle – beef cattle – pigs – poultry – sheep – goats. These categories greatly differ in protein-N requirements, N retention and N excretion.

(ii) Herd related aspects, i.e. number of dairy cattle, replacement heifers, calves for replacement, number of fattening and suckling cattle, number of sows and fattening pigs, number of broilers and laying hens; The ratio between productive and supporting animals influence greatly the N utilization efficiency per unit of animal product produced

(iii) Feeding management, i.e., number of grazing days per year, kg of concentrate per dairy cow, percent protein in animal feed. This influences the N utilization efficiency per unit of animal product

(iv) Animal performance, i.e., milk production per cow per year (kg), calving interval (days), number of piglets per sow, feed conversion (kg feed per kg pork; kg feed per kg broiler; kg feed per kg egg); Again, this influences the N utilization efficiency per unit of animal product.

(v) Animal health management, i.e., veterinary cost, in % of total costs. This again influences the N utilization efficiency per unit of animal product

(vi) Manure management, i.e., solid manure or slurry, covered manure storages, manure export; m^3 per year, low-emission manure application. This affects the N losses from manure and manure storages and the effectiveness of manure N as N fertilizer. Animal manure is a main source of N in EU-28, which is used to fertilize cropland and grassland but att he same time is a main source of nitrate pollution of groundwater and surface waters (Oenema et al., 2007).

The management of crop and livestock farms can be captured by the N balance. Table 5 presents the input and output items for the farm N balance. These data allow to be estimated N use efficiency (NUE) and N surplus at farm level, for basically all farm types. Input and output items have to be reported only once on the balance. In the case that animals are imported to the farm and other animals are exported, only the net results should be presented, i.e., on the right-hand side of the balance[4]. Similarly, in the case that animal manure is imported to the farm and other manure exported, only the net manure N input should be reported, as input (Table 5). Hence, manure is seen as an input (and not as a harvested output). Reporting the inputs and outputs on the proper side of the balance is important, as it allows a better comparison between farms.

Table 5. Input and output items considered for the farm N balance

Nitrogen input items		**Nitrogen output items**	
Mineral fertilizers	I1	Crop products	O1
Feed and fodder (net)	I2	Animals (net)	O2
Biological nitrogen fixation	I3	Animal products (milk, egg, wool)	O3
Atmospheric N deposition	I4	(orchard) trees (net)	O4
Compost and sewage sludge	I5		
Seed and planting material	I6		
Bedding material (straw, saw dust)	I7		
Animal manure (net)	I8		
Irrigation water	I9	Surplus	∑I-∑O
Total	sum	Total	sum

The soil is a main store of N, especially the top soil (plough layer). A small percentage of the total amount of N in soil (2000 to 10000 kg ha^{-1}) is in the form of ammonium and nitrate and directly available to plants. Most of the N is stored in soil organic matter and not directly available to plants. Changes in soil organic N are common following changes in crop rotation and especially following the conversion of permanent grassland to arable land and vice versa. Changes are also common following changes in manuring and fertilization, changes in soil cultivation practices, and changes in weather conditions (mean temperature, rainfall). These changes can have a large effect on nitrate leaching losses.

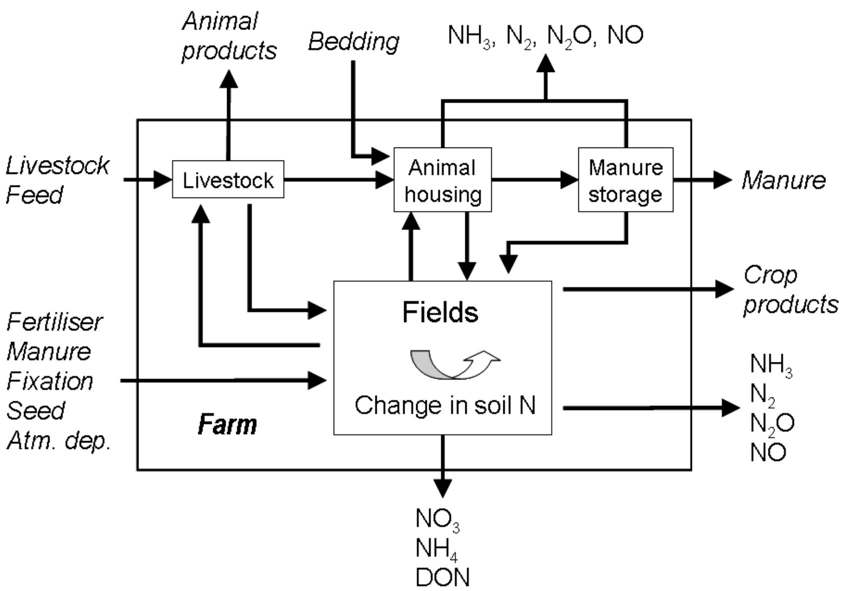


Figure 8. Schematic diagram of annual nitrogen flows on a mixed crop-animal farm. Main inputs are listed on the left-hand side of the system Outputs in the form on crop and animal products and N losses are shown at the left-hand side and at the top and bottom (after Jarvis et al., 2011).

[4] Evidently, the calculation should be made animal-specific, using animal-specific N content

The main inputs to the farm are via mineral fertiliser, imported animal manure, fixation of atmospheric nitrogen by leguminous crops (beans, pulses, clover, alfalfa), N deposition from the atmosphere, and import of livestock feed (Table 5; Figure 7). Inputs in seed and bedding used for animals are generally minor inputs, although the latter can be significant for some traditional animal husbandry systems. The main outputs from the farm are in crop and animal products. The main N flows within mixed crop-livestock farms are the consumption of feed by livestock, the return of nitrogen to the field in the excreta of grazing animals, and the removal of manure from manure storages to the field.

Farms differ greatly in the relationship between total N input, N output and the resulting NUE and N surplus. For intensively managed grassland-based dairy farms N surpluses may range from 80 to 300 kg per ha per year (Figure 9). For arable farms, N surpluses are usually in the range 0 to 100 kg per ha year. This wide variation is related to differences in farming systems (Chapters 4.1) and management (Chapter 4.2). It is also related to interactions between crop, soil and climate, which affect N demand (because of differences in crop yield) and soil N supply (because of differences in net soil N mineralisation).

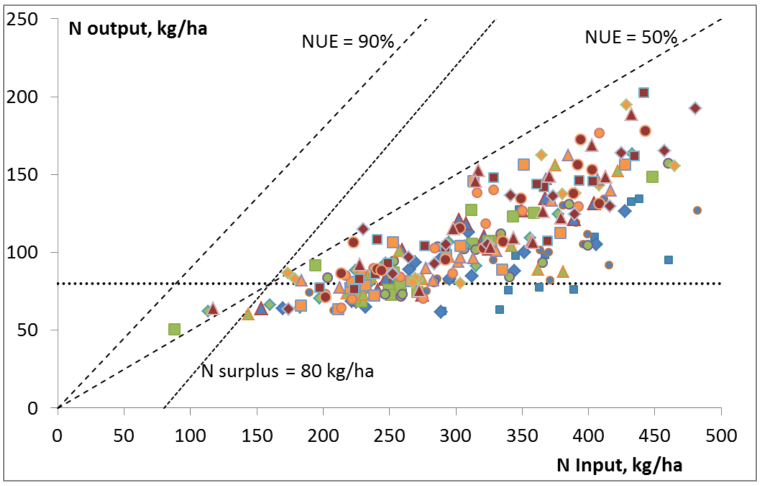


Figure 9. Relationship between total N input via N fertilizer, purchased animal feed, biological N_2 fixation by clover, and atmospheric N deposition, and total N output via sales of milk and cattle on 16 specialized dairy farms in The Netherlands. Different symbols indicate different years; blue symbols 1998-2001; green symbols 2001-2005; orange symbols 2006-2009; and purple-brown symbols 2010-2013 (after Oenema, 2013).

Figure 10 shows response curves of wheat and barley yields to N applications for different sites and years in the UK. There were huge differences in economic optimal fertilizer application rates, which are almost impossible to assess by the farmer at the start of the growing season. As farmers benefit more from high yields than from low yields, there is a tendency that farmers fertilize for high yields. This is one of the reasons that NUE is relatively low in years when yields are low and that N losses are relatively high in these years. Table 6 shows the average and the ranges of the fertilizer N use for main crops in EU-27. Evidently, the minimum and maximum N input differ by a factor or 3 to 4 between farms.

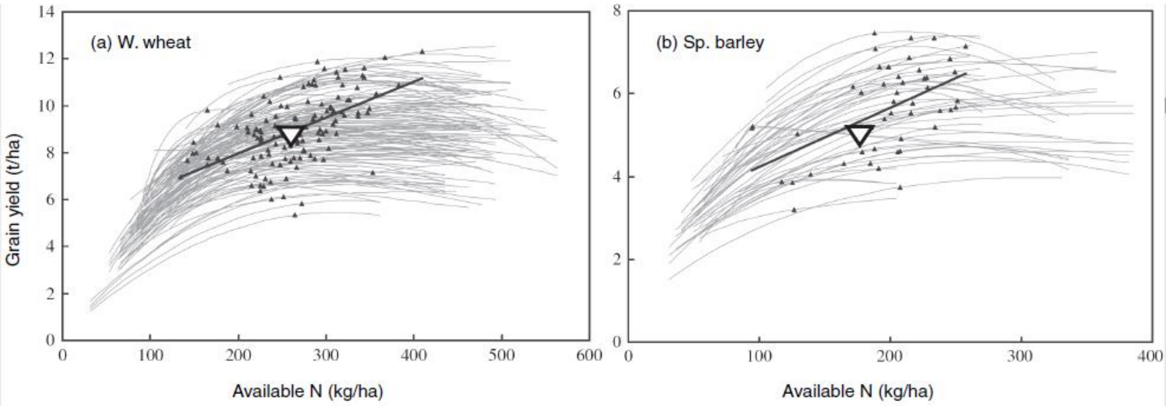


Figure 10 Fitted responses of grain yield to available N in the soil for (a) winter wheat (129 response curves) and (b) spring barley (47 response curves) from different combinations of season, site, and cultivar in the UK. Economic N optima (at fertilizer N:grain price ratio = 5) for each response curve are indicated by small triangles, mean of all economic optima with large triangle (Sylvester-Bradley and Kindred, 2009 in Stoumann Jensen and Schjoerring, 2011).

Table 6 *Average annual, minimum, maximum fertilizer N-use for main European crops in EU-27 (Stoumann Jensen and Schjoerring, 2011)*

Crop	Average (kg/ha)	Range (min-max) kg/ha	Crop area million ha
Oilseed rape	148	50-195	6.1
Sugar beet	123	50-160	1.9
Wheat	113	25-200	25.9
Grain Maize	106	26-200	9.0
Potato	98	40-185	2.2
Barley	88	15-145	13.9
Grassland	69	10-170	30.5
Silage Maize	65	10-126	4.7
Rye, triticale, oats, rice	64	10-110	8.7

Summarizing, total N use at farm level mainly depends on farming system and management. The potential for N losses depend on the difference (N surplus) between total N input and total N output, both of which greatly vary between farms and across EU-28 (Figure 11). The surplus of N in agriculture is highest in western Europe. Main N sources are N fertilizers and animal manures, while soils may also act as a N source following ploughing-up grassland and changes in soil cultivation (not shown in Figure 10). In addition, there are N inputs via biological N_2 fixation and atmospheric deposition. The estimations shown in Figure 11 have not been checked and corrected by estimations at national scales by experts from Member States.

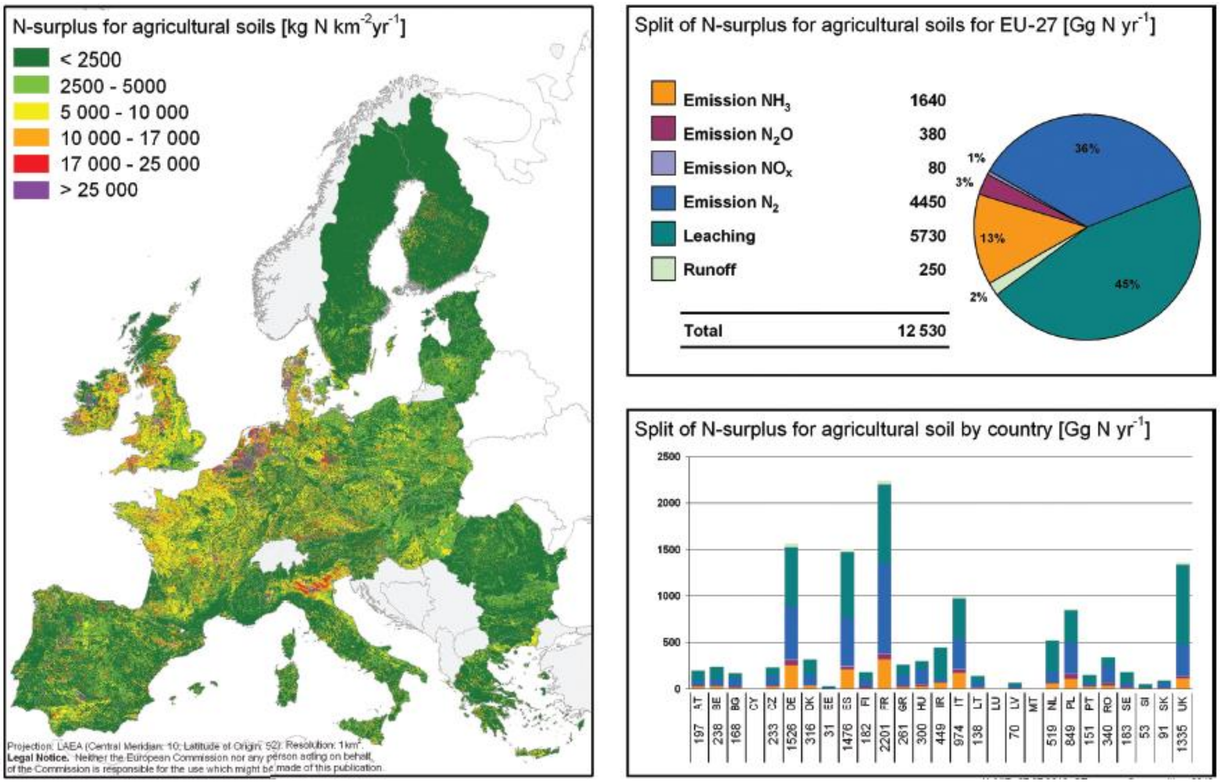


Figure 11. Nitrogen surplus of agricultural land in EU-27 for the year 2002, in kg per km^2 per yr (which is equivalent to 100 kg per ha per yr). The pie diagram at the right side gives the partitioning of the N surplus into different N losses, in Gg N year for EU-27, for the loss pathways: NH_3 emissions, NO_x emissions, N_2O emissions, N_2 emissions, N leaching and runoff. The histogram shows the split of the N surplus in Gg N per yr by country (Leip et al., 2011).

5. PROCESSES AND FACTORS THAT TRANSFER NITRATES TO DRINKING WATER RESOURCES

Most of the drinking water used in EU originates from groundwater (66%) followed by surface waters (30%) (Figure 12). The use of groundwater is dominant in Germany, France, Spain, Italy, Denmark, Belgium, The Netherlands. The use of surface water is dominant in United Kingdom, Portugal, Czech Republic, Finland, Estonia, and Ireland. The use of groundwater and surface waters greatly depends on the availability of fresh and clean groundwater and surface waters.

The pollution of groundwater and surface waters with nitrate from agriculture depends on the nitrate sources in agriculture, the hydrological pathways and the nitrate removal/retention processes during transport (Klages et al., 2018). This chapter briefly discusses the hydrologic cycle, hydrological pathways and the factors that contribute to groundwater recharge and nitrate removal/retention processes during transport.

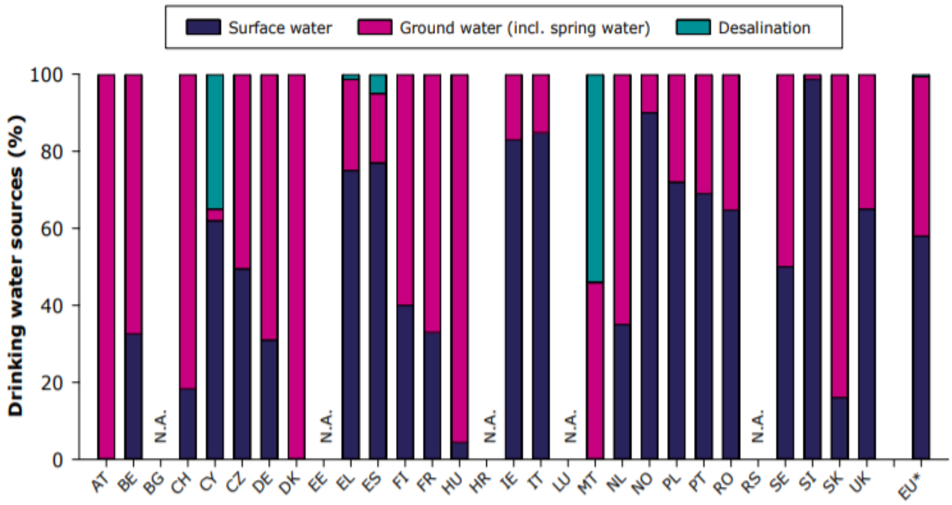


Figure 12. Relative contributions of surface water, groundwater and desalinization to the production of drinking water in EU Member States. The production of drinking water is expressed in terms of number of people served with drinking water per country (http://www.eureau.org/resources/publications/1460-eureau-data-report-2017-1/file).

5.1 THE HYDROLOGICAL CYCLE

Solar radiation is the basic driver of the hydrological cycle (Figure 13). It ‘fuels’ evapotranspiration from plants, soil and water surfaces. The moist air moves up but once in cold air layers it condenses to form clouds, and thereafter returns to the surface as precipitation. Some of the rain evaporates back into the atmosphere, some enters surface waters through surface runoff, and some infiltrates the soil and percolates into groundwater and may ultimately seeps its way to rivers, lakes and oceans, and then is released back into the atmosphere through evaporation (Figure 13).

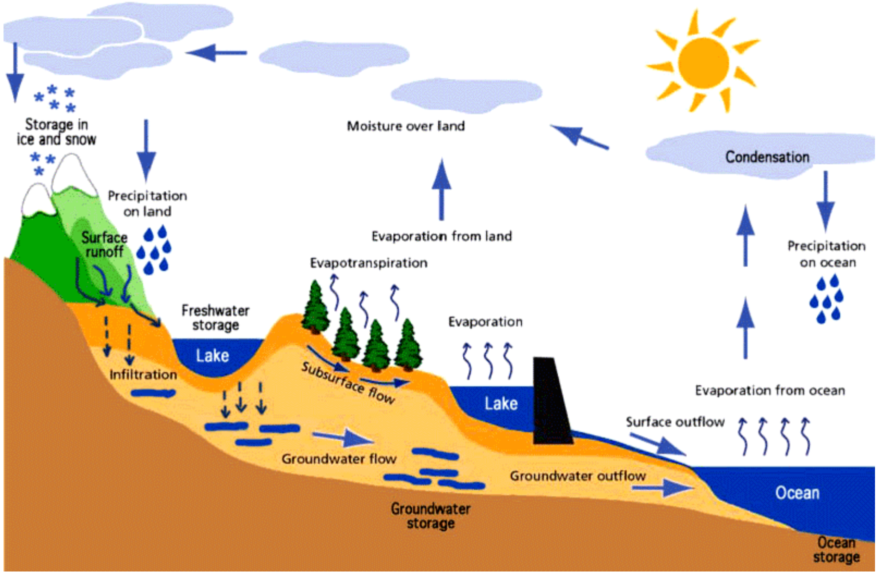


Figure 13. The hydrologic cycle (Source: http://geofreekz.wordpress.com/the-hydrosphere).

The geomorphology determines the drainage system that is formed by the pattern of streams, rivers, and lakes in a particular drainage basin. The drainage basin is the topographic region from which a stream receives runoff, through flow, and groundwater flow. The number, size, and shape of the drainage basins varies from region to region. The geomorphology influences also the partitioning of water between groundwater and surface waters, depending also on the balance of precipitation and evapotranspiration. Factors affecting the water balance are plant-atmosphere interactions, surface runoff, infiltration, flow in the unsaturated-saturated zone and subsurface runoff. The dynamics of the groundwater itself also influences the partitioning between groundwater and surface waters; at high groundwater levels infiltration decrease and surface runoff increase.

Groundwater is often divided in two subsystems (i) the shallow groundwater with the (partly) unsaturated zone with rapid transport of solutes through shallow groundwater to local water courses (subsurface runoff) and (ii) the deep groundwater saturated zone with slow transport towards larger streams and rivers. Shallow groundwater flow is assumed to occur in the top layer of the soil, and is characterised by short residence times before water enters local surface water (small rivers) or deeper groundwater. Deep groundwater flow occurs in unconsolidated aquifers of ~50 m thickness and has often a much longer residence times before water enters large rivers.

The infiltration capacity of the soil depends on its porosity, which depends on its texture and structure, as well as on the soil moisture content before the rainfall started. The initial infiltration capacity of a dry soil may be high but, as the rain continues, it decreases until it reaches a steady state infiltration rate. When the rate of rainfall (intensity) exceeds the infiltration capacity of the soil, runoff will be generated and continues as long as the rainfall intensity exceeds the actual infiltration capacity of the soil. The vegetation exerts influence on the infiltration capacity of the soil; a dense vegetation cover shields the soil from the raindrop impact and reduces crusting effects.

Meteorological factors that affect runoff are type of precipitation (rain, snow, etc.) and rainfall intensity, amount and duration. Biophysical factors affecting runoff are land use and vegetation, soil type and depth, type of underlying bedrock, drainage area, geomorphology (slope of the land), basin type, and drainage network patterns, including ponds, lakes, reservoirs, sinks, which prevent or delay runoff from continuing downstream. Human activities that may affect runoff are the removal of vegetation and soil, grading the land surface, including terracing, and constructing drainage networks. These activities increase runoff volumes and shorten runoff time into streams from rainfall and snowmelt. Also, soil sealing in urban and infrastructural areas, and soil compaction by heavy machinery decrease the infiltration of water into the soil and thereby surface runoff. As a result, the peak discharge, volume, and frequency of floods may increase in nearby streams.

The residence time of water in a groundwater systems is important for the prognosis of the long-term behaviour of groundwater systems in response to nitrate inputs. The longer the residence time, the older the water, the greater the chance that the groundwater has been influenced by anthropogenic influence, and the greater the chance that natural remediation can improve the quality of polluted groundwater.

5.2 SURFACE RUNOFF AND NITRATE LEACHING

There are two loss pathways at the soil surface that are causing nitrogen losses to surface waters, namely surface runoff and erosion. Nitrogen losses through surface runoff are in general much larger than N losses via erosion. Losses of N via runoff and erosion are related to the factors controlling runoff and erosion (Chapter 5.1), slope and geomorphology, vegetation cover, and to the amounts of soil mineral N and particulate N in the soil surface layers. The potential of N loss via surface runoff is much higher directly following applications of fertilizer N and manure than following crop harvest when mineral N has moved from the soil surface into the (sub)soil and/or has been taken up by the crop. In contrast, losses of particulate N via erosion may by higher following crop harvest when the soil surface is exposed to the impacts of rain than during the growing season when the soil surface is shielded by vegetation.

The N losses via downward leaching are related to (a) the factors controlling infiltration (Chapter 5.1), (b) the amounts of mineral N in the soil profile, and (c) the removal of nitrate via uptake by the crop and denitrification. The amounts of mineral N in the soil profile depend on the balance of total N inputs to the soil and total N output via harvested crops and soil surface losses (NH_3 and N_2O emissions, surface runoff and erosion), corrected for net N mineralisation of organically bound N and denitrification in the soil. Factors controlling denitrification are (i) the presence of an energy source for denitrifying bacteria, mostly easily decomposable organic carbon, (ii) near anoxic (anaerobic) conditions, and (iii) the availability of nitrate in soil. If any of these three conditions is not fulfilled, denitrification is unlikely.

The leaching of nitrate to below the rooting zone moves further to either subsoil lateral leaching to surface waters or to groundwater (Figure 13). Groundwater transport of nitrate may take place over long distances and time-scales, and the groundwater system may act as a temporary sink, depending on denitrification, i.e. the reduction of nitrate (NO_3^-) and nitrite (NO_2^-) to N_2O, NO and N_2. The importance of denitrification in groundwater reservoirs itself is uncertain (Van Drecht et al., 2003; Rivett et al., 2008; Bouwman et al., 2014).

Increases in precipitation will generally lead to an increase in N leaching. As a result, there is often a good relationship between precipitation amount and nitrate loads to a river and nitrate concentrations in a river. The relationship between nitrate concentration and river flow result from the leaching of nitrate from the soil during periods of high rainfall. Hence, the leaching of nitrate is affected by dry and wet climatic cycles and by variation in precipitation, both between and within years. This has consequences for the interpretation of the results of the monitoring of groundwater quality, for example for assessing the effectiveness of measures to reduce nitrate leaching. Hence, measured nitrate concentration in monitoring programs may be corrected for dilution associated with differences in actual precipitation and average precipitation (Fraters et al. 2015).

Soil texture influences soil porosity and drainage, which in turn influences nitrate leaching and the aeration of the subsoil, which subsequently control mineralisation and (de)nitrification processes. In general, denitrification losses will increase in the order: sandy soil < loamy soils < clay soils <

peat soil (Rivett et al., 2008; Fraters et al., 2015). The risk of nitrate leaching decreases when the rooting depth increases, as deeply rooting crops can remove NO_3^- from the subsoil (Kristensen & Thorup-Kristensen, 2004). Organic matter-rich soil may mineralize NO_3^- from the soil organic matter, which may leach via subsurface tile drainage, especially in wet years follow dry years (Randall & Mulla, 2001; Hatfield, 1996). However, a high organic C content of the soil may also increase the denitrification capacity (Bijay-Singh et al., 1988; Munch & Velthof, 2006). Conversely, denitrification is low and nitrate leaching risk high when the organic C content of the soil is low, because the denitrification capacity is low when the total degradable C content of the soil is low (Bijay-Singh et al., 1988; Kronvang et al., 2005). Since the organic matter content of grassland is generally higher than that of arable land, grasslands have a higher denitrification capacity and a lower risk for nitrate than arable land per unit N surplus.

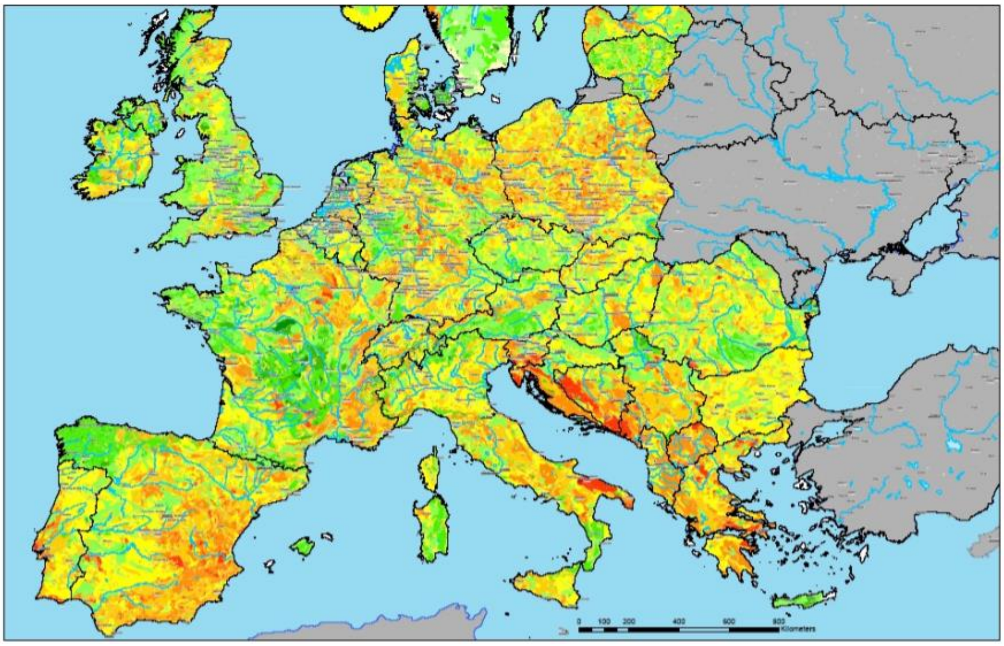


Figure 14. Map of Europe showing the distribution of excess rainwater; dark green colour indicates where transport of excess water to surface waters is maximal; dark red colour indicates where groundwater recharge is maximal; intermediate colours indicate that both pathways are important (Source: Reichenberger et al., 2007).

Drainage of poorly drained soils will lead to a lowering of the groundwater level, which may result in increased mineralisation, especially in organic matter-rich soils, which in turn may result in an increase in nitrate leaching. Sub-surface irrigation, i.e., water delivered from below soil surface, may also lower nitrate leaching losses because of less downward water flows and less mineralisation (due to dryer topsoil) (Elmi et al., 2002; Randall & Mulla, 2001).

Summarizing, the source-pathway-receptor linkage is complex and greatly varies between landscapes and regions, also because the traveling pathway and the traveling time of the groundwater may vary before it seeps into surface waters. Commonly, a distinction is made between (i) surface runoff of N, which leads to nitrate pollution and eutrophication of surface waters, and (ii) downward leaching of nitrate, which leads to groundwater pollution by nitrates, and upon seepage of this groundwater may lead to nitrate pollution and eutrophication of surface waters. The risk of nitrate leaching and runoff is related to a combination of (i) incidence of occurrence, i.e., frequency of surface runoff and erosion, and (ii) the presences of nitrate in the soil. Risks are termed high when both the incidence of occurrence and the amounts of nitrate in soils are high.

5.3 THE POTENTIAL POLLUTION OF GROUNDWATER AND SURFACE WATERS WITH NITRATES

The demand for nutrients and water, and the demand for pest and disease control depend on the crop growth potential and management. Crop growth potential is an important determinant for the demand of nitrogen, and indirectly also for the leaching of nitrate to groundwater and surface waters. The spatial patterns of the potential crop biomass yields resemble similar spatial patterns as for climate, geomorphology and soil types. Areas with a high potential biomass yield demand more nutrients than areas with a low potential biomass yield. A large difference between potential biomass yield and water-limited biomass yield indicates the areas where irrigation may be important and hence, where irrigation induced nutrient losses may occur.

The potential risk of runoff and leaching of nitrate to surface waters is determined by a combination of pedo-climatic factors and the amounts of nitrate and in the top soil. The important pedo-climatic factors are: (i) rainfall amount and distribution, especially heavy rainfall events, and (ii) Water infiltration rate into the soil. The latter is determined by slope, soil texture, soil structure, including soil cracking, slaking and preferential flow characteristics, soil depth to underlying rock, including karst formations and impermeable soil layers, vegetation cover, which determines evapotranspiration and affect surface roughness, snow and frost and freeze-thaw cycles, and the presence of terraces, tree-lines, buffer zones, riparian zones, which all contribute to intercepting overland flows.

The potential risk of downward nitrate leaching to groundwater is also determined by a combination of the amounts of nitrate in soil and pedo-climatic factors. The amounts of nitrate in soil are mainly determined by fertilization practices and the uptake capacity of the growing crop(s). Important pedo-climatic factors are rainfall surplus (i.e., rainfall minus evapo-transpiration), rainfall distribution, water infiltration rate into the soil and the hydrological conductivity of the soil, which is determined by soil texture, soil structure, including soil cracking, slaking and preferential flow characteristics, soil depth to underlying rock, slope, soil cover, and denitrification capacity of the soil. Soils with a high nitrate leaching vulnerability have a high infiltration rate and a high hydrological conductivity, such as coarse-sandy soils and shallow soils overlying karst formations. This vulnerability is increased in case of crops with short growing periods in a climate with high rainfall.

The potential risks of surface runoff in EU-27 is shown in Figure 15. Three classes of risk have been distinguished, namely low, medium and high. Most areas in Europe have a low to medium high risk of surface runoff. The potential risks of downward leaching in EU-27 is shown in Figure 16. Again, three classes of risk have been distinguished, namely low, medium and high. Most areas in Europe have a medium to high risk of leaching.

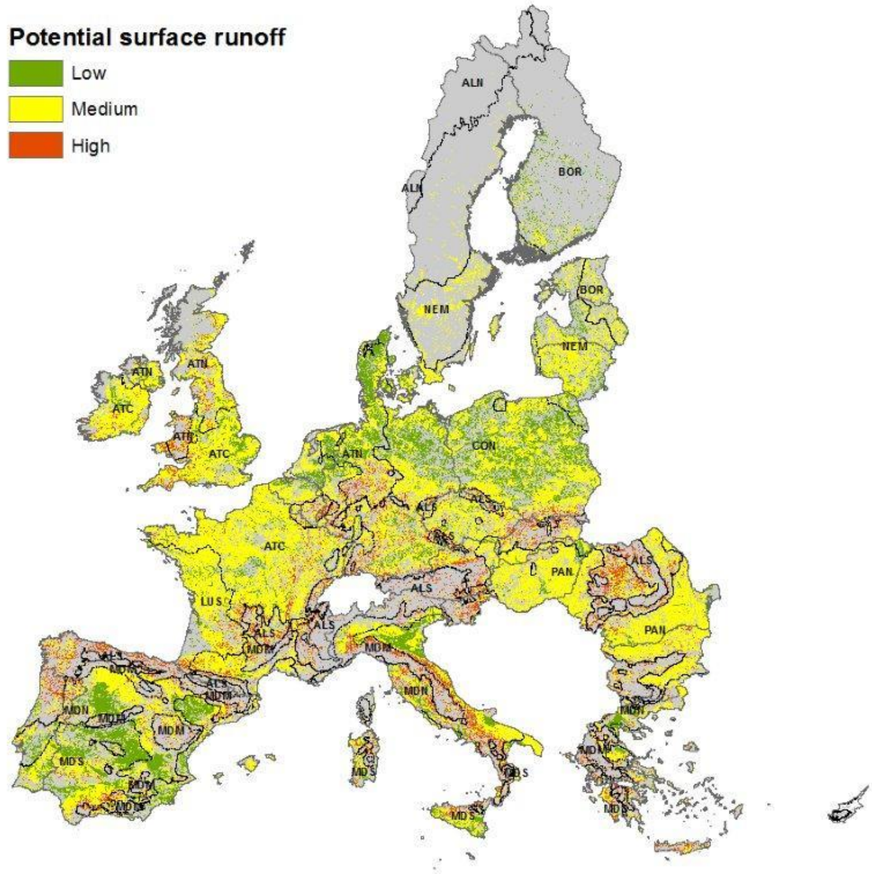


Figure 15. Map showing the surface runoff risk potential for agricultural land in the EU-27. Abbreviations in the map indicate Environmental Zones. Grey areas indicate non-agricultural areas. (source Anonymous, 2011).

Summarizing, the surface runoff and leaching risk maps depicted in Figures 15 and 16 provide only a general overview, based on pedo-climatic factors. The maps show that the potential risks of surface run off to surface waters and leaching to groundwater are wide-spread across EU-27. The actual surface runoff and leaching also depend on the presence of nitrate sources, as discussed in Chapter 4. The maps are too course to derive the risks for individual drinking water resources, because the influencing pedo-climatic factors and N use in agriculture greatly vary at small spatial scales.

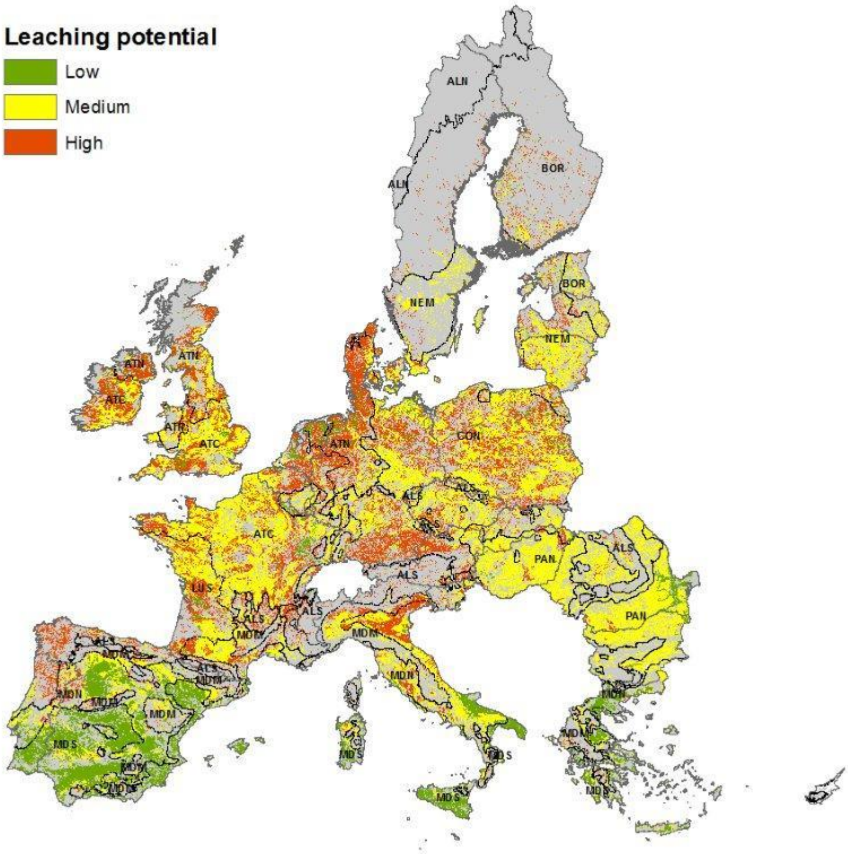


Figure 16. Map showing the leaching risk potential for agricultural land in the EU-27. Abbreviations in the map indicate Environmental Zones. Grey areas indicate non-agricultural areas. (source Anonymous, 2011).

5.4 MONITORING OF THE POLLUTION OF GROUNDWATER AND SURFACE WATERS WITH NITRATES

The EU-Nitrates Directive demands Member States to monitor the nitrate concentrations in groundwater and surface waters, and to report to the European Commission the results of the monitoring programs every four years. The most recent synthesis report provides a detailed overview of the monitoring network and of the results of the monitoring. In the reporting period 2012-2015, the total number of groundwater monitoring stations in the EU-28 was 34,091 which is an average of 7.8 stations per 1,000 km^2 of land. The station density varied from 0.6 in Finland to 130 stations per 1,000 km^2 of land in Malta. The average sampling frequency of groundwater was nearly twice a year, and varied from less than once a year in Denmark, Latvia, Poland and Sweden to around 5 times a year in Belgium and Croatia. The total number of fresh surface water monitoring stations in the EU-28 was 33,042 which is an average of 7.6 stations per 1,000 km^2 of land. The station density varied from 0.5 per 1,000 km^2 in Finland to 34 stations per 1,000 km^2 of land in the United Kingdom. The average sampling frequency was around four times a year, and varied from almost once a year in Sweden to 20 times a year in Ireland (EC, 2018).

The average annual nitrate concentration exceeded 50 mg/L in 13% of groundwater monitoring stations in the EU-28 during 2012-2015. This varied from no exceeding stations in Ireland, to more than 20% in Spain, Germany and Malta. At EU-28 level, there was a slight improvement compared to the previous reporting period, when 14% of the groundwater monitoring stations exceeded an average annual nitrate concentration of 50 mg/L. Compared to the previous reporting period 2008-2011, 26% of all stations in the EU-28 showed an increasing trend and 32% a decreasing trend.

Figure 17 shows a maps with the location of the groundwater monitoring station and their average nitrate concentration. Stations with nitrate concentrations exceeding 50 mg/L are diffusively spread across EU-28, with the exception of Sweden, Finland and Ireland. Yet, there are also a few hot spot regions.

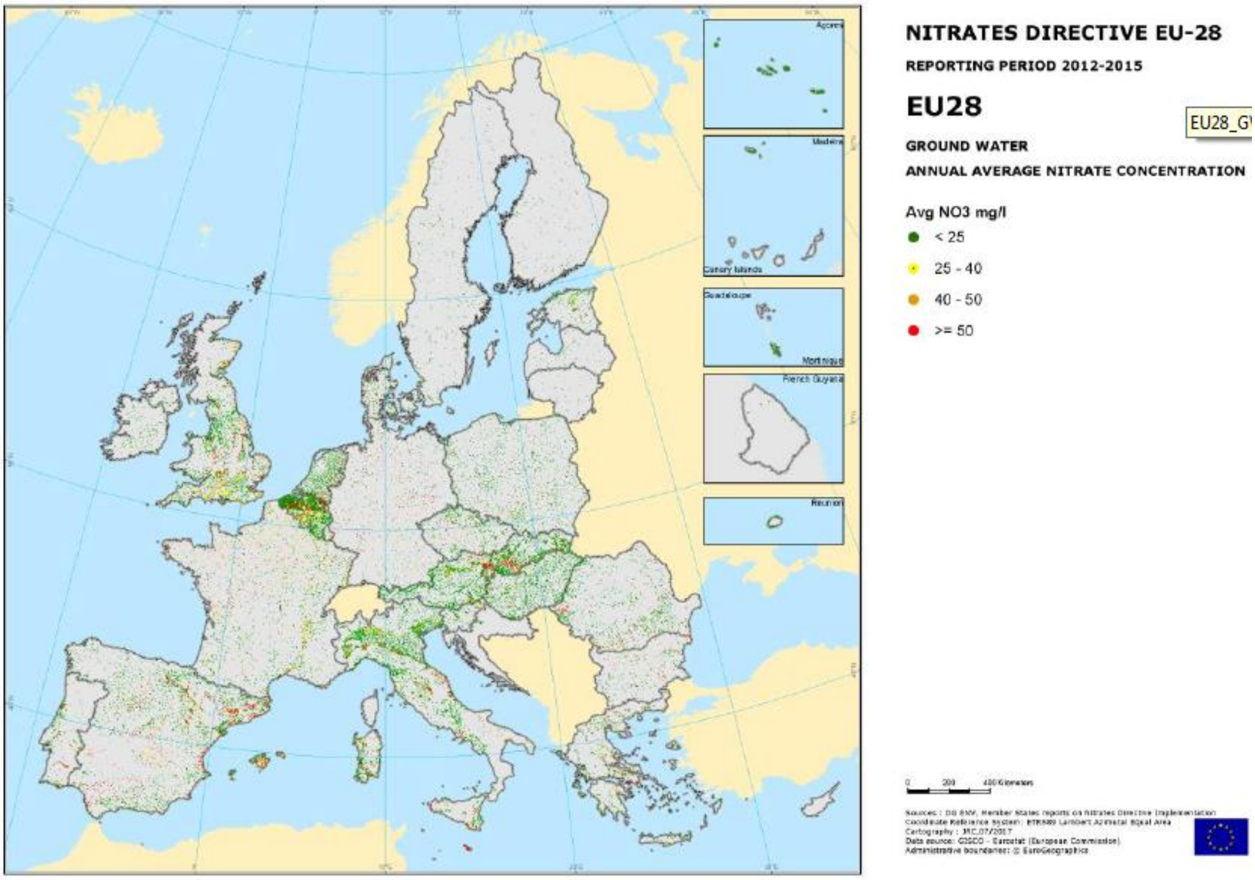


Figure 17. Annual mean nitrate concentrations in the shallow groundwater during the reporting period 2012-2015 (EC, 2018).

The average annual nitrate concentration exceeded 50 mg/L in 1.8% of the fresh water monitoring station in the EU-28 during 2011-2015. Another 2.0% of the stations had average annual nitrate concentrations between 40 and 50 mg/L and 8.8% between 25 and 40 mg/L. Low average nitrate concentrations in fresh surface water were found in Sweden, Ireland and Greece, and relatively high in the United Kingdom, Belgium and Malta. High nitrate concentrations are generally observed in rivers. There was a slight improvement compared to the previous reporting period, in which 2.4% of the monitoring stations had annual average nitrate concentrations exceeding 50 mg/L and 2.4% showed concentrations between 40 and 50 mg/L. Compared to the reporting period 2008-2011, a decreasing trend in annual average nitrates concentrations was observed in 31% of all freshwaters monitoring stations, and an increasing trend was observed in 19% of freshwaters monitoring stations. Figure 18 shows a maps with the location of the freshwater monitoring station and their average nitrate concentration. Stations with nitrate concentrations exceeding 50 mg/L are again diffusively spread across EU-28, with the exception of Sweden, Finland and Ireland. Yet, there are also a few hot spot regions.

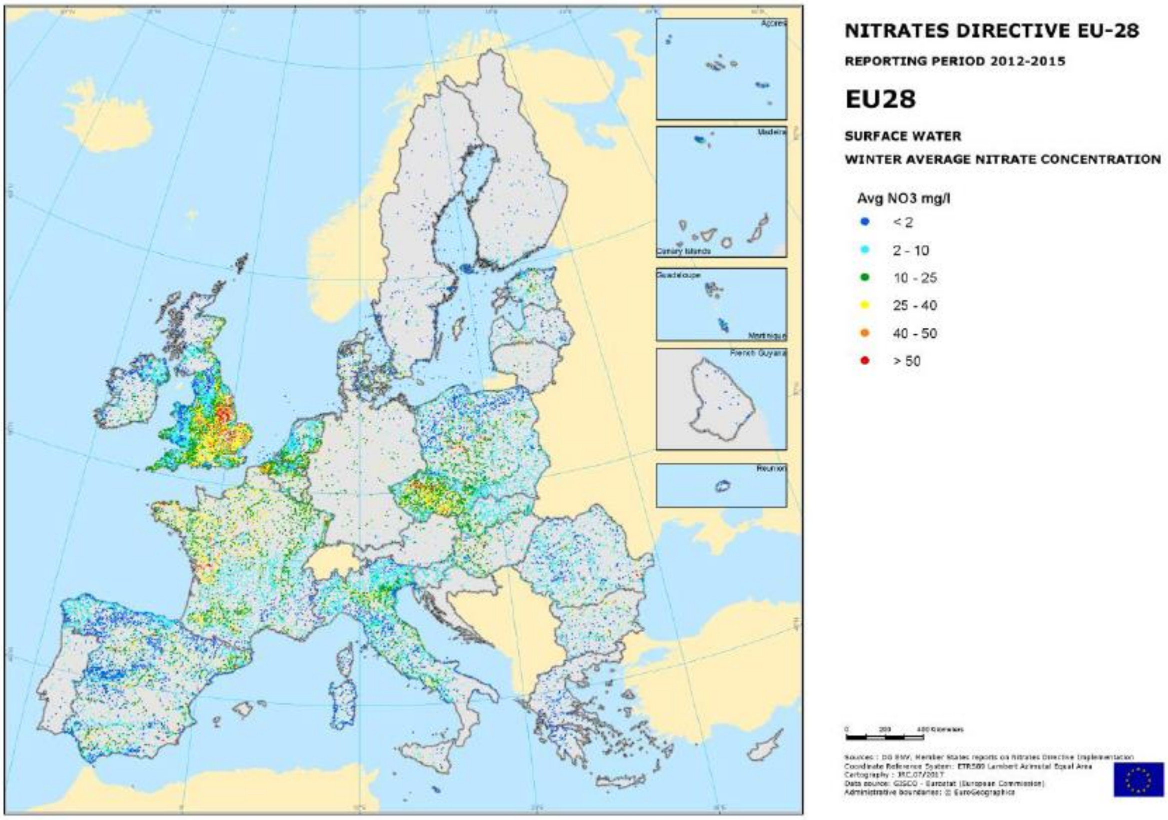


Figure 18. Winter mean nitrate concentrations in surface water during the reporting period 2012-2015 (EC, 2018).

6. OVERVIEW OF MEASURES AND PRACTICES THAT DECREASE NITRATE LOSSES

This Chapter and annexes 1 and 2 provide overviews of the measures and practices that decrease nitrate losses to groundwater and surface waters. It discusses the (cost) effectiveness of the measures as reported in literature, and it discusses the mechanisms and rationales of the measures and practices.

The actual vulnerability of a site to N losses via surface runoff and leaching depends on the pedo-climatic conditions and farming practices (Chapters 4 and 5). As pedo-climatic conditions are largely defined by Mother Nature and are not easy to manipulate, they govern the available options for farming practices for ensuring environmental protection. Farming practices will hence have to be adjusted to the pedo-climatic conditions, when the objective is to decrease the risk of water pollution with nitrates.

6.1 SUMMARY OVERVIEW OF MAIN DOCUMENTS

This section is largely based on data and information provided by Osterburg et al (2007); Anonymous (2011); Newell Price et al (2011); Bittmann et al (2014); Van Boekel (2015). These reports provide comprehensive overviews of a wide range of measures and practices, based on literature reviews and expert judgement.

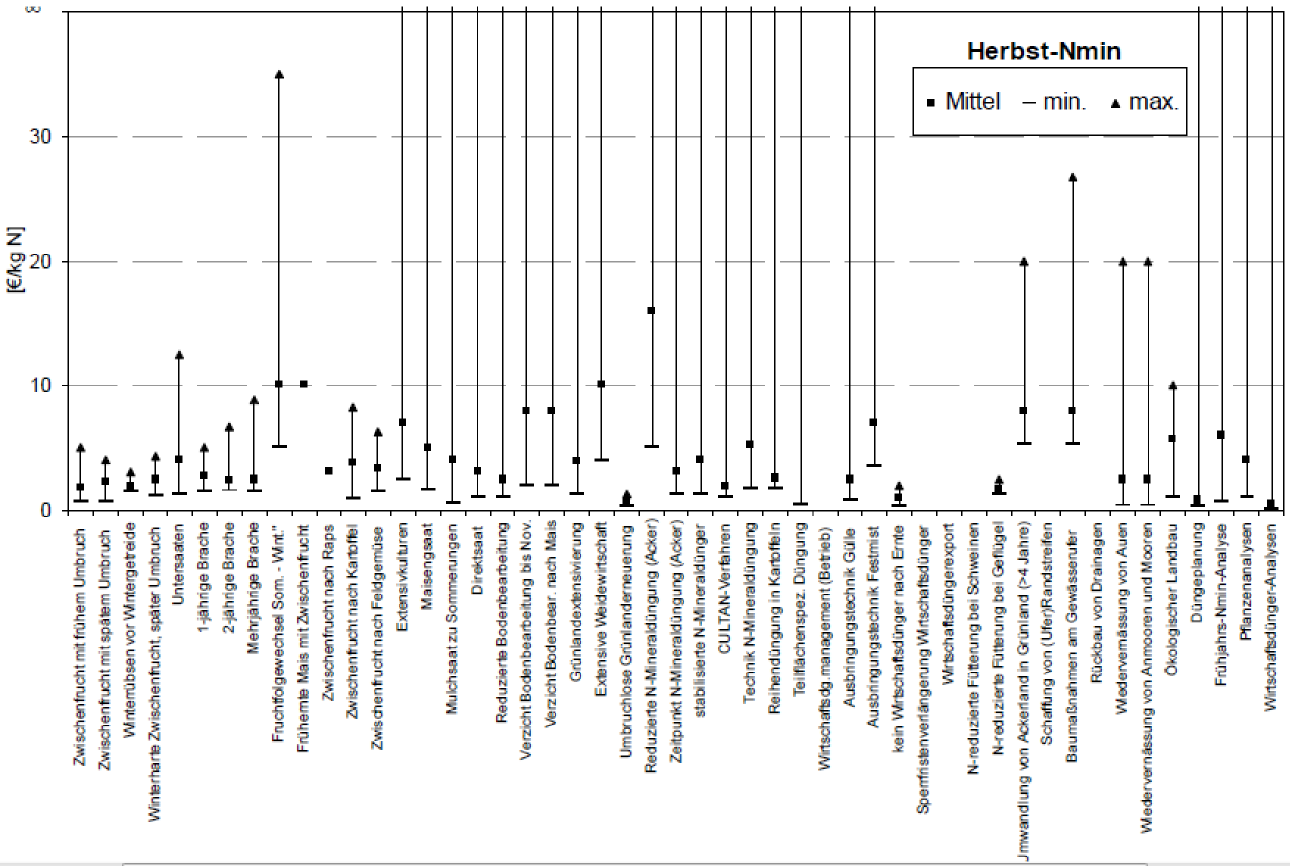


Figure 19. Summary overview of the cost effectiveness of 49 measures for decreasing nitrate losses from agricultural land in Germany. For each measure, lower, medium and upper estimates are presented, in euro per kg N. See also Table 7. (Source: Osterburg et al., 2007).

Osterburg et al (2007) made a comprehensive overview of 49 measures to decrease the potential for nitrate leaching to groundwater and surface waters for Germany within the context of the EU Water Framework Directive (Table 7). The measures were compiled and assessed qualitatively for various farm types and environmental conditions on the basis of literature review, interviews and expert judgement. They used three indicators, namely, (i) the soil N balance (N surplus), (ii) the amount of soil mineral N (0-90 cm) in autumn, and (iii) the net N load that is lost to groundwater or surface waters. The cost-effectiveness of the 49 measures are summarised in Figure 19 for the indicator soil mineral N (0-90 cm) in autumn (Herbst-Nmin). The median cost of most measures ranges from 1 to 5 euro per kg N, but the uncertainty of the estimates is large for most of the measures (range 0 to 40 euro per kg N).

Table 7. Summary overview of the estimated effectiveness, efficiency, applicability and acceptance of 49 reviewed measures (Osterbrug et al., 2007). Effectiveness is expressed in terms of reduction in soil mineral N in autumn (kg N per ha), efficiency is expressed in euro per kg soil mineral N reduced, applicability is qualitatively estimated: low: +, medium: ++, high: +++. Acceptance by farmers is also qualitatively estimated, ranging from no: 0, low: +, medium: ++, high: +++.

Nr	Measure	Effectiveness Kg N/ha	Efficiency Euro/kg N	Applicability	Acceptance
1	Cover cropping, early plough down	20-60	0.7-5.0	++	+++
2	Cover cropping, late plough down	30-60	0.7-4.0	++	+++
3	Growth of rapeseed before winter wheat	20-40	1.5-3.0	++	++
4	Growth of winter hardiness cover crop	30-60	1.2-4.3	++	++
5	Growth of cover crop in between cereals	10-40	1.3-12.5	++	+
6	Growth of annual grass fallow crop, with plough down in autumn	30-60	1.5-5.0	+++	++
7	Growth of two-year grass fallow crop, with plough down in autumn	30-70	1.6-6.7	+++	++
8	Growth of many-years grass fallow crop, with plough down in autumn	40-80	1.5-8.8	+++	+
9	Crop rotation; growth of less N demanding crops	10-30	5.0-35.0	++	++
10	Early harvest of maize followed by cover crop	20-40	7.5-15	++	+
11	Growth of cover crop after rapeseed	30-70	1.7-8.3	++	+
12	Growth of cover crop after potato	30-60	1.0-8.3	++	+
13	Growth of cover crop after vegetables	40-80	1.5-6.3	++	+
14	Crop rotation; growth of less N demanding crops	0-20	2.5-9999	+	++
15	Increasing planting density of maize	0-15	1.7-9999	++	+
16	Mulching of crop residues	0-20	2.0-9999	++	++
17	Zero tillage	0-20	2.0-9999	+++	+
18	Minimum tillage after rapeseed	0-40	0.6-9999	+++	+
19	No soil cultivation in autumn after harvest of cereals	0-20	1.0-9999	+++	++
20	No soil cultivation in autumn after harvest of maize	0-20	1.0-9999	+++	++
21	Intensification of grassland	0-20	4.0-9999	++	+
22	Restricted grazing in autumn	0-40	1.3-9999	+	++
23	No reseeding and cultivation of grassland	40-80	0.3-1.3	++	++
24	Small reduction of N fertilization of arable crops	0-10	5.0-9999	0	+
25	No N fertilization of arable crops in late summer and autumn	0-20	1.0-9999	0	++
26	Use enhanced efficiency fertilizers, including nitrification inhibitors	0-20	1.3-9999	++	++
27	Use of CULTAN; injection of liquid fertilizers	0-20	1.3-9999	+++	++
28	Improved fertilizer spreading	0-10	1.8-9999	++	++

Nr	Measure	Effectiveness Kg N/ha	Efficiency Euro/kg N	Applicability	Acceptance
29	Band application of fertilizer with potato	0-15	1.7-9999	+	++
30	Precision N fertilization	0-20	0.5-9999	+++	+
31	Covering manure storages	1-3	0.7-4.0	+++	++
32	Low-emission manure application	0-20	0.8-9999	+++	+++
33	Improved application technique for solid manure	0-10	3.5-9999	+++	+++
34	No manure application to land after 15 September	20-40	0.3-1.5	++	++
35	Ban on manure application from 1 October to 15 February	10-20	1.3-2.5	++	++
36	Lowering the maximum manure application rate to 150 kg per ha	?	?	++	++
37	Low-protein feeding of pigs	?	?	+++	+++
38	Low-protein feeding of poultry	?	?	+++	+++
39	Transformation of arable land into grassland	30-70	5.3-20.0	+++	0
40	Bufferstrips	?	?	+++	+
41	Contour cropping on sloping land	?	?	+++	0
42	Reduced drainage	30-70	5.3-26.7	+++	0
43	Introduction of riparian zones	50-300	0.4-20.0	+++	0
44	Re-introduction of wetlands	50-300	0.4-20.0	+++	0
45	Transformation to organic farming	20-80	1.0-10.0	+++	+
46	Nutrient management planning	0-30	0.3-9999	+++	+++
47	Using soil mineral N analyses for nutrient management planning	0-30	0.7-9999	+++	++
48	Using plant N analyses for nutrient management planning	0-20	1.0-9999	+++	+++
49	Using manure N analyses for nutrient management planning	0-40	0.1-9999	+++	++

Anonymous (2011) describe the background and rational of the measures of the EU Nitrates Directive in Annexes II and III, based on literature review and expert judgement (see also chapter 6.3). This study includes also maps for the EU-28 showing the vulnerability of the landscapes for nitrate losses to groundwater and surface waters. Evidently, the vulnerability differs greatly across EU-28 and hence, site-specific timing and implementation of the measures are important.

Newell Price et al (2011) made a comprehensive overview of 83 measures to decrease the potential for nitrate and phosphorus leaching to groundwater and surface waters and for decreasing the emissions of ammonia and greenhouse gases to the atmosphere for United Kingdom within the context of the EU Water Framework Directive, the UNECE Convention on Long-Range Transboundary Air Pollution (the Gothenburg Protocol), the EU National Emission Ceilings Directive (NECD), and the Kyoto Protocol. The emission mitigation options for reducing diffuse water pollution, air pollution and greenhouse gas (GHGs) emissions, were compiled on the basis of literature review and expert judgement. The aim is to help users in developing policies and selecting suitable mitigation methods. The cost of the measures range from a few hundred British pounds to more than a few thousands of British pounds per farm per year. Table 8 provides a summary overview of the estimated effectiveness, economic cost, applicability and adoptability of 42 reviewed measures (see also Annex 1). Effectiveness was expressed in relative decreases of nitrate losses to groundwater and/or surface waters, using four classes (i) negative, i.e. losses increase, (ii) low; losses decrease by on average 10% (range 1-30%), (ii) moderate; losses decrease by on average 40% (range 20-80%), and (iv) high; losses decrease by on average 70% (range 50-90%). Costs were expressed in British pounds per farm, which have been transferred into euro per farm. Applicability was evaluated from low to high, based on expert judgement. Adoptability was also evaluated from low to high, based on expert judgement. Land use changes were most effective but had low adoptability scores. Quite a few measures had unknown effectiveness score but relatively high costs. Enhanced efficiency measures had relatively high adoptability but the effectiveness was scored as low (to moderate).

Table 8. Summary overview of the estimated effectiveness, economic cost, applicability and adoptability of 42 reviewed measures (after Newell-Price et al., 2011; see also Annex 1).

Nr	Measure	Effectiveness	Efficiency Euro/farm	Applicability	Adoptability
1	Change the land use from arable cropping to unfertilised grassland (without livestock) and associated manure inputs	High	200 – 4000	Specific areas only	Low
2	Change the land use from arable cropping to permanent grassland, with a low stocking rate and low fertiliser inputs	High	1000-50000	Specific areas only	Low
3	Conversion of arable land to permanent woodland	High	500-1000	Specific areas only	Low
4	Convert land to biomass cropping (i.e. willow, poplar, miscanthus)	High	500-1000	Specific areas only	Low
5	Establish cover crops in the autumn	High	100-400	After specific crops only	moderate
6	Establish autumn sown cover crops earlier	High	1000-15000	After specific crops only	Low
7	Plough out grassland in spring rather than the autumn	high	100-4000	Specific areas only	Low-moderate
8	Minimum tillage	moderate	-4500- -500	Specific areas only	Low-moderate
9	Amelioration of compacted soils and cover cropping	unknown	50-2000	Specific areas only	moderate
10	Contour soil cultivation on sloping land	unknown	50-600	Specific areas only	moderate
11	Leave autumn seedbeds rough	unknown	100-3000	Specific areas	low
12	Use tines to disrupt tramlines (compacted soils)	Unknown	10-1000	Specific crops, areas	Low-moderate
13	Maintain and enhance soil organic matter	unknown	-7000 - 1000	Moderate to high	Moderate to high
14	Establish grass buffer strips	Unknown	50 - 4000	Moderate to high	Low to Moderate
15	Establish riparian buffer strips	Unknown	1000 - 12000	Specific areas	moderate
16	Reduce surface runoff by loosening topsoil	Low	1000 - 2000	High	moderate
17	Allow existing (old) drainage systems to naturally deteriorate i.e. cease to maintain them	Low or negative	50 - 2000	Specific areas only	low
18	Actively maintain drainage systems	unknown	500-3000	Specific areas only	low
19	Clear out ditches regularly	Negative	0-1500	high	high
20	Use genetic resources to improve lifetime efficiency of livestock systems	low	-9000- -2000	high	high
21	Develop new plant varieties	low	-3000 – -150	high	high
22	Improve accuracy and spread patterns of fertiliser spreaders	unknown	50-200	high	high
23	Use of a recognised fertilisation recommendation	unknown	-4000 -500	high	moderate
24	Use of a recognised fertilisation recommendation + make full allowance of nutrients from manure	unknown	-8000 – -1000	high	moderate

Nr	Measure	Effectiveness	Efficiency Euro/farm	Applicability	Adoptability
25	Reduce the amount of manufactured N and P fertiliser applied to crops below the economic optimum rate.	low	1200 - 54000	high	low
26	Keep fertilisers away from water course	low	20 - 4000	high	Moderate to high
27	Do not spread fertiliser on wet soils	low	50-1000	high	Moderate to high
28	Place nutrients close to germinating or established crops to increase fertiliser N and/or P recovery.	low	20-100	high	Moderate to high
29	Use of nitrification inhibitors	high	500-4000	high	Low to moderate
30	Replace urea-based fertilisers by ammonium-nitrate based fertilizers	low	-900- 200	high	low
31	Use of urease inhibitor in urea fertilisers	unknown	<1000	high	Low to moderate
32	Use of clover in grassland to replace N fertiliser	moderate	<500	high	moderate
33	Do not apply manufactured N and P fertilisers to soils when soil fertility levels are high	unknown	<100	high	moderate
34	Low-protein and low-P animal feeding	low	1000-7000	high	Low to moderate
35	Phase feeding	low	400-2000	high	Low to moderate
36	Extension of the grazing season	negative	-1500--6000	moderate	Low to moderate
37	Extension of grazing when soils allow so	unknown	-1500-500	high	low
38	Reduced grazing, especially on wet soils	moderate	1000-6000	high	Low to moderate
39	Strip grazing	unknown	100-600	moderate	Moderate
40	Construct water troughs with a firm base to reduce poaching damage to the soil.	low	200-1000	high	moderate
41	Reduce the total number of livestock on the farm i.e. the number of stock per unit of land area.	moderate	5000-35000	high	Very low
42	Use of buffer strip to slow down water (and solute) transfer to surface water	moderate	500 - 5000	moderate	low

Bittmann et al (2014) made a comprehensive overview of 7 measures to decrease the emissions of ammonia to the atmosphere within the context of the UNECE Convention on Long-Range Transboundary Air Pollution. The measures have been described in detail for various farming systems and also the possible side-effects in terms of nitrate leaching and greenhouse gas emissions have been highlighted. Measure 1 relates to farm N management, with impact on basically all N loss pathways, including nitrate leaching losses. The cost of the measures are in the range of <1 to >5 euro per kg NH3-N per year. Management and feed measures are relatively cheap (<1 euro), and those for adaptation of buildings and manure storage relatively high (>5 euro per kg NH3-N per year).

Van Boekel (2015) reviewed the measures implemented to address nutrient problems of groundwater and surface water for countries in northwest Europe. A total of 7 mitigation options were selected and analysed. However, the requested data and information was not available for all countries. Table 9 presents a summary of the cost effectiveness of selected measures. Van Boekel (2015) concluded that there are large variations in cost and cost-effectiveness among the mitigations options and between country estimates. For some measures the cost and cost effectiveness are not known, because the amount of data is very low.

Table 9. Overview of the cost (€/year) and cost-effectiveness (€ kg-1 N, € kg-1 P) of mitigation options for reducing N and P-leaching to groundwater and surface water (Source: Van Boekel, 2015.

Mitigation option	Costs €/year				Cost-effectiveness € kg^{-1} N-reduction				Cost-effectiveness € kg^{-1} P-reduction			
	NL	DK	UK[1]	NIE	NL	DK	UK[1]	NIE	NL	DK	UK[1]	NIE
Catch crops	85-88	56	676	-	3.1-5.0	4.0	56	-	-	-	4228	-
Application time	-	-	195	7599	-		167	-	-	-	8739	86
Buffer strips	0 - 135[2]		58-12741	-	0-9	3.3	3-554		22	15	588-3117647	-
Wetlands	42000[3]		-	4000	-	-	-	-	-	-	171	16

1. UK = England + Wales
2. € ha^{-1} year
3. € km^{-1} wet buffer

None of these review papers addressed measures that could be adopted by citizens. However, cities are increasingly targeted as centers for sustainable development and innovation of food systems. Urban agriculture (UA) is advocated by some as a multi-faceted approach to help achieve urban sustainability goals, as it is provides possible social, economic and environmental benefits. The role of UA in restoring resource cycles receives increased attention, especially with regard to assimilating urban waste. However, there is little information on how nutrients are managed in UA in developed countries. Wielemaker et al. (in review) examined nutrient management in 25 ground-based UA initiatives in the Netherlands on i) preferences for types of fertilizers, and ii) quantity, quality of fertilizers used including nutrient composition and organic matter content, and nutrient outputs in harvested products. Results show that mean nutrient inputs exceeded mean crop demand by 100-300% for nitrogen, by 600% for phosphorus and 260% for potassium. The need to improve nutrient management in urban agriculture is evident. Soil tests, harvest logging and book keeping of nutrient inputs would improve data quality and may help balance nutrient inputs with nutrient outputs.

In summary, the aforementioned five reports provide comprehensive overviews of measures to decrease nitrate losses from agriculture to groundwater and surface waters. The findings presented in these reports have been summarized into the so-called long list of measures in Annex 1, using the common format presented in Table 2 of Chapter 2. Four categories of measures have been distinguished:

- Efficiency enhancing measures (19 measures)
- Land use management (12 measures)
- Soil management (10 measures)
- Water management (3)

Evidently, most measures relate to improving the use of available nitrogen sources in the soil or applied nitrogen on the land; the more N is taken up and removed by harvest crop, the less is available for leaching and surface runoff.

Annex 2 of this report provides an overview of the measures that have been implemented at the case-study sites to reduce pollution of drinking water resources with nitrates, based on the results of a Questionnaire. Most of the measures relate to efficiency enhancing measures and land use management measures. Unfortunately, the effectiveness and efficiency at the sites are not yet well known at the study-sites.

6.2 GOOD AGRICULTURAL PRACTICES OF THE EU NITRATES DIRECTIVE

The notion of ‘good agricultural practices’ is probably as old as sedentary agriculture itself. Farmers have learned how to maximize the economic and social benefits from their land over time; in the beginning through trial and error and word of mouth, later through formal education and guidelines from extension services, institutions, governments and processing industries.

The notion of ‘good agricultural practices’ changed following increased awareness of the environmental consequences of the intensification of agricultural practices. The term ‘nutrient management’ was introduced in the second half of the 1980s; the term replaced in part fertilization and fertilizer management, and emphasized the importance of (i) including all sources of nutrients in fertilization recommendations, including animal manures, and (ii) nutrient losses to air and water. The term ‘best environmental management’ reflects the increased awareness of the environmental implications of modern farming probably even better.

The discussion on good and best management practices remained rather academic in the agricultural arena until the acceptance of the Nitrates Directives by the EU Member States in 1991. The aim of this Directive is (i) to reduce water pollution caused or induced by nitrates from agricultural sources, and (ii) to prevent further such pollution. For the first time in history a set of coherent measures was introduced to decrease nitrate losses from agriculture. It does so from a farm perspective as well as from a landscape perspective. The Nitrates Directive requires Member States

- (i) to monitor nitrate pollution and eutrophication of groundwater and surface waters,
- (ii) to promote the implementation of Good Agricultural Practices (see Annex II of the Directive),
- (iii) to designate so-called Nitrate Vulnerable Zones (NVZs) where nitrate concentrations are higher than 50 mg per litre, and
- (iv) to establish Action Programmes with specific measures (see Annex III of the Directive) for NVZs to decrease nitrate pollution.

The measures of Annexes II and III of the Nitrates Directive are presented in Tables 10 and 11.

Although the Code of Good Agricultural Practices were implemented on a voluntary basis, and many Member States have been struggling with its implementation, it is clear that the notion of ‘Good Agricultural Practice’ has changed in the EU since the implementation of the Nitrates Directive. This is also related to the measures of Annex III of the Nitrates Directive, which have to be implemented in nitrate leaching vulnerable zones (NVZs) and are obligatory for all farmers in those areas. The scientific basis for codes of good agricultural practice was first presented in 1993 (Jordan, 1993) and then further elaborated in 2011 (Anonymous, 2011). Interestingly, the Nitrates Directive is only 8 pages (including the annexes), and the Code of Good Agricultural Practice covers only a half a page. Yet, it has far-reaching implications for agriculture in the EU. In contrast, the recent Commission report ‘Best environmental management practice for the agriculture sector - crop and animal production’ (Antonopoulos et al 2018) covers 628 pages, but will likely have less impact. The guidance document on ammonia mitigation cover 96 pages (Bittman et al., 2014).

Most measures in Annexes II (Table 10) and III (Table 11) of the Nitrates Directives are source-based measures; these relate to the amount, method, and timing of manure and fertilizer applications. Examples of pathway-based measures are the irrigation measures, buffer strips, green covers, and land use management. Some measures though could be classified as a mixture of source-based and pathway-based. The Nitrates Directive does not explicitly demand for receptor or effects-based measures, but does not exclude such measures as creation of riparian zones and dredging could be considered part of land use management.

The list of measures of the Nitrates Directive is much smaller than the list of possible measures shown in Tables 7 and 8. Notably, precision fertilization is not mentioned

Table 10. Measures referred to in Annexes II of the Nitrates Directive; Code of Good Agricultural Practice

1. Periods when the land application of certain types of fertilizer is prohibited or inappropriate;
2. The land application of fertilizer to steeply sloping ground
3. The land application of fertilizer to water-saturated, flooded, frozen or snow-covered ground;
4. The conditions for land application of fertilizer near water courses;
5. The capacity and construction of storage vessels for livestock manures, including measures to prevent water pollution by run-off and seepage into the groundwater and surface water of liquids containing livestock manures and effluents from stored plant materials such as silage;
6. Procedures for the land application, including rate and uniformity of spreading, of both chemical fertilizer and livestock manure, that will maintain nutrient losses to water at an acceptable level;
7. Land use management, including the use of crop rotation systems and the proportion of the land area devoted to permanent crops relative to annual tillage crops;
8. The maintenance of a minimum quantity of vegetation cover during (rainy) periods that will take up the nitrogen from the soil that could otherwise cause nitrate pollution of water;
9. The establishment of fertilizer plans on a farm-by-farm basis and the keeping of records on fertilizer use;
10. The prevention of water pollution from run-off and the downward water movement beyond the reach of crop roots in irrigation systems.

The Groundwater Directive, Water Framework Directive and Drinking water Directive do not prescribed specific measures as in the Nitrates Directive. Rather, these Directives require Member States 'to take all necessary measures to ensure that water bodies are not polluted' and that 'the water intended for human consumption is wholesome and clean'.

Table 11. Measures referred to in Annexes III of the Nitrates Directive, to be included in Action Programmes of Member States.

A. The measures shall include rules relating to:

1. Periods when the land application of certain types of fertilizer is prohibited;
2. The capacity of storage vessels for livestock manure; this capacity must exceed that required for storage throughout the longest period during which land application in the vulnerable zone is prohibited, except where it can be demonstrated to the competent authority that any quantity of manure in excess of the actual storage capacity will be disposed of in a manner which will not cause harm to the environment;
3. Limitation of the land application of fertilizers, consistent with good agricultural practice and taking into account the characteristics of the vulnerable zone concerned, in particular:
   (a) soil conditions, soil type and slope;
   (b) climatic conditions, rainfall and irrigation;
   (c) land use and agricultural practices, including crop rotation systems, and to be based on a balance between :
      (i) the foreseeable nitrogen requirements of the crops, and
      (ii) the nitrogen supply to the crops from soil and fertilization corresponding to:
      - the amount of nitrogen present in the soil at the moment when the crop starts to use it to a significant degree (outstanding amounts at the end of winter),
      - the supply of nitrogen through the net mineralization of the reserves; of organic nitrogen in the soil,
      - additions of nitrogen compounds from livestock manure,
      - additions of nitrogen compounds from chemical and other fertilizers.

B. These measures will ensure that, for each farm or livestock unit, the amount of livestock manure applied to the land each year, including by the animals themselves, shall not exceed a specified amount per hectare. The specified amount per hectare be the amount of manure containing 170 kg N. However:

(a) for the first four year action programme Member States may allow an amount of manure containing up to 210 kg N;

(b) during and after the first four-year action programme , Member States may fix different amounts from those referred to above. These amounts must be fixed so as not to prejudice the achievement of the objectives specified in Article 1 and must be justified on the basis of objectives criteria , for example:

— long growing seasons,
— crops with high nitrogen uptake,
— high net precipitation in the vulnerable zone,
— soils with exceptionally high denitrification capacity.

If a Member State allows a different amount under subparagraph (b), it shall inform the Commission which will examine the justification in accordance with the procedure laid down in Article 9.

C. Member States may calculate the amounts referred to in paragraph B on the basis of animal numbers.

6.3 FURTHER CHARACTERIZATION OF KEY MEASURES

Measures to prevent and reduce the risk of leaching and surface runoff are usually categorized according to the *source-pathway-receptor* concept, i.e., there are (i) source-based measures or input-based measures, (ii) pathway-based measures, and (iii) receptor or effects-based measures (e.g. Burt et al., 1993; Van Boekel 2015). Examples of source-based measures are N application limits, balanced fertilization, appropriated storage of animal manures and fertilizers, and prohibition periods for the application of manures and fertilizers. Source-based measures are often a combination of N application amounts, methods and timing, commonly referred to as the 4R strategy (IPNI, 2018). Examples of pathway-based measures are irrigation measures, drainage, buffer strips, green covers, terracing. Examples of receptor or effects-based measures are dredging, creation of riparian zones, water purification. These three categories can be understood also from the 'hole-in-the-pipe-model' in Figure 5 and discussed in chapter 3.

Source-based measures are often seen as effective measures, because of the restriction on N input. However, it has to be realized that the response of crop production to N input is nonlinear, which is known as the law of diminishing returns (or the law of diminishing marginal returns). When the availability of N in soil is low, the crop response is high, and the risk of N losses will be relatively low. Conversely, when the availability of N in soil is high, the response of the crop to N input is low, and the risk of N losses will be relatively high, because the crop is unable to recover the applied N. Hence, the risk of leaching is the reverse of the law of diminishing crop yield returns; the risk increase more than proportional with N input, until a certain N input level. Thereafter, the risk of leaching is more or less linearly related to N input.

This section discusses the rational and mechanism of key measures more in depth. It starts with nitrogen management in general, as this measure is increasingly seen as the overall integrative measure, also to minimize pollution swapping.

6.3.1. Nitrogen management

Nitrogen management can be defined as "a coherent set of activities related to N use of farms to achieve agronomic and environmental/ecological objectives" (Oenema and Pietrzak, 2002). The agronomic objectives relate to crop yield and quality and animal performance. The environmental/ecological objectives relate to N losses from agriculture. Taking account of the whole N cycle emphasizes the need to consider all aspects of N cycling, to circumvent pollution swapping. Nitrogen management planning at farm level is increasingly seen as the starting point also of all measures aimed at reducing nitrate losses. The importance of a broader look is also emphasized by the term *integrated* nitrogen (nutrient) management (Sutton et al., 2011; 2013; FAO, 2018)

Depending on the type of farming systems, N management at farm level involves a series of management activities in an integrated way, including:
(a) Fertilization of crops;
(b) Crop growth, harvest and residue management;
(c) Growth of catch or cover crops;
(d) Grassland management;
(e) Soil cultivation, drainage and irrigation;
(f) Animal feeding;
(g) Herd management (including welfare considerations), including animal housing;
(h) Manure management, including manure storage and application;
(i) Ammonia emission abatement measures;
(j) Nitrate leaching and run-off abatement measures;
(k) N2O emission abatement measures;

Nitrogen management at farm level involves the reiterative cycle of analysing, making decisions, planning, acting, evaluation & control, and adjustment (Bittman et al., 2014). It depends strongly on the availability of easy accessible information of individual fields (i.e. soil analysis), the available nutrients in manures as well as the nutrients from additional sources, and the exports of nutrients in crops and animal products, as foreseen in view of experiences in preceding years. In addition to data of inputs and outputs, information is needed on the available time windows suitable for applying nutrients, based on pedo-climatic conditions. The success of any planning procedure also depends on the timely availability of information. A true planning must therefore not be restricted to a listing of the required items of information, but also define the recurring temporal flows of information (Anonymous, 2011). Extension services play an essential role in providing these conditions. The nutrient management planning has to be linked to all the other measures to reduce the risk of nitrate pollution of groundwater and surface waters, especially also to the application limits. It requires also regular soil fertility analyses and analyses of the compositions of the animal manures and harvested crops; these provide a solid basis for the nutrient management planning. Effects of nitrogen management do show up in nitrate concentrations of groundwater aquifers (e.g. Kirchman et al., 2002; Hansen et al., 2018).

6.3.2. Land use management and crop rotations.

Land use management can have a significant effect on surface run-off and leaching of nutrients (e.g. Goulding, 2000). Crop rotations systems and the proportion of the land area devoted to permanent crops relative to annual tillage crops may be adjusted when the surface run-off potential and downward leaching potential are high, because crop species differ greatly in their ability to intercept and absorb applied and mineralised N (e.g. Dalgaard et al., 2014; Hashemi et al., 2018; Schröder et al., 2010). A sequence of crops differing in ability to intercept and absorb applied and mineralised N can transfer N between individual crops, and thereby maximize N utilization. In commercial farms, however, there is a certain specialisation and consequently individual farmers may have less opportunity to optimize nutrient management through balanced rotations i.e. mitigate the adverse environmental effect of one crop with the beneficial effect of another crop. Crop rotations systems and the proportion of the land area devoted to permanent crops relative to annual tillage crops should be adjusted when the surface run-off potential and downward leaching potential are high (Hashemi et al., 2016).

Growing 'leaky' crop types can be compensated by the growth of crops that are much less leaky or by the nearby presence of unfertilised natural vegetation (e.g. Schröder et al., 2007; Wendland et al., 2009). Several vegetables (e.g., spinach, lettuce, strawberries, leek) and some arable crops (e.g., potatoes, peas) with shallow rooting systems and relatively short growing seasons are 'leaky' crops; hence, these crops should be rotated with cover crops and cereals that can mop up residual mineral N from the soil. Also, tree-lines, border strips, riparian zones, and mixed cropping systems may contribute to decreasing the risk of surface runoff and increasing biodiversity and buffering against diseases. Ploughing-up grass-leys should be done in early spring, to allow a subsequent crop to mop up the N released from the mineralized sod (e.g. Schröder et al., 1999).

6.3.3. Balanced fertilization and application limits

Nutrient inputs must be 'balanced' with nutrient outputs to minimize the risk of N losses. Balanced fertilization often has two meanings, i.e., (i) all 14 required nutrient elements should be made available in the proper ratios that reflect the requirement of the crop for these nutrient elements, and (ii) the total input of N should balance the total crop N requirements. Here, we discuss the importance of the second interpretation of balanced fertilization.

Balancing N inputs to the N demand of the crop involves the assessment of the availability of the various possible N inputs, also termed the N fertiliser replacement value of the inputs. In addition, it is important to assess the recovery of the available N in the soil by the crop, the extent to which the N taken up by crops is invested in harvested plant parts, and the fate of the resultant surplus N input (Kirchman et al., 2002; Wendland et al., 2009). As far as the various types of inputs are concerned, crops can derive N from the soil mineral N present at the start of the growing season, N mineralising from earlier inputs (manures, crop residues, peat), mineral N in fertilisers and manure, atmospherically deposited N, biologically fixed N, and N in irrigation water. The N fertiliser equivalency of these sources depends partly on intrinsic characteristics, such as ratios of (readily available) carbon and (readily available) N, but also strongly on the time and method of their application, the soil type and the manuring history (Schröder et al., 2005a, 2007a).

The soil N surplus can be defined as the difference between the total N input (fertilisers, manures, biologically fixed N, mineralised N, atmospherically deposited N, N in irrigation water) and the N output (harvested N, volatilized ammonia N, N temporarily immobilised to sustain the mineralisation, N lost via denitrification). Underlying factors for the discrepancy between inputs and outputs are (i) the fertiliser equivalency (N fertiliser replacement value: *NFRV*) of the various input sources determining the amount of N available to crops, (ii) the uptake efficiency (apparent recovery: *ANR*) of the available N, determining the ultimate crop uptake, (iii) the harvest efficiency (harvest index: *HI*) indicating to which extent the N taken up is exported from the field (Schröder et al., 2005a, 2007a). The soil N surplus is vulnerable to N losses via leaching and denitrification; a large N surplus is a proxy indicator for the nitrate leaching losses (Osterbrug et al., 2008; Klages et al., 2018).

The utilization of inputs is determined by the product of NFRV x ANR x HI. This product is determined by the intrinsic properties of N input sources and crops, the ability of crops to assimilate N and the combined effects of climate and weather, soil characteristics, and management. As far as N demand of a farm as a whole is concerned, the relative share of crops represented in the rotation as well as their attainable yield must be considered.

The nitrate concentration in water bodies is the result of a specific load being dissolved in a specific volume of water. The N load is determined by the extent to which the soil N surplus effectively leaches or runs-off. The N load and the soil N surplus are not necessarily the same, as the initial soil N surplus can be exposed to various conversions, including denitrification (i.e. the conversion of dissolved N form into gaseous N forms) or retentions in a broad sense (e.g. N captured in vegetated buffer strips). The factor linking the soil N surplus to the N load can be called 'leaching fraction' (Schröder et al., 2005a, 2007b; Osterburg et al., 2007). Balanced N fertilization is considered as a most effective measure to reduce nitrate leaching losses (Velthof et al., 2009; Oenema et al., 2009).

6.3.4. Precision fertilization and manuring

Fertilizers and manures must be applied to land in such a way that the nutrients can be utilized by the growing crop in an effective way. Basically, this means that the fertilizers and manure must be applied at the right time, right amount, right place and the right depth. This requires that appropriated techniques are used. Split application, band application, injection, variable rate application are common techniques with a proven high effectiveness, but application in practice will depend on the local site conditions. The spatial positioning of fertilisers and manures in the field is one of the factors determining to what extent nutrients will be available to crops or exposed to loss processes (Anonymous, 2011; Chen et al., 2014).

Precision fertilization can be seen as a further clarification of balanced fertilization, i.e., precision fertilization involves in the first place balanced fertilization. Positioning has a horizontal and a vertical component. Horizontal aspects pertain to the evenness of application, variable-rate application as a function of the soil nutrient status, and the ability of machines to position nutrients to just the rooted parts of the soil profile in case of row crops. Vertical aspects pertain to the ability of (combinations of) machines to incorporate fertilisers and manures in such a way that the risks of volatilization and run-off losses are minimized, whilst assuring that the nutrients can still be timely intercepted by plant roots. In some cases, top dressings via spraying of dissolved nutrients are practices to ease the uptake by the crop.

Precision fertilization can increase the use efficiency of applied N and thereby decrease the risk of leaching loss. The use efficiency of N is highest when high-yielding crop varieties are used, all other essential nutrients and water are in adequate supply, and pest and diseases and weeds are controlled. Increasing crop yield and N withdrawal with the harvested crop, through for example genetic improvement or improved pest and disease control and/or weed control, at constant N input, reduces the risk of N leaching. Hence, N use efficiency enhancing measures reduce the risk of N leaching, especially when the N input is adjusted. The term 'efficiency enhancing measures' is often preferred over 'source-based measures', because efficiency enhancing measures address the output : input ratio, and thus consider both increases in N output and decreases in N input. However, a high efficiency may be achieved at low N input and at relatively high N input; the N surplus will be higher in the latter case than in the former. This is why the EU-Nitrogen Expert Panel recently suggested to report both NUE, N surplus and N output (EU-Nitrogen Expert Panel, 2015).

Precision fertilization may decrease potential N leaching especially in grazed pastures with a huge spatial variability in N input through the uneven spreading of urine and dung from grazing animals (Di and Cameron, 2002). However, it is notoriously difficult to identify urine and dung patches in the field and to adjust N applications via N fertilizer and/or manure (Buckthought et al., 2015; Roten et al., 2017)

6.3.5. The growth of cover crops

Cover crops are crops grown after main crops and intended to intercept the mineral N left by or liberated from the residues of these main crops, or to minimize erosion risks (Aronsson et al., 2016; Ostenburg et al., 2007; Van Boekel., 2015. Instead of becoming lost, residual N can in this way be transferred to a next growing season where it can contribute to the N supply of subsequent main crops. Cover crops should not be fertilised, unlike the so-called green manures *sensu strictu* of which the production is often maximized by the application of plant nutrients to increase the input of organic matter into the soil. Crop species largely differ in their ability to scavenge soil mineral N and transpose this N effectively. The ideal species should be able to germinate in a relatively dry seedbed, should be frost or even cold resistant and should be deep rooting where residual soil mineral N happens to find itself at greater depths (Dalgaard et al., 2014).

Leguminous species may be very suitable to act as a green manure in low input cropping systems in need of additional N sources, but are less apt as scavenger of N residues. The amounts of N fixed by this type of crops may increase instead of mitigate the risks of N emissions. A successful establishment and growth of cover crops is often more difficult after crops typically associated with a late harvest (potatoes, maize) than after early crops (cereals), whereas the amounts of residual mineral N are greatest in these late crops. The potential yield of a green canopy is strongly related to the length of the period during which weather conditions (temperature, light) favour biological processes. The larger the fraction of this period being used for the production of the main crop, the smaller the remaining fraction available for a subsequent cover crop. The available heat sum (‘degree days’, i.e. the summed daily average temperatures above a threshold value allowing biological processes) determines to which extent residual N can indeed be taken up by cover crops. As a result, it is difficult to grow cover crops in cool regions (Aronsson et al., 2016).

Results indicate that cover crops are effective to reduce nitrate leaching losses, especially when the main crop is harvested early. This allows the cover crop to establish well and to mop up residual mineral nitrogen from the soil. It is also a rather cost-effective method (Ostenbrug et al., 2007; Dalgaard et al., 2014; Aronsson et al., 2016).

6.3.6. Manure storage capacity in leak-tight containers

The storage capacity of containers for livestock manure must be large enough to store the manures produced during the period when the application of manures are inappropriate. It is one of the main measures of the Annex II of the Nitrates Directive, but not included in the list of measures of Osterbrug et al., (2007) and Van Boekel (2015). The investment costs are rather high (3-10 euro per m^3) but depending on the type and volume of the storage (Bittman et al., 2014).

The construction of the storage container (or vessel, lagoon or pit) must be robust and leak-tight, and should be covered preferably to minimize the loss of gaseous ammonia and the influx of rain water. The required storage capacity may range from 3 to 9 months per year, depending the pedo-climatic zones, land use and the vulnerability of the nearby water resources. The size of the containers depends on the number of housed animals on the farm and the volume of manure produced per animal, corrected for the possible influx of spilled drinking water, cleaning water and the efflux of evaporation losses. The manure production per animal depends on animal category, production level, live weight, and the digestibility of the offered feed stuffs.

The governing factors for defining the manure storage capacity are length of the period when the land application of manure is inappropriate, number and type of animal species, manure production per animal species, manure type (solid, liquids and slurries), addition of bedding material and litter, addition of cleaning, spilling and rain water, presence of storage cover, manure processing and transport, evaporative losses and decomposition losses during storage.

The effectiveness of this measure strongly depends on the reference (or control treatment). When the reference method is daily spread (including the non-growing period), the effectiveness may be high. If the reference method is an unsealed lagoon, the effectiveness may be high too. However, if the reference is a proper storage for 4 months and the treatment measure is a storage capacity of 6 month, the effectiveness may be limited. However, there are no studies that have examined the effects of storage capacity in experimental studies.

6.3.7. Manure application limits

The maximum application rate of animal manure is 170 kg N per ha per year according to the EU Nitrates Directive, irrespective of land use and climate zone. However, there is opportunity to derogate from this limit, when justified on scientifically sound arguments. The regulation of the application rate requires an accurate assessment of the amounts of N and P applied in the form of animal manure (Schröder et al., 2007b). As far as N is concerned, the effects on water quality are not only determined by the applied rate of total N, but also by the ratio of mineral-N (Nm) and organically bound N (Norg) in the manure. One of the major factors determining the Nm:Norg ratio is the housing type i.e. the decision to keep animals on slatted floors resulting in slurries or provide ample bedding material (potentially) resulting in solid manures. To be able to respect the limit of 170 kg N per ha per year, farmers have to account for the total amount of N excreted by all farm animals, and correct this amount for gaseous N losses from housing and manure storages. Farmers have usually access to tables to find out how much N is in the manure per animal. Alternatively, farmer may estimate the amounts of N per animal on the basis of the mass balance:

$N_{\text{excretion}} = N_{\text{intake by the animal}} – N_{\text{retention by the animals}}$.

The amount of N excreted must be corrected also for the gaseous N losses during storage (which may range from 10-40%, depending on the manure type and storage condition and duration. This assessment (book keeping) of amount of N (and P) in manure is likely the most accurate way of estimating N production, provided accurate information is available about total feed intake, weighted mean protein content of the feed and the amount of animal protein exported from the farm.

The manure N application limit of the EU Nitrates Directive is effective in the sense that it limits the manure N application. There is a considerable amount of literature that has investigated the differences between manure N and synthetic fertilizer N efficiency, also in terms of reducing N leaching. In short-terms experiments, N leaching losses from treatments with manure N are commonly lower than the N leaching loss from treatments with synthetic N fertilizer, because part of the N in manure is organically bound and hence not available to the crop nor vulnerable to leaching. However, long-term experiments often indicate that leaching losses from treatments with manure N are often higher than the N leaching loss from treatments with synthetic N fertilizer, because the mineralization of organic N from manure is not well synchronized to the N uptake by the crop (Basso and Ritchie, 2005; Schröder et al., 1993).

6.3.8. Closed periods for the application of fertilizers and manures

Risks of nutrient leaching are most imminent when 1) the natural precipitation exceeds the evapo-transpiration and the water holding capacity of the soil, 2) soils tend to crack which may lead to preferential flow, or tend to seal which may lead to overland flow, 3) the land is sloping, and 4) soils contain considerable amounts of water-soluble N and P, while there is no growing crop. Hence, application of fertilizers and manures is inappropriate when the demand by the crop of nutrients is low and the risk for surface runoff and leaching of nutrients are high. The risk of leaching depends also on the ratio of mineral N to organically-bound N; solid manures with litter commonly have a Nm/Ntotal ratio of <0.3, and are less vulnerable to leaching (but not to surface run off).

Application of fertilizers and manures just before and during the growing season has been shown to be an effective method to reduce nitrate leaching losses (Schröder et al., 1993; Thomsen et al., 1993; Beckwith et al. 1998).

6.3.9. Restriction on the application of fertilizers and manures to steeply sloping land.

The application of fertilizers and manures to steeply sloping land is associated with high risk for surface run-off of N and P, which may result in the pollution and eutrophication of surface waters. Hence, the application of fertilizers and manures to steeply sloping land must be limited and done in such a way that the risk of surface run-off of N and P is strongly minimized. Risks of surface run-off are greatest where there are nutrients (sources), and where the infiltration capacity of soils and potential residence time of water are low. This implies that risks are positively related to the soil fertility status of a soil, application rates of fertilizers and manures and the extent to which they are left on the surface, the surface roughness as related to the infiltration capacity, and the extent to which water is hold *in situ* instead of allowed to flow run-off as quickly as possible. Infiltration capacity can be increased by minimum tillage without the removal of crops residues (mulching), sub-soiling, ridge tillage, cover cropping, the conversion of arable land into grassland, agro-forestry or complete reforestation. Incorporation of fertilizers and manure may help to reduce the risks. This is technically feasible, but it may be more difficult in the case of the presence of stones. As nutrients in solid manures are generally less mobile than those in slurries, solid manures are somewhat less risky than slurries

The length and steepness of the slope define the slope classes:

- Flat: 0 to 2%; negligible risk of surface run-off (green)
- Rolling: 2 to 8%; moderate risk of surface runoff (yellow)
- Sloping: 8 to 15%; high risk surface runoff (pink)
- Moderately steep: >15%; very high risk of surface runoff (red)

Various studies have indeed verified that application of fertilizers and manures on sloping lands is conducive to surface run off and losses of N and P (Smith et al., 2001a, 2001b; Gilley and Risse (2000). Management practices used to control runoff include contouring, permanent green covers (grassland), strip cropping, conservation tillage, terraces, buffer strips, and appropriate timing and subsurface application of manure and fertilizer. More than one runoff-control practice may be necessary in areas with high runoff potential. Alternatively, the application of fertilizers and manure is prohibited.

6.3.10. Restrictions on fertilizer and manure applications to saturated or frozen land.

The application of fertilizers and manures to water-saturated, flooded, frozen or snow-covered ground is associated with very high risk for surface run-off of N and P, which may result in the pollution and eutrophication of surface waters. Moreover, applications of fertilizers and manures are not effective as there will be no growing crop and a demand for nutrients. Hence, the application of fertilizers and manures to water-saturated, flooded, frozen or snow-covered ground should be prohibited.

However, the application of fertilizers and manures on frozen but dry soils without snow cover may be advantageous in pedo-climatic zones with a short growing season and on soils with high risk of soil compaction by traffic. Farmers may appreciate frozen soils for their carrying capacity allowing land spreading of manures without negatively affecting the soil structure. Even without a snow cover this practice can still be conducive to serious nutrient losses because of the very low permeability of the soils. The low permeability can trigger superficial run-off, also when the frozen soil layer is below the soil surface (i.e., the soil surface is thawed already) and thin. Hence, manures and fertilisers applications should be avoided when the soil is frozen and snow covered, irrespective of the thickness of the snow cover. On dry (without any snow cover) frozen soils, overgrown by a winter cereal, starter fertilizer application could be beneficial, when the soil would become compacted otherwise. However, special pre-cautionary measures should be taken in this case, such as unfertilized buffer strips, to minimize the risk of pollution of surface waters.

There is indeed quite some empirical evidence that manure application on frozen, snow covered and/or flooded soils may contributes to increased leaching and surface run-off losses. This evidence mainly comes from studies in northern America (Converse et al., 1976; Srinivasan et al., 2006; Williams et al., 2011), and less from northern Europe. The increased potential for losses of N and P originates from the facts that (i) nutrients may not easily infiltrate frozen, snow-covered and/or flooded soils, (ii) there is no growing crop that can take up the applied nutrients, (iii) rainfall may not infiltrate frozen, snow-covered and/or flooded soils, and (iv) snow and ice melt may contribute to increased surface runoff.

6.3.11. Buffer strips near water courses.

Application of fertilizers and manures near water courses is accompanied with the risk of direct application of fertilizer and manures into surface waters. One of the reasons for that is the inevitable lack of preciseness of spreading equipment and the ones in charge of operating that equipment. Moreover, the indirect discharge of fertilizer and manure nutrients into surface waters through surface runoff and leaching may be also significant, especially on sloping grounds, and soils with very low infiltration capacity or just permeable soils. Unfertilized buffer strips where fertilizer and manure applications are withheld can be highly effective in this case. Unfertilised buffer strips further contribute through an increased residence time of nutrients in the field as a whole, thus enlarging the probability of denitrification (N) and retention in soil (P). If vegetated and left unfertilised, strips can also act as effective interceptors of the nutrients passing by.

The effectiveness of buffer strips is variable. Differences in width, slope, vegetative cover, and soil composition and hydrology represent some of the reasons for this. On sloping fields with relatively impermeable subsoil, water is mainly discharged via run-off and superficial flow. The effectiveness of strips acting as a filter is greater on sloping fields than when strips are established in flat landscapes on deeply drained soils. Besides, if strips are intended to remove N via denitrification, the environment needs to be conducive to that process by providing sufficient carbon substrate and by having a low oxygen concentration. When groundwater level is high and the land is drained via subsurface or surface drains, the effectiveness of buffer strips is low. In summary, buffer strips along water courses seem most appropriate whenever there is a risk of surface run-off i.e. on both sloping land and on flat land whenever the upper soil is periodically water-saturated, in particular when the discharge of water is not evenly distributed in time (e.g. summer storms, thawing snow cover. The need for buffer strips is greater if the land is tilled, managed intensively and receiving considerable inputs of nutrients.

The effectiveness of buffer strips and riparian zones has been extensively studied in COST869 (2011), and results have been summarized in among others Van Boekel (2015). Buffer strips seem to be effective measures for reducing P-loads to surface water in sloping land.

6.4 Discussion

Farmers make a myriad of tactical and operational decisions annually. From the early 1990s onwards they have to consider an increasing number of governmental constraints related to nitrogen use, which have their origin in the EU Nitrates Directive, EU Water Framework Directive, the EU National Emission Ceiling Directive and the UNECE Gothenburg Protocol (Oenema et al., 2011). All these Directives have paragraphs related to nitrogen management and to targets for nitrogen emissions. These regulations have made decision making of farmers much more complex. Suppliers and processing industries have also released a range of good and best management practices and guidelines, related to the environment and climate change, but also to product quality and production methods. These guidelines also affect the way nitrogen is used in agriculture.

Evidently, there is a wide range of possible measures to reduce nitrate losses from agriculture to groundwater and surface waters (Annex 1 and Annex 2). However, there is no “golden bullet” solution available, which would allow farmers to achieve high crop yields and at the same time reduce nitrate losses drastically. Yet, some measures are more effective than others. Reducing total N input was identified as the least cost-effective measure (on average 16 euro per kg N per year) in the study of Osterbrug et al (2007), while precision fertilization and timing, and using enhanced efficiency fertilizers were evaluated as cost-effective (1-3 euro per kg N per year) by Osterbrug et al (2007). They did not include a measure ‘comply with fertilization recommendations’. The DEFRA Guide Book does not include an option to reduce N input; rather they include the option ‘to comply with fertilizer recommendations’, which was evaluated as a cost-effective measure, as it give a net gain of 400 to 3000 British pounds per farm per year (Newell Price et al., 2011). Van Boekel (2015) did not identify N input control as a possible measure. In contrast, balanced N fertilization has been identified as the most effective measures of the EU Nitrates Directive (Velthof et al., 2009), although the cost of this measure is significant (Oenema et al., 2009). The diversity of possible and identified options to decrease nitrate losses from agriculture to the groundwater and surface waters may reflect differences in environmental conditions, notions of the N cycle and in culture. It may also reflect the wide variations in measured effectiveness.

The EU Nitrates Directives includes 10 measures in Annex I (Table 10) and 5 in Annex III (Table 11), but two of the Annex III measures overlap with those of Annex II. Demanding measures are A3 (N application limits) and B (manure N application limit) of Annex III, especially for intensive agricultural systems. These measures (with slight modifications) have been described in detail in Chapter 6.3, because most of these measures have been implemented in all EU Member States, and because these measures seem highly effective (although not equally across EU-28), and are formulated in such a manner that they are applicable across EU-28.

Based on the review of measures discussed in this chapter, a priority list of measures was formulated; the so-called short list of measures (Table 12). This list serves two purposes, (i) it provides a quick overview of effective measures, and as such is a first attempt to derive most promising measures (which is deliverable D4.3, in month 32), and (ii) it was used to focus the literature research for the further in-depth analysis of the measures, based on experimental results.

The quantitative analysis of the literature results is further discussed in Chapter 7.

Table 12. So-called shortlist of measures aimed at decreasing nitrate pollution of groundwater and surface waters, based on literature review, expert judgement and joint discussions. For these measures ***quantitative*** *data and information have been collected from the literature, stored in the Excel tool and then statistically analysed.*

Nr	Name of the measure	Characterization of the measures
1	Nitrogen fertilization; balanced nitrogen fertilization (dose of application)	Matching nitrogen input to the average nitrogen demand of the crop is termed balanced nitrogen fertilization. This measure includes terms like “reduction in fertilization”, nutrient management planning, and more drastic measures such as withholding nitrogen fertilizer inputs. Typically, this measure has been studied in nitrogen fertilizer trials. This measure includes also the combined use of synthetic fertilizers, animal manures, organic fertilizers, bio-based fertilizers, composts, etc. Evidently, crop type (crop rotation), soil type, soil tillage, etc. have to be specified as well (see below)
2	Precision nitrogen fertilization (optimization in space and time)	Precision nitrogen fertilization builds on balanced fertilization, and includes “variable rate fertilization” and “split applications”. This includes measures like a ban on fertilization in winter, on sloping land, on frozen land, etc. Evidently, crop type (crop rotation), soil type, soil tillage, etc. have to be specified as well (see below)
3	Enhanced efficiency nitrogen fertilizers	Enhanced efficiency fertilizers include various types of nitrogen fertilizers, with or without nitrification inhibitors, urease inhibitors, special coatings (slow-release fertilizers). Evidently, crop type (crop rotation), soil type, soil tillage, etc. have to be specified as well (see below)
4	Changes in crop types and/or crop rotations	Changes in crop types and rotation (without much change in nitrogen fertilization input) may change the nitrogen output with harvested crop and thereby nitrogen leaching. This measure includes a change to high-yielding crop varieties, and energy crops Evidently, crop type (crop rotation), Nitrogen input, soil type, soil tillage, etc. have to be specified as well (see below)
5	Cover crops	Cover crops or catch crops or green manures are grown after the harvest of the main crops, and serve to mop up residual mineral nitrogen from the soil and/or to improve soil quality. These crops may be sown in between the main crops (relay cropping) or after the harvest the main crop. Evidently, crop type, sowing/harvesting data, soil type, soil tillage, etc. have to be specified as well (see below)
6	Mulching	Mulching refers to the covering of the soil with crop mulch or with plastic mulch, mainly to reduce evaporation, modify soil surface temperature, and suppress weed growth. Due to changes in crop yield and soil water flow and utilization, leaching may be suppressed.
7	Restricted grazing	Restricted grazing includes zero grazing, spring-season grazing only, and siesta-grazing. This measure refers to a decrease in the animal-grazing hours per year relative to year-round grazing or day-and-night grazing during the growing season.
8	Buffer strips	Buffer strips refer to the strips of land along water courses. These strips have adjusted management (fertilization, crops, tillage) and thereby minimize the leaching and overland flow to surface waters. The width and management of the strip are critical
9	Riparian zone	Riparian zones refer to wetland areas along water courses which intercept and scavenge nutrients from leaching and overland flow pathways before entering the water courses. It includes constructed wetlands. Special vegetation and management may increase the scavenging of nutrients and thereby the pollution of the surface waters
10	Irrigation	This measure includes sprinkler irrigation, drip irrigation, furrow irrigation, flood irrigation, and fertigation. Irrigation may both increase or decrease leaching, depending on irrigation practice, crop type, soil type and weather conditions.

7. QUANTITATIVE ANALYSES OF MEASURES AND PRACTICES

7.1. Introduction

A systematic literature search and inventory has been conducted to collect experimental data and information for a quantitative analysis of the effectiveness of measures aimed at decreasing nitrate pollution of ground water and surface waters. All data were stored in a database and analysed statistically using R-programming (https://www.r-project.org/).

This chapter presents the results of the literature search and data analyses. A total of 84 literature sources have been collected about nitrate pollution. A total of 44 papers contained data about pollution of surface waters, and 80 papers about pollution of groundwater, indicating that 40 papers contained data for both surface waters and groundwater pollution. Table 13 provides an overview of the database. Annex 3 presents the list of references of the studies that have been examined.

Table 13: Summary of the database on measures aimed at decreasing nitrate pollution of groundwater and surface waters (Status 1 October 2018). In total, there were 228 experimental comparisons, but 55 of these were as yet excluded due to treatments and data that could not be interpreted.

Measures:	Number of studies	Response ratio (±sd)	Number of comparisons	Outliers
Nitrogen input control	14	0.67 (0.29)	33	1
Fertilization type and method	15	1.04 (0.36)	25	1
Timing of application	3	0.99 (0.43)	16	0
Nitrification inhibitors	2	0.50 (0.16)	10	0
Crop types and crop rotations	20	0.56 (0.36)	27	7
Cover crops	12	0.61 (0.36)	32	0
Mulching/Tillage methods	9	0.66 (0.22)	16	1
Irrigation	4	0.98 (0.69)	13	0
Other*	5	-	9	-

*e.g. experiments about energy crops and drainage, among others

The literature search and data screening took more time than initially expected and the number of studies included in the database is too limited to conduct a full meta-analysis. The 84 studies included in the database have been conducted mostly in the EU-28, but some studies originate from other continents. Most of the studies from EU originated from western Europe. Most studies dealt with nitrogen input control, fertilization type and application method, crop type and cover crops (Table 13).

A full meta-analysis of an updated database will be reported in the report (D4.3) on 'most promising measures to decrease nitrate pollution of groundwater and surface waters', which will be released by the end of 2019.

7.2. Summary overview of the effectiveness of measures

Here, effectiveness of measures was derived from the response ratio (RR), which is the nitrate leaching loss from a treatment measure divided by the nitrate leaching loss of the reference treatment (control treatment). The latter is usually current practice or conventional practice. The ratio may vary from 0 to more than 1; a value smaller than 1 indicates that the treatment measure decreases the nitrate leaching loss relative to the reference treatment. A ratio of 1 means no effect. Instead of a relative comparison of nitrate leaching loss, the response ratio was sometimes derived from a comparison of nitrate concentration in waterbodies or from the amounts of soil mineral N in the soil between treatments, depending on the availability of the data in the reviewed publications (Chapter 2).

Table 11 provides an overview of the response ratio RR of some key treatment measures. The overall mean RR ranged from 0.5 to 1.04, indicating a wide range of effectiveness of the measures. Most measures had an RR in the range of 0.5-0.7. Treatments related to fertilizer type and application method, and time of application had a RR close to 0. The same holds for irrigation. This overview suggests that N input control measures, adjusting crop type/crop rotation, growing cover crops, adjusting mulching/tillage and use of nitrification inhibitors are the most effective measures.

Treatment measures greatly differ in their effectiveness. There is also a large variability in effectiveness within a set of treatment measures. A few additional comments have to be made here. Firstly, the number of studies/comparisons differed greatly between treatment measures; some of the treatment measures (e.g. N input control measures, adjusting crop type/crop rotation, growing cover crops) have a much greater experimental basis than others (e.g., use of nitrification inhibitors, time of application). Secondly, the standard deviation of the mean response ratio tended to be very large, indicating large variability in the effectiveness. Third, the mean response ratios have as yet not been corrected for the number of measurements and variance within studies. Fourth, the effectiveness of the treatment measures has not been analysed yet for different environmental and socio-economic conditions.

7.3. Nitrogen input control

Nitrogen input control measures appear effective; the mean response ratio was 0.67 (Table 13). It suggest that reducing N input decreases nitrate leaching. As discussed in Chapter 6, the relationship between N input and nitrate leaching loss is expected to be curve-linear, i.e., nitrate leaching loss is relatively low at low N input, but increase progressively when N input increases to a level where the crop is less and less able to take up the applied N (diminishing returns).

Our results clearly indicate that the response ratio RR increases the stronger the N input decreases (Figure 21). The results indicate that there is large variation in RR, which has not been examined in depth yet. A main source of variation between studies is the difference in environmental conditions, e.g., soil type, crop type, rainfall surplus). Another source of variation will be the reference treatment; if the reference treatment is a situation with excess N input, the response of a reduction in N input will large on average. However, if the reference treatment is a situation where N input is at or below the optimal level of N, seen from the perspective of crop growth, the response of a reduction in N input may be relatively small, as discussed before.

7.4. Fertilization type and method

Changing the type of fertilizer used, from mineral to organic, or from ammonium-based to nitrate-based, or from nitrate-based to urea-based fertilizers appears to have no robust effect on the nitrate leaching loss (Figure 22). Also the method of application (e.g., broadcasting versus band application versus injection) appears to have no robust effect (included in these data). The mean response ratio was 0.99, with the 95% confidence interval (±2s) ranging from 0.44 to 1.53.

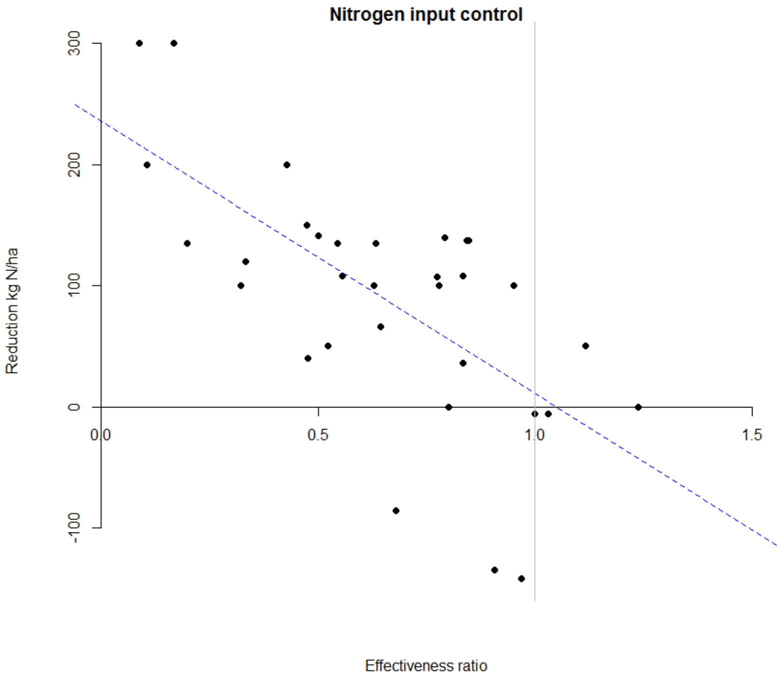


Figure 21. Relationship between a reduction in N input (Y-axis, kg/ha/yr)) and response ratio (effectiveness ratio) of nitrate leaching loss (dimensionless).

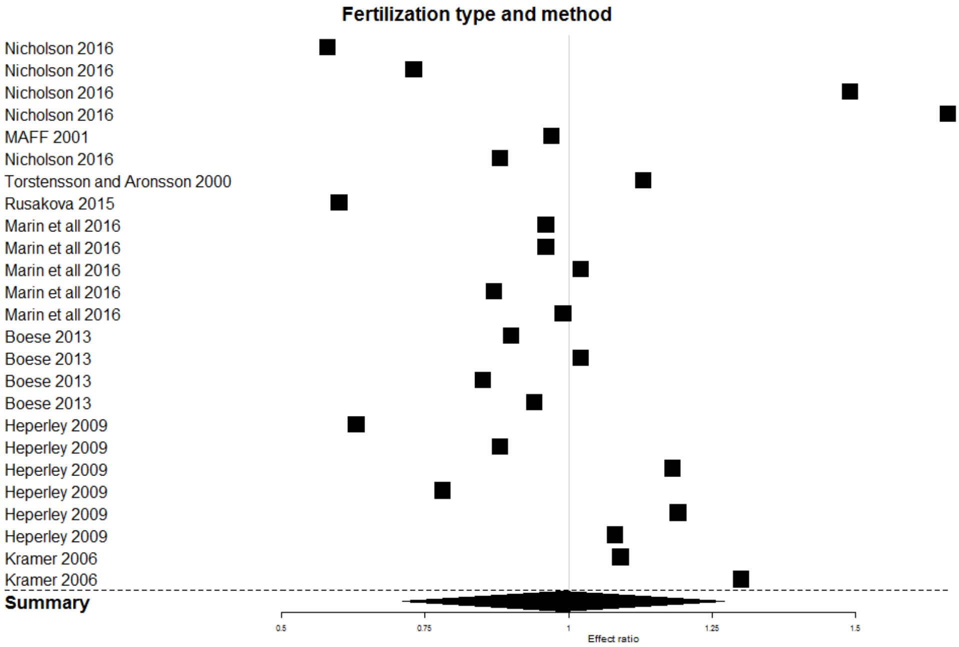


Figure 22. Response ratios of changing fertilization type and methods (n = 25 from 9 studies). The diamond at the bottom indicates the standard deviation interval (±1s).

7.5. Timing of N application

The time of N application appeared to have no robust effect on nitrate leaching loss either (Figure 23). The mean response ratio was 1.04 and the 95% confidence interval (±2s) was from 0.44 to 1.53. There is a huge variation in response ratio, which is likely related to the differences in the set-up of the various studies and in the treatments examined. Response ratios <1 likely relate to the comparison of autumn fertilization versus spring fertilization. Response ratios >1 likely relate to different variants of autumn application (early autumn versus late autumn). Evidently, the response are large (two ways), indicating that timing is important, but the different treatments have to be sorted in a more logical manner before more definite conclusions can be made.

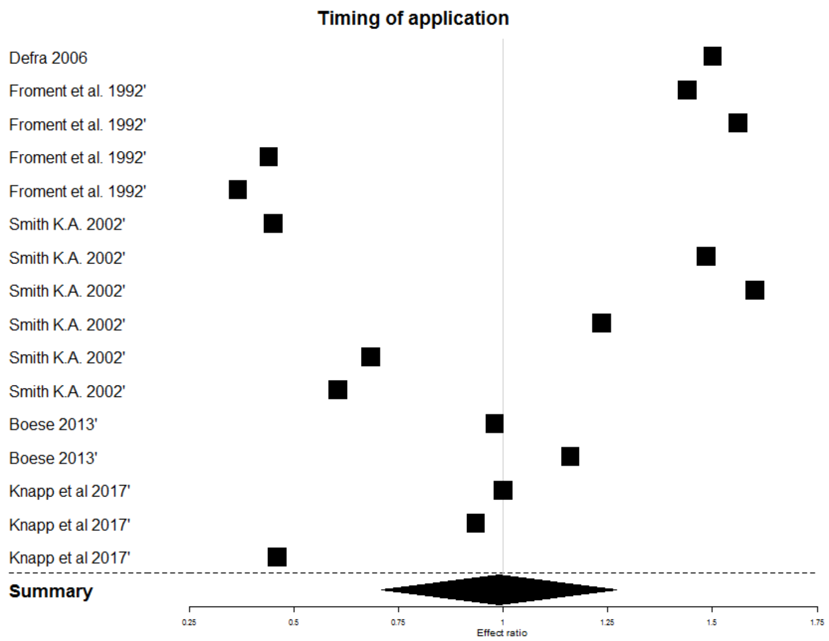


Figure 23. Response ratios of time of N application on nitrate leaching loss (n = 16 from 5 studies). The diamond at the bottom indicates the standard deviation interval (±1s)

7.6. Nitrification inhibitors

Nitrification inhibitors added fertilizers and/or animal manure delay the microbial oxidation of ammonium (NH_4^+) into nitrate (NO_3^-), and thereby may decrease the risk of nitrate leaching, depending also on the presence of crop that can take up the ammonium from the soil. Nitrification inhibitors may also decrease the emission of the intermediate nitrous oxide (N_2O), which is a powerful greenhouse gas. So far, only 2 studies have been included in the database, with results from 10 experiments. The mean response ratio was 0.5, and the 95% confidence interval (±2s) was from 0.44 0.14 to 0.87. These results suggest that using nitrification inhibitors gives a robust decrease in nitrate leaching loss (Figure 24). However, the number of studies and comparisons is too low to derive such conclusion now.

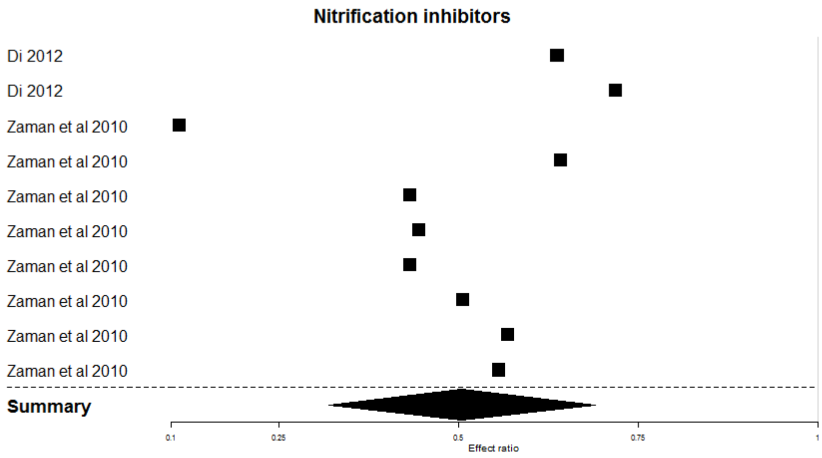


Figure 24. Response ratios of the use of nitrification inhibitors on nitrate leaching loss (n = 10 from 2 studies). The diamond at the bottom indicates the standard deviation interval (±1s).

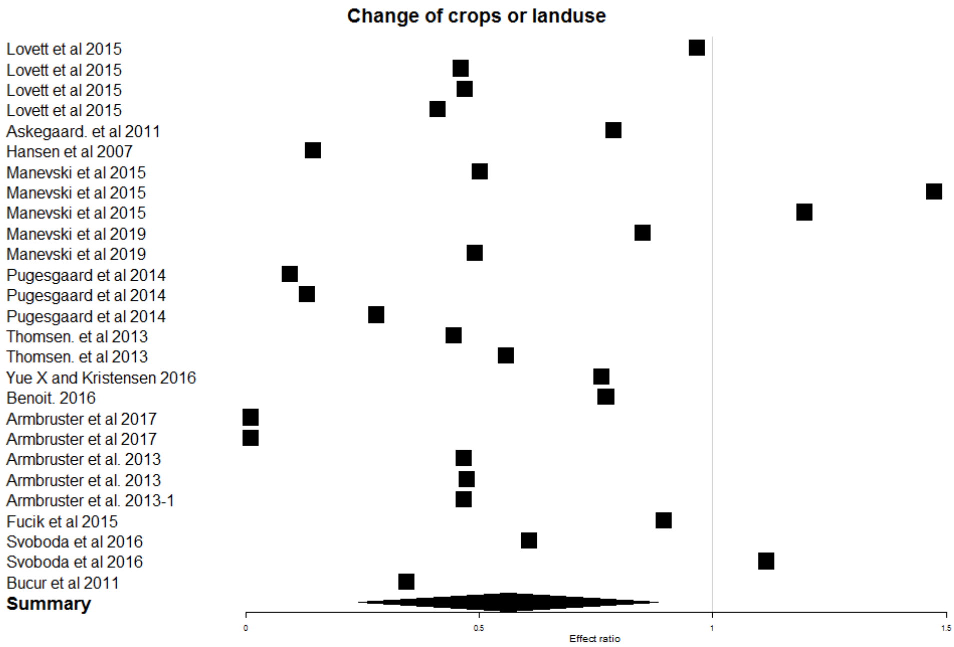


Figure 25. Response ratios of changing crop types and/or crop rotations on nitrate leaching loss (n = 27 from 14 studies). The diamond at the bottom indicates the standard deviation interval (±1s)

7.7. Crop types and crop rotations

Figure 25 summarizes the response ratios of changing crop types and/or crop rotations on nitrate leaching loss. The mean response ratio was 0.56 and the 95% confidence interval (±2s) was from 0.15 to 0.98. These results suggest that changing crop types and/or crop rotations give a robust decrease in nitrate leaching loss (Figure 25). Further analyses are needed to unravel the effects of co-variables on the mean response ratio. The response ratio of introducing a change in crop type and/or crop rotations may also depend on climate and soil types. Also, the measured response ratio of a treatment may be related to the duration of the experiment. These possible effects need to be examined further.

7.8. Cover crops

Cover crops grown after the harvest of the main crop may mop up residual mineral nitrogen in the soil, but also increase evapotranspiration, and add organic matter to the soil when the cover crop is ploughed down in the top soil. Figure 26 shows that the results collected in the database so far. The mean response ratio was 0.61 and the 95% confidence interval (±2s) ranged from 0.27 to 0.94, suggesting a robust decrease in nitrate leaching loss. Some treatments showed an increase in nitrate leaching loss (positive RR), which may be related to N fertilization of the cover crop, the growth of leguminous cover crops, and/or to the effects of soil cultivation associated with the growth of the cover crop. Evidently, this needs to be examined further.

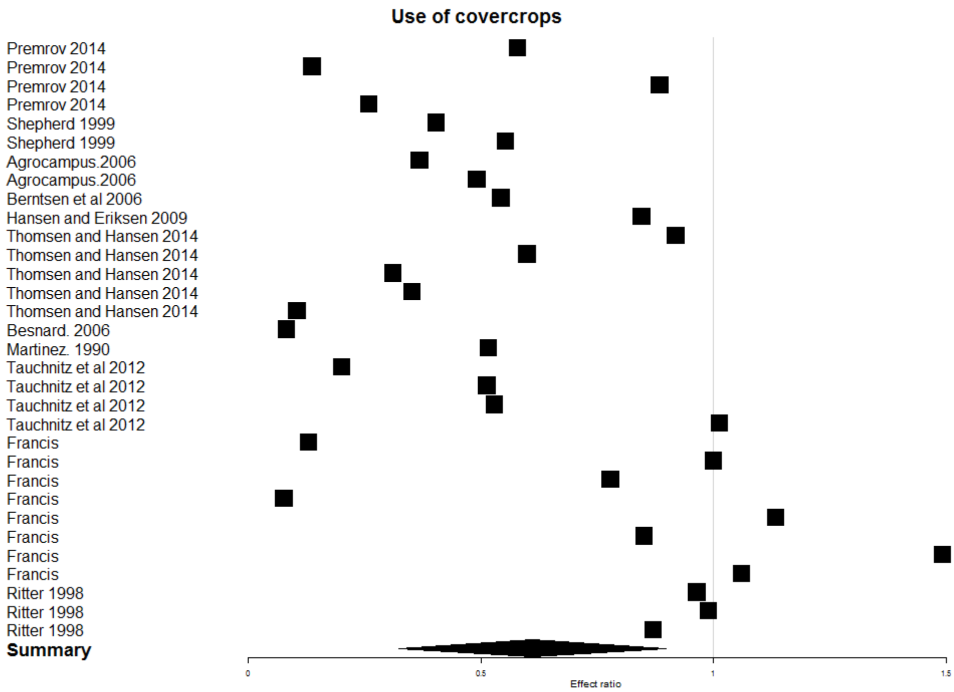


Figure 26. Response ratios of the growth of cover crops on nitrate leaching loss (n = 32 from 10 studies). The diamond at the bottom indicates the standard deviation interval (±1s)

7.9. Tillage and mulching

Minimum tillage and mulching measures influence the infiltration capacity of the soil and the potential for overland flow and runoff, and thereby the nitrate leaching loss (Figure 27). The overall mean response ratio was 0.66 and the 95% confidence interval (±2s) ranged from 0.08 up to 1.23. The mean response ratio for mulching was 0.57 and that for minimum tillage was 0.74, while the 95% confidence intervals (±2s) ranged from 0 to 1.22 for mulching and from 0.17 to 1.31 for tillage.

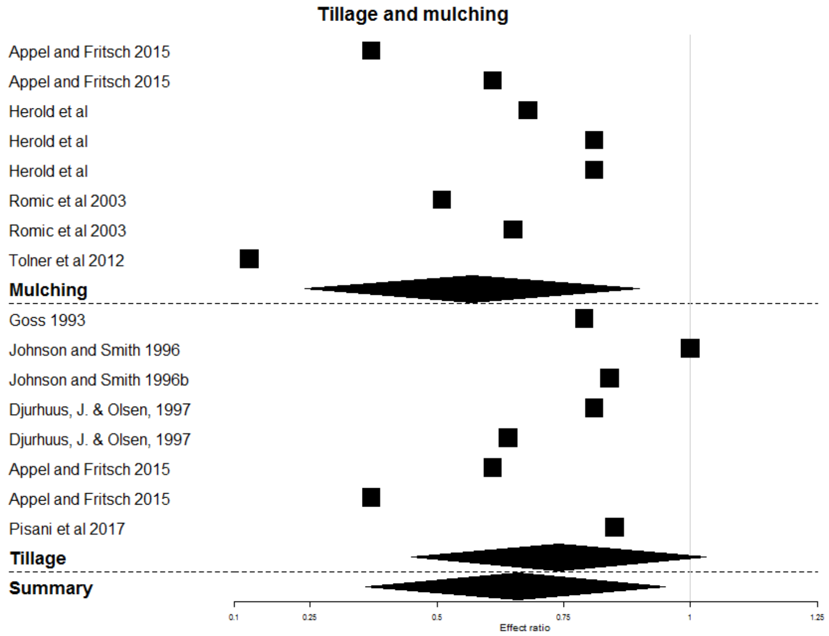


Figure 27. Response ratios of the effects of mulching (upper panel) and changes in tillage (bottom panel) on nitrate leaching loss (n = 19 from 9 studies). The diamonds indicate the standard deviation intervals (±1s)

7.10 Irrigation

Results of changes in irrigation on nitrate leaching loss were highly variable, with a 95% confidence interval (±2s) ranging from 0.41 to 2.34 (Figure 28).

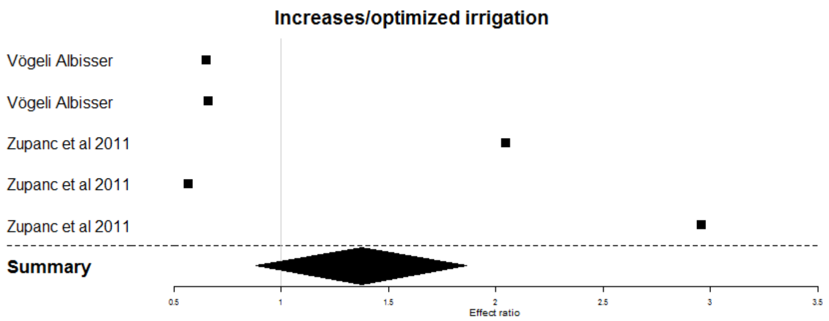


Figure 28: Response ratios of the changes in irrigation on nitrate leaching loss (n = 5 from 2 studies). The diamond at the bottom indicates the standard deviation interval (±1s)

8. DISCUSSION

8.1 IMPORTANCE OF MEASURES TO DECREASE NITRATE LOSSES

Large amounts of nitrate have accumulated in the vadose zone, the unsaturated zone between the land surface and the top of the groundwater phreatic zone. The total amount has been estimated at 605–1814 Tg, most of it is in North America, China and Europe where there are thick vadose zones and intensive agriculture (Ascott et al., 2016). These amounts are roughly equivalent to 6 to 18 times the global N fertilizer us in 2015. The rate of accumulation has strongly increased from the 1950s onwards, coinciding with the rapid intensification of agricultural production through increased use of fertilizers, pesticides and irrigation. Authors estimate that the accumulation of nitrate-N in the vadose zone increases by 15 to 25 Tg N per year, which is 15 to 25% of the global N fertilizer use. The nitrate in the vadose zone migrates to aquifers and surface waters but some may have been denitrified before entering aquifers and surface water bodies. Similar or larger amounts have already accumulated in aquifers and surface waters, and thereby already affect drinking water resources.

Most of the leaching losses occur in nitrogen-intensive cropping systems. Zhou and Butterbach-Bahl (2013) conducted a meta-analysis of nitrate leaching losses from maize and wheat cropping systems in the world, which cover approximately 40% of the utilized agricultural area. They used results of 32 studies and 214 observations. The average nitrate leaching loss was two times higher loss for maize (57 kg per ha) than for wheat (29 kg per ha). On average, 15 % and 22 % of applied fertilizer N to wheat and maize systems were lost through nitrate leaching, respectively. The higher leaching losses from maize cropping systems were related to higher nitrogen fertilizer applications and wetter and warmer climate conditions. However, yield-scaled nitrate leaching losses were comparable between maize and wheat cropping systems. Low yield-scaled leaching losses can be achieved at near optimal N input for both maize and wheat cropping systems. Hence, low nitrate leaching loss per kg product can be achieved economical optimal N input. These results support also the view that about 15 to 25% of the current fertilizer N application are lost via nitrate leaching Ascott et al., 2016).

Following the increased awareness of the implications of the pollution of groundwater and surface waters from the 1980s onwards, series of best management measures and good agricultural practices have been proposed and implemented. The EU Nitrates Directive, approved in 1991 by the Member States of the European Union, has been a milestone in addressing nitrate leaching losses from agricultural sources. Its influence covers some 160 million ha of agricultural land now, where some 10 different measures are being applicable. Through the EU Water Framework Directive, approved in 2000, a range of additional measures have been proposed within river basin plans (Newell Price et al., 2011; Schoumans et al., 2011; Van Boekel, et al., 2015). In North America and Oceania, also a range of measures have been proposed, see e.g. Natural Resource Conservation Service Field Office Technical Guide (NRCS, 2018). Annex 1 presents a gross list of some different 40 measures that have been proposed and/or have been implemented to decrease nitrate leaching losses. Annex 2 provides an overview of measures that have been implemented in the case-study sites of FAIRWAY.

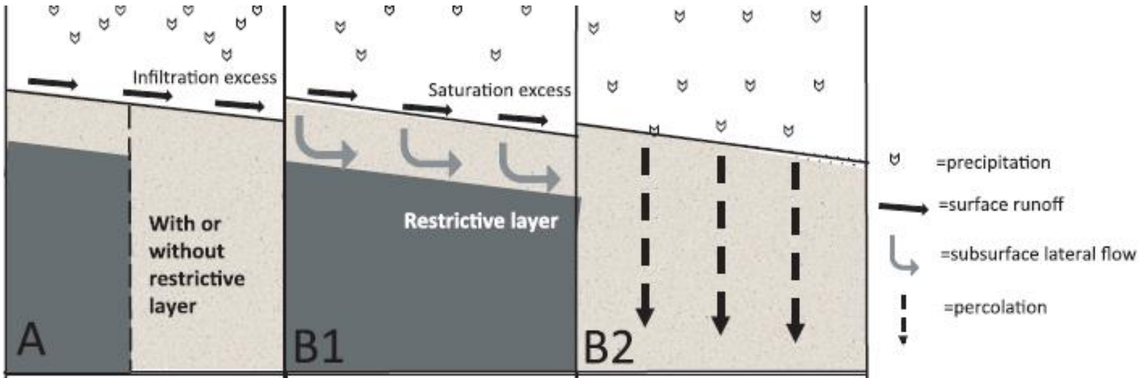
There are various regional success stories in member states of the EU showing that the implementation of measures have decreased the nitrate concentration in the soil solution of the vadose zone, in shallow groundwater and surface waters. In particular, some of the measures of the Nitrates Directive have been effective, including the storage of the animal manures in leak-tight storages, a ban on the application of fertilizers and manures during periods of the years when there is no or little crop growth, and application limits for N fertilizers and animal manures (e.g., Osterburg et al., 2007; Oenema et al., 2009; Dalgaard et al., 2014; Velthof et al., 2014; Van Grinsven and Bleeker, 2016; Hellsten et al., 2018).

Despite all these measures and regional success stories, the nitrate pollution problem continues to exist, as shown also by the recent synthesis report of European Commission (EC, 2018). A number of possible reasons have been put forward for the apparent ineffectiveness of policy measures to decrease the nitrate pollution problem sufficiently in some regions (Oenema et al., 2011). A main reason is the trade-off between decreasing nitrate pollution and farm income; nitrogen is an essential nutrient and farmers have learned over time that increasing N input has been beneficial for farm income, especially when the cost of N is low. As a result, there is hesitance to lower N input to the level of the economic optimal N input or to slightly below that level. Also, building manure storages for 6 to 9 months, and growing cover crops can be costly. Another important factor is the myriad of factors and processes that influence the nitrate loss from agriculture to groundwater and surface waters, and the variability of these factors and processes in space and time. As a result, blanket recommendations and measures are not always equally affective.

8.2 EFFECTIVENESS OF MEASURES

Our results presented in Chapter 7 do support the abovementioned general observations. In short, most measures are on average effective, but some measures turn out to be not effective on average. Effective measures were (i) N input control, (ii) adjustment of crop type and/or crop rotation, (iii) growth of cover crops, (iv) minimum tillage and surface mulching, and (v) nitrification inhibitors (Chapter 7). Somewhat surprising, fertilizer type and time and method of application turned out to be not effective. These initial results need further underpinning. Moreover, the effective measures do show a wide variation; the 95% confidence interval of the mean response ratio was often very large (Chapter 7), which is probably related to site-specific variations in socio-economic and environmental conditions. Though this variability will have to be explored further, it goes without saying that this variability affects the effectiveness of the measures. It is important to discuss this variability a bit further.

Rittenburg et al (2015) distinguished three hydrological situations in practice, for which different best management practices apply (Figure 29). They relate different agricultural best management practice (BMP) to these three situations. The hydrological situation depends on the location of the restrictive layer in the soil profile. Hydrologic land type A has the restrictive layer at the surface and BMPs that increase infiltration are effective. In land type B1, the surface soil has an infiltration rate greater than the prevailing precipitation intensity, but there is a shallow restrictive layer causing lateral flow and saturation excess overland flow. Here, N control measures may reduce nitrate losses. Land type B2 has deep, well-draining soils without restrictive layers that transport nitrate to groundwater via percolation. Authors reviewed a large number of studies (~180 papers) and assigned BMPs to each of the hydrologic land types, but they did not make a quantitative assessment of the effectiveness of the BMPs.



	A	B1	B2
	Precipitation intensity>infiltration capacity	Precipitation intensity<infiltration capacity	Precipitation intensity<infiltration capacity
Soil depth	Shallow or Deep	Shallow	Deep
Dominant Flow Paths	**Infiltration excess**, regardless of presence of restrictive horizon or slope	**Lateral flow** and/or **saturation excess; tile drainage**	**Percolation** and/or **tile drainage**
Probable Pollutant Transport	Pesticides, phosphorus, soil loss	Pesticides, nitrates, phosphates, soil loss	Pesticides, nitrates, phosphates
Effective BMPs	Mulch tillage, no tillage, terraces, CRP, buffers*, cover crops, NMPs, IPMs, constructed wetlands	Mulch tillage, no tillage, CRP, cover crops, tile drainage, NMPs, IPMs, constructed wetlands	CRP, buffers*, Cover crops, controlled drainage, crop rotations, forested buffers, NMPs, IPMs, constructed wetlands

Figure 29. Three different hydrologic land types (A, B1 and B2), for which different best management practices (BMPs) apply. NMP = Nutrient Management Plan; IPM = Integrated Pest Management; CRP = Conservation Reserve Program. (Source: Rittenburg et al., 2015).

Eagle et al (2015) conducted a meta-analysis of 4R nutrient management for corn-based systems in the US, focussed on nitrate leaching losses and N2O emissions. The final dataset consisted of 408 observations of N_2O losses from 27 studies (18 distinct locations) and 396 observations of NO3 leaching losses from 22 studies (16 distinct locations). They found no statistical significant effect of 4R strategies (right fertilizer source, right method and time of application) on nitrate leaching loss, but significant effects on N_2O emissions. Nitrate leaching losses were only weekly related to total N input (Figure 30). Leaching losses were higher in relatively wet climates. There was a large variability between sites and years (Eagle et al., 2015).

The variability in the relationship between N input and nitrate leaching is much less when environmental conditions are more homogenously and when the measurements are carried out under semi-controlled conditions. Boy-Roura et al., 2016) present the results of a meta-analysis of 12 lysimeter experiments that quantify nitrate-N leaching losses from grazed pasture systems in alluvial sedimentary soils in New Zealand. Nitrate leaching losses increased exponentially with Urinary N input (Figure 31). Mean measured nitrate-N leached (kg N/ha× 100 mm drainage) losses were 2.7 when no urine was applied, 8.4 at the urine rate of 300 kg N/ha, 9.8 at 500 kg N/ha, 24.5 at 700 kg N/ha and 51.4 at 1000 kg N/ha. Nitrate leaching decreased when nitrification inhibitors (e.g. dicyandiamide (DCD)) were applied.

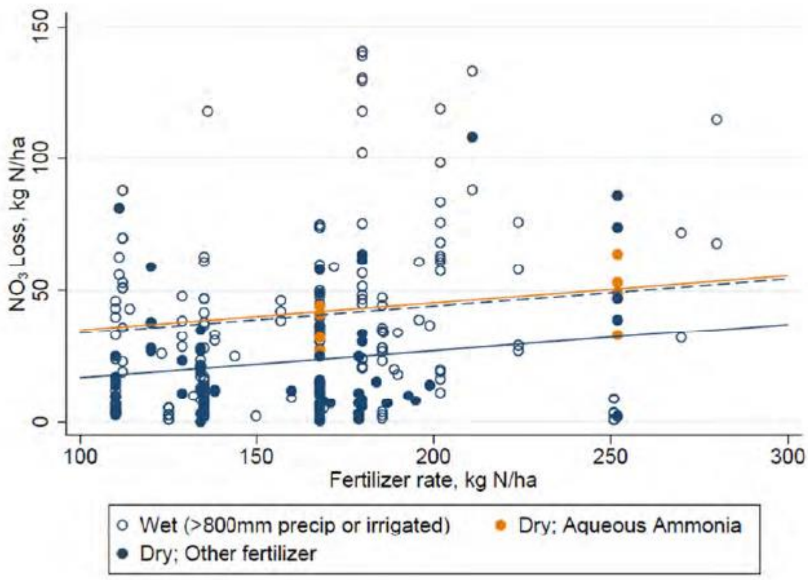


Figure 30. Nitrate loss responses to fertilizer N rate, precipitation or irrigation, and fertilizer source in corn/maize field experiments in North America, with fertilizer N application rates between 110 and 270 kg N/ha. (Source: Eagle et al., 2015).

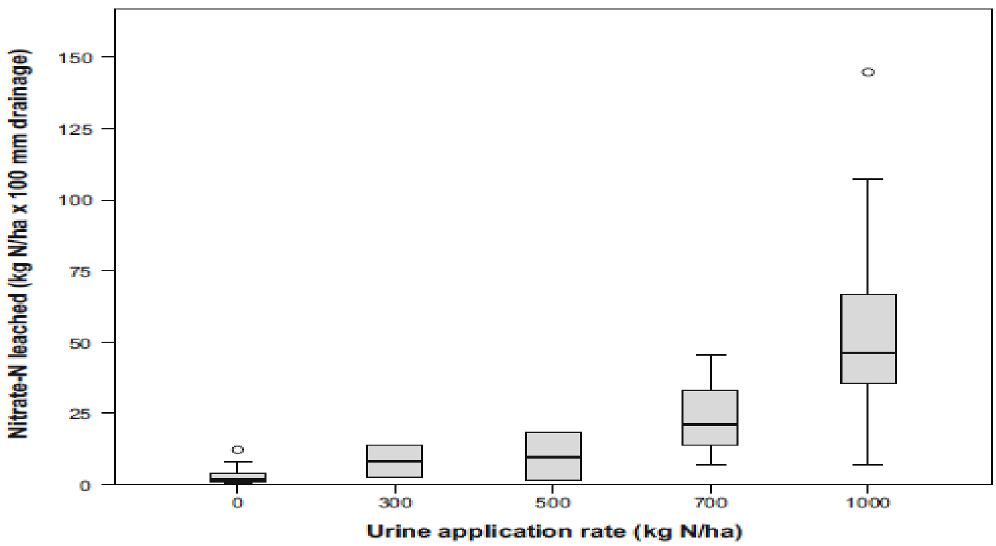


Figure 31. Relationship between urinary N applied and nitrate leaching (corrected for drainage volume); results of a meta-analysis of 12 lysimeter studies in New Zealand (Source: Boy-Roura et al., 2018).

Mondelaers et al (2009) conducted a meta-analysis of the differences in nitrate leaching between organic and conventional farming systems. There were 14 studies and 116 paired comparisons. Nitrate leaching was significantly lower for organic farming; the confidence interval was <1 for most comparisons. The lower leaching loss was accompanied with a ~ 20% yield penalty. Nitrate leaching per kg product produced was not significantly different between organic and conventional systems. There were large differences between studies, probably originating from differences in soil types (from sand to clay), climate (12 different countries), farming type, research method and the time of measurement. Based on 12 studies the weighted average leaching of nitrate was 9 kg/ha for organic farming and 21 kg/ha for conventional farming. The main drivers behind the higher nitrate leaching in conventional farming were the larger amounts of N fertilizer application, lower use of green cover crops, lower C to N ratio and a higher stocking density per ha.

Quite a number of studies have been published on cover crops (catch crops) and nitrate leaching. Dabney et al (2001) conducted a review on the effects of cover crops to improve soil and water quality. They argued that growing cover crops has more advantages than disadvantages, but they did not quantify the advantages and disadvantages in either monetary terms or ecosystems services. Arronson et al. (2016) summarized the literature on the role of cover crops in reducing nitrate leaching for Scandinavia. The mean relative reduction in N leaching was 43%, based on ~95 comparisons at 11 different sites, but it ranged between 62% increase instead of a reduction after a red clover cover crop to a reduction of 85%, equivalent to a decrease in nitrate N leaching of 36 to 51 kg per ha per yr (Figure 32). These results are overall similar to the results of our current database (Figure 26). In 2015, cover crops were grown on 8% of arable land in Denmark, 5% in Sweden, 1% in Finland, and 0.5% in Norway. Authors argues that there is potential for increased use of cover crops, but there is reduced interest among farmers. Therefore, there is need to develop implementation strategies.

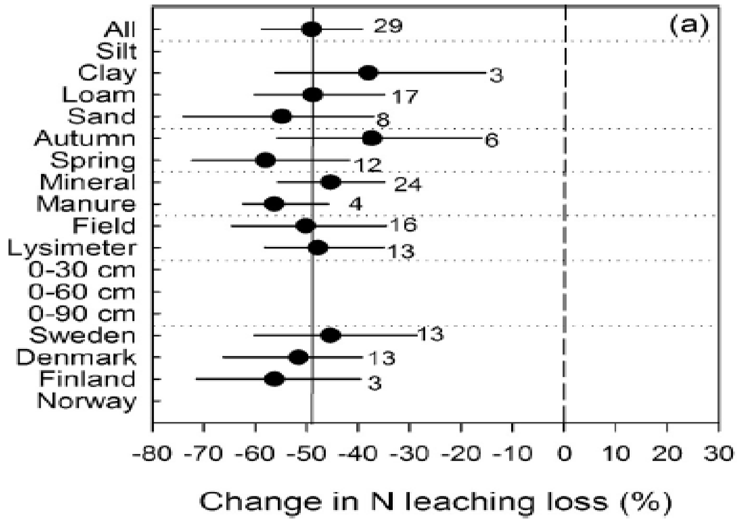


Figure 32. Changes in nitrate-N leaching loss due to catch crops compared to the controls with no catch crops. Results were further subdivided according to soil textures (silt, clay, loam, sand), ploughing time (autumn, spring), fertilizer types (mineral, manure), methods for measuring N leaching (field, lysimeter), and Nordic countries. Symbols indicate weighted average responses with 95% CIs. "All" and vertical line indicate summarized effect across all studies. The dashed line indicates the control groups. The numbers indicate the number of observations (Source: Arronson et al., 2016) .

Valkama et al. (2015) conducted a meta-analysis of 35 studies in Scandinavian countries dealing with the effect of both non-legume and legume catch crops undersown in spring cereals on nitrogen (N) leaching loss or its risk as estimated by the content of soil nitrate N or its sum with ammonium N in late autumn. Compared to control groups with no catch crops, non-legume catch crops, mainly ryegrass species, reduced N leaching loss by 50% on average, and soil nitrate N or inorganic N by 35% in autumn. Italian ryegrass depleted soil N more effectively (by 60%) than did perennial ryegrass or Westerwolds ryegrass (by 25%). In contrast, legumes (white and red clovers) did not diminish the risk for N leaching. The effect on N leaching were consistent across the studies conducted in different countries.

Van Boekel (2015) concluded on the basis of a literature review also that cover crops are effective in reducing the nitrate losses from the root zone (mean reduction in N leaching was 15 to 41 kg per ha), but the variation was high.

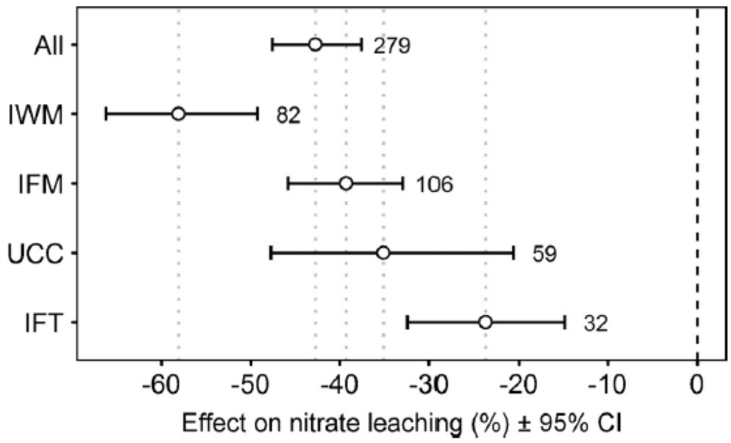


Figure 33. Changes in nitrate-N leaching loss of various measures in irrigated cropping systems: All is all management strategies examined, IWM is improved water management, IFM is improved fertilizer management, UCC is use of cover crops, IFT is improved fertilizer technologies. Mean values and 95% confidence intervals of the back-transformed response ratios are shown. The number of comparisons are shown on the right of the confidence intervals (Source: Quemada et al., 2013).

Quemada et al (2013) conducted a meta-analysis of published experimental results from irrigated systems. They examined 44 studies with 279 observations on nitrate leaching and 166 on crop yield. Management practices that adjust water application to crop needs reduced nitrate leaching by a mean of 80% without a reduction in crop yield (Figure 31). Improved N fertilizer management reduced nitrate leaching by 40%, and the best relationship between yield and nitrate leaching was obtained when applying the recommended fertilizer rate. Replacing a fallow with a non-legume cover crop reduced nitrate leaching by 50% while using a legume did not have any effect on leaching. Improved fertilizer application technology also decreased NL but was the least effective of the selected strategies. The risk of nitrate leaching from irrigated systems is high, but optimum management practices may mitigate this risk and maintain crop yields while enhancing environmental sustainability. Evidently, these results are convincing and are in stark contrast with the results of our current database (Chapter 7.11), which suggest that irrigation management does not decrease leaching. This requires further attention. Also, compared to conventional practices, the study of Quemada et al (2013) indicate the optimal and reduced N applications, and improved timing of the application decreased nitrate leaching significantly. Surprisingly, fertigation did not decrease nitrate leaching significantly (Figure 34). This is in contrast with the study of Qin et al. (2015).

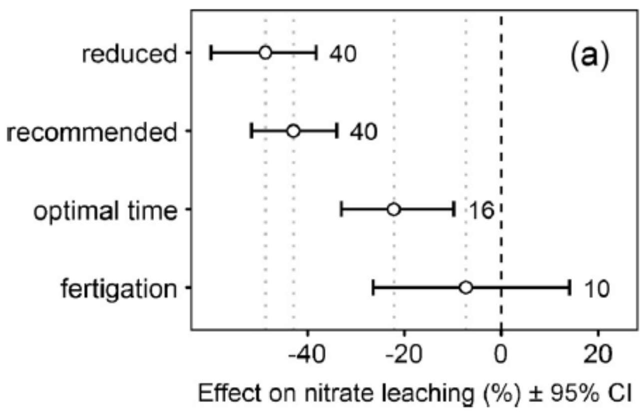


Figure 34. Changes in nitrate-N leaching loss of various measures in irrigated cropping systems: reduced is reduction in fertilizer N application, recommended is recommended fertilizer rate, optimal time is optimized timing of fertilizer application, and fertigation is the combined application of N with irrigation water. Mean

values and 95% confidence intervals of the back-transformed response ratios are shown. The number of comparisons are shown on the right of the confidence intervals (Source: Quemada et al., 2013).

Summarizing, there is overwhelming evidence of the effectiveness of various measures to decrease nitrate leaching losses. Nitrogen input control, cover crops and optimization of irrigation strategies all seem on average highly effective. However, there is a huge variability in the effectiveness of measures, especially when results are combined from different studies conducted in different environments. This calls for making measure more site specific.

8.3 COST-EFFECTIVENESS OF MEASURES

Few studies in our database with experimental data have examined the cost implications of measures aimed at decreasing nitrate leaching. Therefore, cost data come from other sources than the sources that were used for estimating the effectiveness of the measures (Table 7 and 8). Cost of the measures were estimated by experts from extension services in different countries, but mainly from Schoumans et al., (2011), Van Boekel (2015), Osterbrug et al., 2007 and the ADAS/DEFFRA report.

All 43 measures of the gross list in Annex 1 include cost estimates, expressed in terms of euro per farm. Three cost classes were distinguished, namely low (<1000 euro per farm per year), moderate (1000-5000 euro per farm per year) and high (>5000 per farm per year). Most of the listed measures fall in the class low and moderate, and only a few in the class high. The uncertainty is relatively high, which shows up in wide ranges; the low and high cost estimates differ usually more than 1000 euro, and incidentally more than 10000 euro per farm per year. These data do not allow as yet to derive accurate estimates of the cost-effectiveness (or efficiency) of the measures, as the uncertainty in the effectiveness (see Chapter 8.2) and in cost estimates are large.

Accurate estimates of the cost-effectiveness require farm-specific data, because the implementation costs and the operational costs of measures depend on farm type, farm size, and hydrological situation. Most often, coherent packages of several measures are needed to decrease the nitrate leaching loss sufficiently. This indicates that the cost-effectiveness of a single measure greatly depends on the implementation of other measures, which can only be estimated when the specific farm conditions are known. Depending on the specific combination of measures, the total cost of the implementation of coherent packages of measures will be in the range of -500 euro per farm per year to more than 10,000 euro per farm per year. These costs are in the same range as the farm payments from pillar 1 of the Common Agricultural Policy.

Howarth and Journeaux (2016) examined the trade-offs or various measures for grassland-based dairy farms in New Zealand on the basis of a literature review and additional calculations. Overall, reducing leaching by 0-20% resulted in a neutral impact on farm profit of 0 to +2%, whereas above a 20% reduction the impact on farm profit becomes increasingly negative. Supplementary feeding (use of lower protein feeds) showed a large variation in nitrogen leaching reductions of 3-42%, while the change in profit was relatively small (0-7% reduction). Eliminating winter nitrogen use reduced leaching by 12-15% while having a minor reduction on profit of 1%. Reducing N inputs throughout the season or eliminating them completely reduced leaching losses by 26-43%, which gave a ~10% decrease in farm profit, with a greater impact on profit resulting from greater reductions in nitrogen fertiliser and hence milk production. Figure 35 shows the calculated relationships between decreases in nitrate leaching loss and farm profit for a number of different studies. Farm profit decreased following the implementation of measures to decrease nitrate leaching losses. Again, the variability between studies was large.

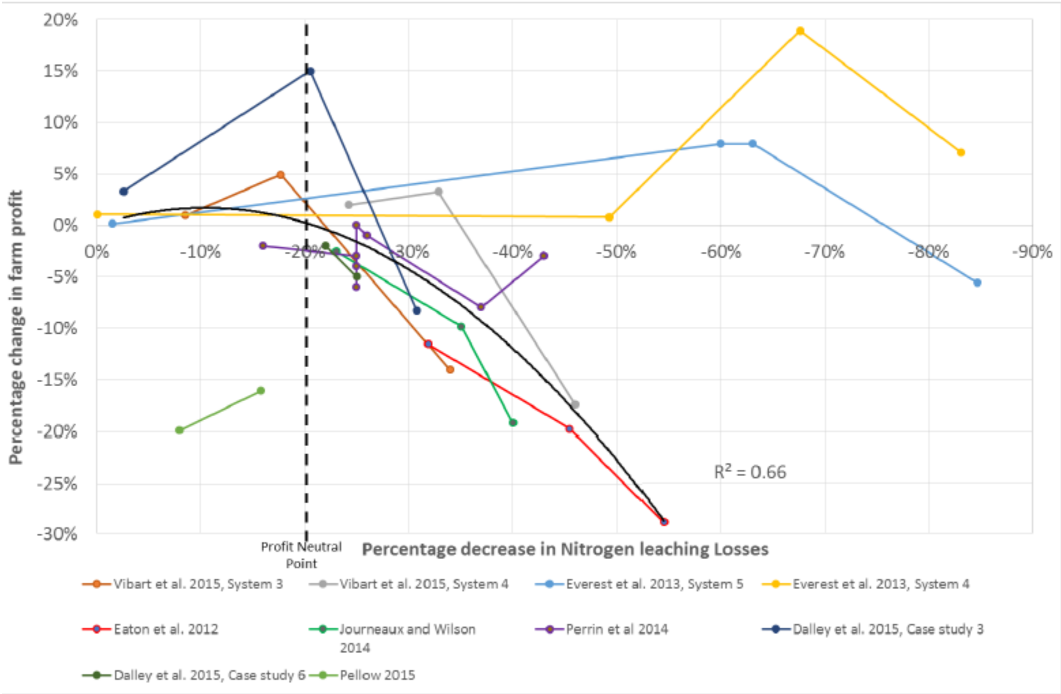


Figure 35. Relationship between decreases in nitrate leaching loss and farm profit for grassland-based dairy farms in New Zealand, based on 10 different studies. (Source: Howarth and Journeaux, 2016).

Summarizing, there is a scarcity of accurate cost estimates of measure aimed at decreasing nitrate leaching losses. A mean reason for this scarcity is that most research on the effectiveness of measures has been carried out in the past by natural scientists who were not always interested in the cost implications. Another reason for the scarcity is the large variation in practice and the need for more than one measure; this makes it difficult to estimate costs accurately. Most of the single measures cost less than 1000 or less than 5000 euro per farm.

8.4 Applicability and adoptability of the measures

Our quantitative literature assessment yielded little information on the applicability and adoptability of the measures, as these factors have not been researched in a systematic manner. The applicability and adoptability depends also on the specific socio-economic and environmental (climate, soils, hydrology) conditions (see Tables 7 and 8). The applicability and adoptability questions depend also on the type of measures; most measures that involve changes in crop type and crop rotation, growth of cover crops, and introduction of minimum tillage and mulching. Introducing changes in crop types and crop rotations are not accepted easily by farmers and landowners, because of questions related to the profitability and suitability of the suggested crop(s) in the rotation and/or the suitability of the soils, or because of lack of knowledge and machines. There may be also cultural barriers, which may be removed only following demonstration and arguing. Similar issues may be raised when proposing minimum tillage and surface mulching.

Conversely, some measures may be almost universally applicable and therefore may be adopted rather easily in practice unless economic cost form barriers. This holds for example for N input control, improved fertilizer spreading technology, use of nitrification inhibitors, change in the timing of fertilization. Such measures do not involve much changes at the farm, yet may have implications for farm income, and/or require investments and/or increased operational costs. The implementation of this category of measures may be facilitated through demonstrations and short-term subsidy programs.

8.5 NEXT STEPS

The overall objective of the FAIRWAY project is:

'*to review current approaches and measures for protection of drinking water resources against pollution caused by pesticides and nitrate from agriculture in the EU and elsewhere, and to identify and further develop innovative measures and governance approaches, together with relevant local, regional and national actors'*.

The current report is accompanying a report on a review of measures to decrease pesticides pollution of drinking water resources. These two reports and the forthcoming report on most promising measures will be important scientific building block basis for the further development of innovative measures and governance approaches for a more effective drinking water protection, together with local, regional and national actors.

The review presents a quantitative analysis of experimental measurement results from 84 publications. During the next 6 month, we will first evaluate the protocol and review process together with partners (see chapter 2), and then extend the database and further analyse and unravel the factors that contribute to both effectiveness of the measures and variability of the outcome. The extended database and results will then be used for the identification of the most promising measures, using the recently framework (Milestone 4.2).

For new empirical data and information about the applicability and adoptability of measures, we will liaison and cooperate with the related EU project WaterProtect. Cooperation with WaterProtect will create synergy; both projects have similar objectives but different approaches. While the FAIRWAY review focusses more on the scientific basis and robustness of measures, the WaterProtect review focusses more on collecting empirical information related to the feasibility and adoptability of measures. Exchange of information and cooperation will yield synergy and prevent overlap in activities.

9. CONCLUSIONS

The objective of the work reported here is 'to review and assess measures and practices aimed at decreasing nitrate pollution of drinking water supplies'. Based on the literature review, a gross list of 40 measures with key characteristics was compiled and is presented in Annex 1 of this report. Next, a quantitative analyses was made of key measures. Ultimately, the aim of the review is to identify so called 'most promising measures to decrease nitrate leaching losses, which will be discussed with stakeholders and tested further in the field. The delivery of the report on the identification of most promising measures is scheduled for the month 32 (beginning of 2020).

The novel aspect of our approach was that the accessible literature has been screened for experimental data related to the effectiveness of measures to reduce nitrate pollution of groundwater and surface waters, in a coherent and quantitative manner, using statistical analyses. This allowed an unbiased comparison of all measures. The review took more time than initially planned, and not all available literature has been screened and analysed in detail yet. Some further work needs to be done, which will be reported together with the report on the most promising measures.

A total of 84 papers with 228 experimental comparisons have been examined quantitatively and utilized for our statistical analyses; these papers report experimental data related to measures aimed at decreasing nitrate leaching losses. Results presented in Chapter 7 show that most measures were on average effective, but some measures turn out to be not effective on average. Effective measures were (i) N input control, (ii) adjustment of crop type and/or crop rotation, (iii) growth of cover crops, (iv) minimum tillage and surface mulching, and (v) nitrification inhibitors.

For some other measures the effects were less clear, which may be related in part to the low number of experimental comparisons. This is evident for example for improving irrigation strategies; our limited data suggest that irrigation does not have a clear effect on nitrate leaching, while a recent meta-analysis study (Quemada et al., 2013) indicates that improving irrigation strategies greatly contributes to decreasing nitrate leaching. Evidently, some further work needs to be done here. Also, fertilizer type and time and method of application turned out to be not effective. These preliminary results need further underpinning.

Though various measures were rated as effective on average, the results show also that the 95% confidence interval of the mean response ratio was often very large. This variation was largely ascribed to spatial and temporal variations in socio-economic and environmental conditions between and within sites. A further examination and discussion of some review papers and single-measure meta-analysis studies confirmed that a wide confidence interval of the mean effect of measures is often observed indeed. This holds especially when the results of measures are being compared across different farming systems, landscapes and climates.

The variability in the effectiveness of measures to decrease nitrate leaching losses across site is possibly one of the reasons for the widespread existence of groundwater and surface water monitoring stations with nitrate concentrations that exceed 50 mg/L, despite the implementation of series of measures during the last 2 to 3 decades. If variability is indeed a main reason for exceedance of the nitrate concentration threshold, then more investments should be made in the development and testing of farm-specific packages of measures.

10. REFERENCES

Abrahamsen, P., S. Hansen (2002) Daisy: an open soil-crop-atmosphere system model, Environmental Modelling & Software, 15 pp 313-330,

Addiscott, T. M., A. P. Whitmore & D. S. Powlson. 1991. Farming, Fertilizers and the Nitrate Problem, Wallingford: CAB International

Addiscott A.M., and N. Benjamin. 2004. Nitrate and human health. Soil Use and Management 20, 98-104.

Andersen, E., Verhoog, A.D., Elbersen, B.S., Godeschalk, F.E., Koole, B., 2006. A multidimensional farming system typology, SEAMLESS Report No.12, SEAMLESS integrated project, EU 6th Framework Programme, contract no. 010036-2, www.SEAMLESS-IP.org, 30 pp, ISBN no. 90-8585-041-X.

Antonopoulos et al 2018 Best environmental management practice for the agriculture sector - crop and animal production. European Commission, JRC. 628 pp. https://ec.europa.eu/jrc/en/research-topic/best-environmental-management-practice.

Arnold, J.G., D.N. Moriasi, P.W. Gassman, K.C. Abbaspour, M.J. White, R. Srinivasan, C. Santhi, R.D. Harmel, A. van Griensven, M.W. Van Liew, N. Kannan, M.K. Jha (2012) SWAT: model use, calibration and validation. Transactions of the ASABE, Vol. 55 pp 1491-1508.

Aronsson, H., E.M. Hansen, I.K. Thomsen, J. Liu, A.F. Øgaard, H. Känkänen and B. Ulén. 2016. The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. Journal of Soil and Water Conservation 71, 41- 55. doi:10.2489/jswc.71.1.41

Baker M.N. 2012. The Quest for Pure Water: The History of Water Purification from the Earliest Records to the Twentieth Century. American Water Works Association;

Basso, B. J.T. Ritchie (2005) Impact of compost, manure and inorganic fertilizer on nitrate leaching and yield for a 6-year maize–alfalfa rotation in Michigan. Agriculture, Ecosystems & Environment 108, 329-341.

Beckwith, C.P., J. Cooper, K. A. Smith and M.A. (1998) Shepherd Nitrate leaching loss following application of organic manures to sandy soils in arable cropping. I. Effects of application time, manure type, overwinter crop cover and nitrification inhibition. Soil Use and Management 14, 123-130

Beusen, A. H. W., Bouwman, A.F., Van Beek, L., Mogollón, J.M. & Middelburg, J. J. (2016). Global riverine N and P transport to ocean increased during the twentieth century despite increased retention along the aquatic continuum, Biogeosciences 13, doi:10.5194/bg-13-2441-2016.

Bittman, S., Dedina, M., Howard C.M., Oenema, O., Sutton, M.A., (eds), 2014, Options for Ammonia Mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen, Centre for Ecology and Hydrology, Edinburgh, UK.

Boy-Roura, M., K.C. Cameron, H.J. Di. 2016 Identification of nitrate leaching loss indicators through regression methods based on a meta-analysis of lysimeter studies. Environ. Sci Pollut Res (2016) 23:3671–3680.

Bouwman AF, Beusen AHW, Billen G. 2009. Human alteration of the global nitrogen and phosphorus soil balances for the period 1970-2050. Global Biogeochemical Cycles, 23,doi:101029/2009GB003576.

Bouwman AF, Klein Goldewijk K, Van der Hoek KW, Beusen AHW, Van Vuuren DP, Willems WJ, et al. 2011. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period. Proceedings of the National Academy of Sciences of the United States of America, doi/101073/pnas1012878108.

Bouwman, A.F., A.H.W. Beusen, J. Griffioen, J.W. Van Groenigen, M.M. Hefting, O. Oenema, P.J.T.M. Van Puijenbroek, S. Seitzinger, C.P. Slomp, E. Stehfest. 2013. Global trends and uncertainties in terrestrial denitrification and N2O emissions. Phil. Trans. R. Soc. B 2013 368, 20130112

Brevé, M.A. , R.W. Skaggs, J.E. Parsons, J.W. Gillham (1997) DRAINMOD-N, a nitrogen model for artificially drained soils Trans. ASAE, 40, pp. 1067-1975

Bruinsma JE. World agriculture: towards 2015/2030. An FAO perspective. London: Earthscan; 2003. 432 p.

Bryan, N.S., and H. van Grinsven (2013) The Role of Nitrate in Human Health. Advances in Agronomy, Volume 119. ISSN 0065-2113, http://dx.doi.org/.

Buckthought, L., T. Clough, K.C. Cameron, M. Shepherd (2015) Urine patch and fertilizer N interaction: effects of fertilizer rate and season of urine application on nitrate leaching and pasture N uptake Agric. Ecosyst. Environ., 203, 19-28.

Burt, T.P., A.L. Heathwaite and S.T. Trudgill 1993. Nitrate - Processes, Pattersn and Management. Wiley, UK, 444 pp.

Campbell, J.L.; Reinmann, A.B.; Templer, P.H. 2014. Soil freezing effects on sources of nitrogen and carbon leached during snowmelt. Soil Science Society of America Journal. 78(1): 297-308.

Carpenter, S.R., Caraco, N.F. Correll, D.L., Howarth R.W., Sharpley, A.N., Smith, V.H. (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8(3), 559–568.

Carpenter, S.R. (2008) Phosphorus control is critical to mitigating eutrophication. Proc Natl Acad Sci, 105(32): 11039–11040.

Chen, C., J. Pan, S.K. Lam (2014) A review of precision fertilization research. Environ Earth Sci (2014) 71:4073–4080. DOI 10.1007/s12665-013-2792-2.

Mommelin, M. et al (2018) Review of measures to decrease pesticide pollution of drinking water. FAIRWAY Report Series, Wageningen.

Converse, J. C., G. D. Bubenzer, and W. H. Paulson. 1976. Nutrient losses in surface runoff from winter spread manure. Trans. ASAE 19(3): 517-519.

Cost869, (2011) COST action 869: Mitigation options for nutrient reduction in surface water and groundwaters, including four special issues. http://www.cost869.alterra.nl/.

Dabney, S. M., J. A. Delgado & D. W. Reeves (2001) Using winter cover crops to improve soil and water quality. Communications in Soil Science and Plant Analysis 32, 1221-1250, DOI: 10.1081/CSS-100104110.

Dalgaard T, Hansen B, Hasler B, Hertel O, Hutchings N, Jacobsen BH, Jensen LS, Kronvang B, Olesen JE, Schjørring JK, Kristensen IS, Graversgaard M, Termansen M and Vejre H (2014) *Policies for agricultural nitrogen management - trends, challenges and prospects for improved efficiency in Denmark.* Environmental Research Letters, Environ. Res. Lett. 9 (2014) 115002 (16pp). http://dx.doi.org/10.1088/1748-9326/9/11/115002.

De Vries, W., J. Kros, O. Oenema & J. de Klein, 2003. *Uncertainties in the fate of nitrogen II: A quantitative assessment of the uncertainties in major nitrogen fluxes in the Netherlands.* Nutr. Cycl. Agroecosyst. 66 (1), 71-102.

De Vries, W., J. Kros, G.J. Reinds, R. Wieggers, G. Velthof, D. Oudendag, O. Oenema, G.J. Nabuurs, M.J. Schelhaas, M. Perez Soba, W. Rienks, W. de Winter, J. van den Akker, M. Bakker, P. Verburg, B. Eickhout & L. Bouman, 2010. *INTEGRATOR: A modelling tool for European-wide assessments of nitrogen and greenhouse gas fluxes in response to changes in land cover, land management and climate. Calculation procedures, application methodology and examples of scenario results.* Wageningen, Alterra. Alterra Report.

Di, H.J. and K.C. Cameron (2002) Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. Nutr. Cycl. Agroecosyst., 64, 237-256.

Eagle, A.J., K. Locklier, J. Heffernan, E. Bernhardt, T. Vegh, L.P. Olander. 2015. Nitrogen losses; A meta-analysis of 4R nutrient management in US corn-based systems. 4R Research Fund, Project #IPNI-2014-USA-4RM10. Duke University.

EC 1991 Directive of the Council of December 12 (1991) concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC). European Commission, Brussels, 1-8.

EC 2014, Framework for Action for the management of small drinking water supplies, ISBN 978-92-79-44633-7.

EC 2014, Synthesis Report on the Quality of Drinking Water in the EU examining the Member States' reports for the period 2008-2010 under Directive 98/83/EC. Brussels, 16.6.2014 COM(2014) 363 final.

EEA (2015) Nutrients in freshwater (CSI 020) — assessment September 2014. https://www.eea.europa.eu/soer-2015/countries-comparison/freshwater.

Eurostat (2018) http://epp.eurostat.ec.europa.eu.

Evens, L.T. (1975) Crop Physiology. Cambridge University Press, Cambridge, United Kingdom, 375 pp.

FAO, 2011. Water and soil requirements: 2.1.4 Calculation of crop water requirements http://www.fao.org/docrep/u3160e/u3160e04.htm

Faostat (2018) http://faostat.fao.org/default.aspx

FAO (2018) Integrated plant nutrient management. http://www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/scpi-home/managing-ecosystems/integrated-plant-nutrient-management/en/

Feichtinger, F. (1998) STOTRASIM — Ein Modell zur Simulation der Stickstoffdynamik in der ungesättigten Zone eines Ackerstandortes Modelle für die gesättigte und ungesättigte Bodenzone, 7, Schriftenreihe des Bundesamtes für Wasserwirtschaft, Wien. pp. 14-41.

Fowler, D., Coyle, M., Skiba, U., Sutton, M.A., Neil Cape, J., Reis, S., Sheppard, L.J., Jenkins, A., Grizzetti, B., Galloway, J.N., Vitousek, P., Leach, A., Bouwman, A.F., Butterbach-Bahl, K., Dentener, F., Stevenson, D., Amann, M., Voss, M. (2013) The global nitrogen cycle in the twenty-first century. Philosophical Transactions of the Royal Society B Biological Sciences 368(1621), 20130164; http://dx.doi.org/ 10.1098/rstb.2013.0164.

Franko, U., B. Oelschlägel, & S. Schenk (1995) Simulation of temperature-, water- and nitrogen dynamics using the model CANDY. Ecological Modelling, 81, pp. 213-222

Fraters, B., L.J.M. Boumans, G. van Drecht, T. de Haan & W. de Hoop, 1998. *Nitrogen monitoring in groundwater in the sandy regions of the Netherlands.* Environ. Pollut. 102S1 (1), 479-485.

Fraters, Dico Ton van Leeuwen, Leo Boumans & Joan Reijs (2015) Use of long-term monitoring data to derive a relationship between nitrogen surplus and nitrate leaching for grassland and arable land on well-drained sandy soils in the Netherlands, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 65:sup2, 144-154, DOI: 10.1080/09064710.2014.956789

Galloway, J.N., J.D. Aber, J.W. Erisman, S.P. Seitzinger, R.W. Howarth, E.B. Cowling & B.J. Cosby, 2003. *The Nitrogen Cascade.* Bioscience 53 (4), 341-356.

Galloway, J.N. & E.B. Cowling, 2002. *Reactive nitrogen and the world: 200 years of change.* Ambio 31 (2), 64-71.

Galloway, J.N., F.J. Dentener, D.G. Capone, E.W. Boyer, R.W. Howarth, S.P. Seitzinger, G.P. Asner, C.C. Cleveland, P.A. Green, E.A. Holland, D.M. Karl, A.F. Michaels, J.H. Porter, A.R. Townsend & C.J. Vörösmarty, 2004. *Nitrogen cycles: past, present and future.* Biogeochem. 70 (2), 153-226.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A. (2008) Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science 320: 889-892. doi: 10.1126/science.1136674.

Garnier, P., Néel, C., Mary, B. & Lafolie, F. (2001) Evaluation of a nitrogen transport and transformation model in a bare soil. European Journal of Soil Science, 52, 253–268.

Gilley, JE. and L.M. Risse. 2000. Runoff and soil loss as affected by the application of manure. Transactions of the American Society of Agricultural Engineers 43:1583-1588.

Goulding, K. 2000. Nitrate leaching from arable and horticultural land. Soil Use and Management 16, 145-151.

Groenendijk, P., L.V. Renaud, J. Roelsma (2005) Prediction of nitrogen and phosphorus leaching to groundwater and surface waters. Process descriptions of the animo4.0 model. Alterra—Report 983, Alterra, Wageningen.

Hansen, B., Thorling, L., Schullehner, J., Termansen, M. & Dalgaard, T., (2017) Groundwater nitrate response to sustainable nitrogen management. Scientific Reports. 7, 8566

Hashemi, F., Olesen, J. E., Dalgaard, T. & Børgesen, C. D. (2016) Review of scenario analyses to reduce agricultural nitrogen and phosphorus loading to the aquatic environment. Science of the Total Environment. 573, 608-626

Hashemi, F., Olesen, J. E., Børgesen, C. D., Tornbjerg, H., Thodsen, H. & Dalgaard, T., (2018). Potential benefits of farm scale measures versus landscape measures for reducing nitrate loads in a Danish catchment. Science of the Total Environment. 637-638, 318-335.

Hatfield, J.L. & R.F. Follett (eds) 2008 Nitrogen in the Environment: Sources, Problems and Management. Academic Press. 2nd edition. 702 pp.
Hellsten S, Dalgaard T, Rankinen K, Tørseth K, Kulmala A, Turtola E, Moldan F, Pira K, Piil K, Bakken L, Bechmann M and Olofsson S (2018) *Nitrogen and agriculture in the Nordic countries - policy, measures and the way forward*. Journal of Environmental Management (in press).

Hou, Y., A. Bai, J.P. Lesschen, I.G. Staritsky, N. Sikirica, L. Ma, G.L. Velthof, O. Oenema, 2016. Feed use and nitrogen excretion of livestock in EU-27. Agriculture, Ecosystems and Environment 218: 232 - 244.

Hou, Y. ; Velthof, G.L. ; Oenema, O. (2015) Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. Global Change Biology 21 (3). - p. 1293 - 1312.

Howarth, S., Journeaux, P., 2016. Review of Nitrogen Mitigation Strategies for Dairy Farms - is the method of analysis and results consistent across studies? In: Integrated nutrient and water management for sustainable farming. (Eds L.D. Currie and R.Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 29. Fertilizer and Lime Research Centre, Massey University, Palmerston
North, New Zealand. 13 pages.

Højberg, A.L., A.L. Hansen, P. Wachniew, A.J. Żurek, S. Virtanen, J. Arustiene, J. Strömqvist, K. Rankinen, J.C. Refsgaard (2017) Review and assessment of nitrate reduction in groundwater in the Baltic Sea Basin, Journal of Hydrology: Regional Studies, 12, pp 50-68,

Hutson J.L., 2003. LEACHM. Model description and user's guide. School of Chemistry, Physics and Earth Sciences. The Flinders University of South Australia. GPO Box 2100, Adelaide, SA5001

IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Hayama, Japan: IPCC NGGIP Programme, IPCC-TSU/IGES. Published by the Institute for Global Environmental Strategies (IGES), Hayama, Japan on behalf of the IPCC, 2006.

IPNI, 2018 4R Plant Nutrition Manual: A Manual for Improving the Management of Plant Nutrition. http://www.ipni.net/4R

Jarvis, S., N. Hutchings, F. Brentrup, J.E. Olesen & K.W. Van de Hoek, 2011. *Nitrogen flows in farming systems across Europe.* In: Sutton, M.A., C.M. Howard, J.W. Erisman, G. Billen, A.

Bleeker, P. Grennfelt, H. van Grinsven & B. Grizzetti (Eds). The European Nitrogen Assessment. Cambridge, UK, Cambridge University Press, Chapter 10, pp. 211-228.

Jordan, V.W.L. (ed) 1993 Scientific basis for codes of good agricultural practice. Commission of the European Communities. Report EUR 14957 EN

Juuti, P.S., T.S. Katko, and H.S. Vuorinen 2007. Environmental History of Water: Global View of Community Water Supply and Sanitation. IWA Publishing

Kersebaum, K.-C. (2007) Modelling nitrogen dynamics in soil–crop systems with HERMES. Nutrient Cycling in Agroecosystems 77, 1, 39-52.

Keuskamp, J., G. van Drecht & A.F. Bouwman, in press. *European-scale modelling of groundwater denitrification and associated N_2O production.* Environ. Pollut.

Kirchmann, H., A. E. Johnny Johnston and L.F. Bergström 2002. Possibilities for reducing nitrate leaching from agricultural land. Ambio, 31, 404-408.

Klages, S. et al., (2018). Review report of Agri-Drinking Water quality Indicators and IT/sensor techniques, on farm level, study site and drinking water source. FAIRWAY report D3.1.

Kristensen, K., Petersen, J.W., Børgesen, C.D., Vinther, J.P., Grant, R., Blicher-Mathiesen, G., 2008. Re-estimation and Further Development in the Model N-LES, N-les3 to N-les4. Baggrundsnotat Til Vandmiljøplan III − Midtvejsevaluering. Aarhus University

Li, C., N. Farahbakhshazad, D.B. Jaynes, D.L. Dinnes, W. Salas, D. McLaughlin (2006) Modeling nitrate leaching with a biogeochemical model modified based on observations in a row-crop field in Iowa Ecological Modelling, 196, pp. 116-130

Liu, J., J.R. Williams, A.J.B. Zehnder, Hong Yang (2007) GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale, Agricultural Systems, 94, pp 478-493

L'Hirondel, J.L., 2001. Nitrate and Man: Toxic, Harmless or Beneficial? CABI Publishing, Wallingford, UK.

Metzger, M. J., Bunce, R. G. H., Jongman, R. H. G., Mücher, C. A. & Watkins, J. W. (2005) A climatic stratification of the environment of Europe. *Global Ecology & Biogeography*, **14**, 549-563.

Metzger, M. J., Schröter, D., Leemans, R. & Cramer, W. (2008) A spatially explicit and quantitative vulnerability assessment of ecosystem service change in Europe. *Regional Environmental Change*, **8**, 91-107.

Mondelaers, K., Aertsens, J., Van Huylenbroeck, G. (2009). A meta-analysis of the differences in environmental impacts between organic and conventional farming. *British Food Journal 111 (10)*, 1098-1119. 10.1108/00070700910992925

Mosier, A.R., J. Keith Syers and J.R. Freney, (Eds.) 2004 Agriculture and the Nitrogen Cycle - . Assessing the Impacts of Fertilizer Use on Food Production and the Environment. Island Press.

Munch, J.M. & G.L. Velthof, 2006. *Denitrification and agriculture.* In: Bothe, H., S.F. Ferguson & W.E. Newton (Eds). Biology of the Nitrogen Cycle. Amsterdam, Elsevier, pp. 331-341.

Newell Price, J.P., Harris, D., Taylor, M., Williams, J.R., Anthony, S.G., Duethmann, D., Gooday, R.D., Lord, E.I. and 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. User Guide. Defra Project WQ0106. ADAS/Rothamsted, UK, 162 pp.

NRCS, 2018. Natural Resource Conservation Service Field Office Technical Guide http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/fotg/.

Oenema, O., D. Oudendag & G.L. Velthof, 2007. *Nutrient losses from manure management in the European Union.* Livest. Sci. 112 (3), 261-272.

Oenema, O., H.P. Witzke, Z. Klimont, J.P. Lesschen, and G.L. Velthof (2009) Integrated assessment of promising measures to decrease nitrogen losses from agriculture in EU-27. Agriculture, Ecosystems and Environment 133: 280–288.

Oenema, O., Bleeker, A., Braathen, N.A., et al. (2011a). Nitrogen in current European policies. In: *The European Nitrogen Assessment*. ed. M.A. Sutton, C.M. Howard, J.W. Erisman, et al., Cambridge University Press.

Oenema, O., Salomez, J., Branquinho, C. et al. (2011b). Development of integrated approaches to nitrogen management. In: *The European Nitrogen Assessment.* ed. M.A. Sutton, C.M. Howard, J.W. Erisman, et al., Cambridge University Press.

Osterburg, B., I. Ruhling, T. Runge, T.G. Schmidt, K. Seidel, F. Antony, B. Godecke, P. Witt-Altfelder (2007) Kosteneffizienten Massnahmenkombinationen nach Wasserrahmenrichtlinie zur Nitratreduktion in der Landwirschaft. FAL/Lingus, Braunschweig.

Perego, A., A. Basile, A. Bonfante, R. De Mascellis, F. Terribile, S. Brenna & M. Acutis (2012) Nitrate leaching under maize cropping systems in Po Valley (Italy), Agriculture, Ecosystems & Environment, 147, pp. 57-65. https://doi.org/10.1016/j.agee.2011.06.014

Quemada, M., M. Baranski, M.N.J. Nobel-de Lange, A. Vallejo, J.M. Cooper, 2013. Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. Agriculture, Ecosystems and Environment 174, 1– 10

Reichenberger, Stefan & Mardhel, Vincent & Allier, D & Højberg, Anker & Nolan, BT & Dubus, IG & Hollis, John & Jarvis, NJ. (2007). FOOTPRINT Deliverable DL18. 10.13140/RG.2.2.34561.04968.

Rittenburg, R.A., A.L. Squires, J. Boll, E.S. Brooks, Z.M. Easton, and T.S. Steenhuis, 2015. Agricultural BMP Effectiveness and Dominant Hydrological Flow Paths: Concepts and a Review. Journal of the American Water Resources Association 51, 305-329. DOI: 10.1111/1752-1688.12293.

Rivett, M.O., S.R. Buss, P. Morgan, J.W.N. Smith, C.D. Bemment (2008) Nitrate attenuation in groundwater: A review of biogeochemical controlling processes. Water Research 42, 4215 – 4232

Roten R.L., J. Fourie, J.L. Owens, J.A.K. Trethewey, D.C. Ekanayake, A. Werner, K. Irie, M. Hagedorn, K.C. Cameron (2017) Urine patch detection using LiDAR technology to improve nitrogen use efficiency in grazed pastures. Computers and Electronics in Agriculture 135, 128-133

Schlesinger, W.H., Bernhardt, E. S. (2013) Biogeochemistry. An Analysis of Global Change. Duke University, Durham, NC, USA.
Schröder, J.J. (2005a) Revisiting the agronomic benefits of manure: a correct assessment and exploitation of its fertilizer value spares the environment. Bioresource Technology 92 (2): 253-261.

Schröder, J.J. (2005b) Manure as a suitable component of precise nitrogen nutrition. Proceedings 574, International Fertiliser Society, 32 pp.

Schröder, J.J. and Stevens, R.J. (2004) Optimising N additions: can we integrate fertiliser and manure use? In: Hatch, D.J., D.R. Chadwick, S.C. Jarvis and J.A. Roker (Eds.) Controlling nitrogen flows and losses, 586-593.

Schröder, J.J., Ten Holte, L., Van Keulen, H. and Steenvoorden, J.H.A.M. (1993) Effects of nitrification inhibitors and time and rate of slurry and fertilizer N application on silage maize yield and losses to the environment. Fertilizer Research 34: 267-277.

Schröder, J.J., Van Asperen, P., Van Dongen, G.J.M. and Wijnands, F.G. (1996a) Nutrient surpluses on integrated arable farms. European Journal of Agronomy 5: 181-191.

Schröder, J.J., Van Dijk, W. and De Groot, W.J.M. (1996b) Nitrogen fluxes in maize cropping systems as affected by cover crops. Netherlands Journal of Agricultural Science 44: 293-315.

Schröder, J.J. Ten Holte, L., and Brouwer, G. (1997a) Response of silage maize to placement of cattle slurry. Netherlands Journal of Agricultural Science 45: 249-261.

Schröder, J.J., Ten Holte, L. and Janssen, B.H. (1997b) Non-overwintering cover crops: a significant source of N. Netherlands Journal of Agricultural Science 45: 231-248

Schröder, J.J., Neeteson, J.J., Withagen, J.C.M. and Noij, I.G.A.M. (1998) Effects of N application on agronomic and environmental parameters in silage maize production on sandy soils. Field Crops Research 58, 55-67.

Schröder, J.J., Neeteson, J.J., Oenema, O. and Struik, P.C. (2000) Does the crop or the soil indicate how to save nitrogen in maize production? Field Crops Research 62: 151-164.

Schröder, J.J., Aarts, H.F.M., Ten Berge, H.F.M., Van Keulen, H. and Neeteson, J.J. (2003) An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use. European Journal of Agronomy 20 (1-2), 33-44.

Schröder, J.J., Jansen, A.G. and Hilhorst, G.J. (2005a) Long term nitrogen fertilizer value of cattle slurry. Soil Use and Management 21: 196-204.

Schröder, J.J., Uenk, D. and Hilhorst, G.J. (2007a) Long-term nitrogen fertilizer replacement value of cattle manures applied to cut grassland. Plant and Soil 299: 83-99.

Schröder, J.J., Aarts, H.F.M., Van Middelkoop, J.C. , De Haan, M.H.A., Schils, R.L.M., Velthof, G.L., Fraters, B. and Willems, W.J. (2007b) Permissible manure and fertilizer use in dairy farming systems on sandy soils in The Netherlands to comply with the Nitrates Directive target. European Journal of Agronomy 27: 102-114.

Schullehner J, Hansen B, Thygesen M, Pedersen CB, Sigsgaard T (2018) *Nitrate in drinking water and colorectal cancer risk: A nationwide population-based cohort study.* International Journal of Cancer https://doi.org/10.1002/ijc.31306

Šimůnek, J., M. Šejna, H. Saito, M. Sakai, and M. Th. van Genuchten (2008) The HYDRUS-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media, Version 4.0, HYDRUS Software Series 3, Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, pp. 315.

Smil, V. (2000). Feeding the World. MIT Press Ltd. 390 pgs.

Smil, V. (2001) Enriching the Earth Fritz Haber, Carl Bosch, and the Transformation of World Food Production. MIT press.

Smith KA, Jackson DR, Pepper TJ. (2001a) Nutrient losses by surface run-off following the application of organic manures to arable land. 1. Nitrogen. Environ Pollut., 112, 41-51.

Smith KA, Jackson DR, Withers PJ. (2001b) Nutrient losses by surface run-off following the application of organic manures to arable land. 2. Phosphorus. Environ Pollut. 112, 53-60.

Srinivasan, M. S., R. B. Bryant, M. P. Callahan, and J. L. Weld. 2006. Manure management and nutrient loss under winter conditions: A literature review. J. Soil and Water Cons. 61(4): 200-208.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. Science, 347(6223). 10.1126/science.1259855.

Strömqvist, J., B. Arheimer, J. Dahné, C. Donnelly, G. Lindström (2012) Water and nutrient predictions in ungauged basins: set-up and evaluation of a model at the national scale
Hydrol. Sci. J., 57 (2012), pp. 229-247
Syers, J.K., A.A. Johnston & D. Curtin, 2008. *Efficiency of Soil and Fertilizer Phosphorus Use. Reconciling Changing Concepts of Soil Phosphorus Behaviour With Agronomic Information,.* Rome, Food and Agric. Org. of the U. N.

Sutton, M.A., C.M. Howard, J.W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, H. van Grinsven & B. Grizzetti, 2011b. *The European Nitrogen Assessment.* In: Cambridge, UK, Cambridge University Press.

Thomsen, I.K., Hansen, J.F., Kjeller, U.P.V. & Christensen, B.T. 1993. Effects of cropping system and rates of nitrogen in animal slurry and mineral fertilizer on nitrate leaching from a sandy loam. Soil Use and Management 9, 53-58.

UN, 2018. Sustainable Development Goals.
https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

Valkama, E., R. Lemola, H. Känkänen, E. Turtola. 2015. Meta-analysis of the effects of undersown catch crops on nitrogen leaching loss and grain yields in the Nordic countries. Agriculture, Ecosystems and Environment 203, 93–101

Van Boekel, E.M.P.M., 2015. NW European Policy-Science Working Group on Reducing Nutrient

Emissions; Mitigation options: Evaluating the impact of implementing nutrient management strategies on reducing nutrient emissions from agriculture in NW Europe. Wageningen, Alterra Wageningen UR (University & Research centre), Alterra report 2670. 114 pp.

Vanclooster M., Viaene P., Diels J., Christiaens K. (1996) WAVE: A mathematical model for simulating water and agrochemicals in the soil and vadose environment, Reference and user's manual, Release 2.1, Institute for Land and Water Management, KU Leuven, Belgium.

Van Drecht, G., A. F. Bouwman, J. Harrison, and J. M. Knoop (2009), Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050, Global Biogeochem. Cycles, 23, GB0A03, doi:10.1029/2009GB003458.

Van Groenigen, J.W. Velthof, G.L. ; Oenema, O. ; Groenigen, K.J. van; Kessel, C. van (2010) Towards an agronomic assessment of N2O emissions: a case study for arable crops. European Journal of Soil Science 61 (6). - p. 903 - 913

Velthof GL, D Oudendag, HP Witzke, WAH Asman, Z Klimont and O Oenema (2009) Integrated Assessment of Nitrogen Losses from Agriculture in EU-27 using MITERRA-EUROPE. Journal of Environmental Quality 38: 402-417.

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

Velthof, G.L. ; Hou, Y. ; Oenema, O. (2015) Nitrogen excretion factors of livestock in the European Union: a review. Journal of the Science of Food and Agriculture 95 (15). - p. 3004 - 3014

Wade, A.J., Durand, P., Beaujouan, V., Wessel, W.W., Raat, K.J., Whitehead, P.G., Butterfield, D., Rankinen, K. and Lepisto, A. (2002) A nitrogen model for European catchments: INCA, new model structure and equations, Hydrology and Earth System Sciences, 6, 559-582

Wagenet RJ and Hutson JL (1989) LEACHM: Leaching Estimation and Chemistry Model: A process based model of water and solute movement transformations, plant uptake and chemical reactions in the unsaturated zone. Continuum Vol 2 Version 2 Water Resources Inst, Cornell Univ Ithaca, NY

Webb, J. ; Sorensen, P. ; Velthof, G.L. ; Amon, B. ; Pinto, M. ; Rodhe, L. ; Salomon, E. ; Hutchings, N. ; Burczyk, J. ; Reid, J.E. (2013) An assessment of the variation of manure nitrogen efficiency throughout Europe and an appraisal of means to increase manure-N efficiency. Advances in Agronomy 119 . 371 – 442.

Wendland, F., H. Behrendt, H. Gömann, U. Hirt, P. Kreins, U. Kuhn, R. Kunkel & B. Tetzlaff (2009): Determination of nitrogen reduction levels necessary to reach groundwater quality targets in large river basins: the Weser basin case study, Germany. Nutrient Cycling in Agroecosystems, 85, 63-78.

Westhoek, H., Lesschen, J.P., Rood, T., Wagner, S., De Marco, A., Murphy-Bockern, D., Leip, A., van Grinsven, H., Sutton, M.A., Oenema, O. (2014) Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. Global Environmental Change26:196–205. http://dx.doi.org/10.1016/j.gloenvcha.2014.02.004.

Williams, M. R., G. W. Feyereisen, D. B. Beegle, R. D. Shannon, G. J. Folmar, R. B. Bryant (2011) Manure application under winter conditions; nutrient runoff and leaching. American Society of Agricultural and Biological Engineers 54(3): 891-899.

Withers, P.J.A., van Dijk, K.C., Neset, T.S.S., Nesme, T., Oenema, O., Rubæk, G.H., Schoumans, O.F., Smit, B. (2015) Stewardship to tackle global phosphorus inefficiency: The case of Europe. AMBIO. doi:10.1007/s13280-014-0614-8.

Williams, J.R., C.A. Jones, J.R. Kiniry, D.A. Spanel (1989) The EPIC crop growth model Trans ASAE, 32, pp. 497-511

Wolf, J., A.H.W. Beusen, P. Groenendijk, T. Kroon, R. Rötter, H. van Zeijts (2003) The integrated modeling system STONE for calculating nutrient emissions from agriculture in the Netherlands, Environmental Modelling & Software, 18 pp 597-617.

WHO 2011 Nitrate and nitrite in drinking-water. Background document for development of WHO Guidelines for Drinking-water Quality).

WHO, 2017 Guidelines for Drinking Water Quality. 4th edition. World Health Organization. 631 pp http://www.who.int/water_sanitation_health/publications/drinking-water-quality-guidelines-4-including-1st-addendum/en/.

WHO, 2018 Key facts on drinking water. http://www.who.int/en/news-room/fact-sheets/detail/drinking-water).

Wrage-Mönnig, N., M.A. Horn, R. Well, C. Müller, Christoph, G.L. Velthof, O. Oenema (2018) The role of nitrifier denitrification in the production of nitrous oxide revisited. Soil Biology and Biochemistry 123: A3 - A16.

Zhou, M. and K. Butterbach-Bahl. 2013. Assessment of nitrate leaching loss on a yield-scaled basis from maize and wheat cropping systems. Plant Soil DOI 10.1007/s11104-013-1876-9.

ANNEX 1. OVERVIEW OF MEASURES TO REDUCE NITRATE POLLUTION OF DRINKING WATER RESOURCES BASED ON LITERATURE REVIEW; THE LONG LIST OF MEASURES.

Type of measure	Land use and management
Measure	Change the land use from arable cropping to unfertilised grassland (without livestock) and associated manure inputs
Targetted pollutant	nitrate
Mode of action	N uptake by the permanent vegetative cover and N immobilisation into accumulating soil organic matter provide a long-term sink for N. Avoids the frequent cultivations action that stimulate the mineralisation of organic matter and thereby increase the amount of NO3 that is potentially available for leaching
Target of measure	0
Expected effectiveness	reduce NO3 losses by around 90%, annual losses on converted land would typically be <5 kg N/ha.
	High: >25% decrease in concentration/load
Expected implementation costs	200 - 35,000 £/farm, depending on the farm system
cost class:	Unknown
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	The method is applicable to all arable land, but is potentially most suited to marginal and high erosion risk arable land
quantified (classes):	Unknown
Adoptability of the measure	Low, due to the high economic impact on a farm business
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	direct and indirect N2O and NH3 emissions would be reduced by around 90%
(Phosphorous)	Particulate P and associated sediment losses in surface runoff would be reduced by around 50%. Soluble P losses would be reduced in the longer-term
(Carbon / CH4)	increased carbon storage in the grassland soils; initially in the range 1.9 to 7.0 tCO2e/ha/year.
Disadvantages	Yes, decreases crop yield
References	DEFRA report

Type of measure	Land use and management
Measure	Change the land use from arable cropping to permanent grassland, with a low stocking rate and low fertiliser inputs
Targetted pollutant	nitrate
Mode of action	N uptake by the permanent vegetative cover and N immobilisation into accumulating soil organic matter provide a long-term sink for N. Avoids the frequent cultivations action that stimulate the mineralisation of organic matter and thereby increase the amount of NO3 that is potentially available for leaching
Target of measure	0
Expected effectiveness	reduce NO3 losses by around 80-90%; annual losses would typically be <10 kg N/ha.
	High: >25% decrease in concentration/load
Expected implementation costs	1,000 - 50,000 £/farm, depending on the farm system
cost class:	Unknown
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	The method is applicable to all arable land, but is potentially most suited to marginal and high erosion risk arable land
quantified (classes):	Unknown
Adoptability of the measure	Low, due to high economic impact on the farm business; it would require a significant change in farm business outlook and stockmanship skills.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	direct and indirect N2O emissions would be reduced, NH3 emissions from directly deposited excreta in the field and handled manures (during housing, storage and following land spreading) would be increased;
(Phosphorous)	Particulate P and associated sediment losses in surface runoff would be reduced by around 50%. Soluble P losses would be reduced in the longer-term (provided that the grass was not poached)

(Carbon / CH_4)	creased carbon storage in the grassland soils; initially in the range 1.9 to 7.0 tCO_2e/ha/year
Disadvantages	unknown
References	DEFRA report

Type of measure	Land use and management
Measure	Change the land use from agricultural land to permanent woodland
Targetted pollutant	nitrate
Mode of action	Conversion to permanent woodland avoids the frequent cultivations that under arable cropping stimulate the mineralisation of organic matter and thereby increase the amount of NO_3 that is potentially available for leaching.
Target of measure	
Expected effectiveness	reduce NO_3 losses by around 90%; annual losses on converted woodland would typically be <5 kg N/ha
	High: >25% decrease in concentration/load
Expected implementation costs	-500 - -50 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	The method is applicable to all farm types with land, but is potentially most suited to marginal arable land with a high erosion risk and/or close to surface waters
quantified (classes):	Unknown
Adoptability of the measure	Low, due to dramatic change in land use and short-term negative cashflow in the farming business
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	direct and indirect N_2O emissions and NH_3 emissions would be reduced by around 90% (as no fertiliser N would be applied).
(Phosphorous)	Particulate P and associated sediment losses in surface runoff would be expected to be reduced by around 50%
(Carbon / CH_4)	increase soil carbon storage by 1.9 to 7.0 tCO_2e/ha/year; CH_4 emissions would be reduced by a small amount
Disadvantages	unknown
References	DEFRA report

Type of measure	Land use and management
Measure	Convert land to biomass cropping (i.e. willow, poplar, miscanthus); Grow perennial biomass crops to displace fossil fuel use, either through direct combustion or through biofuel generation (e.g. by gasification
Targetted pollutant	nitrate
Mode of action	Conversion to permanent perennial biomass cropping avoids the frequent cultivations that under arable cropping stimulate the mineralisation of organic matter and manufactured fertiliser N inputs are moderate, thereby reducing the amount of NO_3 that is potentially available for leaching.
Target of measure	
Expected effectiveness	NO_3 (plus ammonium and nitrite) leaching losses are likely to be reduced by around 50%
	High: >25% decrease in concentration/load
Expected implementation costs	-450 - -50 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	The method is applicable to all forms of farmland. It
quantified (classes):	Unknown
Adoptability of the measure	Low, due to changes to the farming business and short-term negative cash flow, unless financial incentives are sufficient
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	direct and indirect N_2O emissions and NH_3 emissions would be reduced by around 50%.
(Phosphorous)	Particulate P and associated sediment losses in surface runoff would be reduced by around 50%.
(Carbon / CH_4)	Increased soil carbon storage would be in the range 1.9 to 7.0 tCO_2e/ha/year; CH_4 emissions would be reduced by a small amount
Disadvantages	unknown
References	DEFRA report

Type of measure	Land use and management
Measure	Establish cover crops in the autumn
Targetted pollutant	nitrate
Mode of action	Cover crops help to reduce NO3 leaching by taking up N and reduce particulate P losses by protecting the soil from rainfall induced surface runoff and soil erosion
Target of measure	0
Expected effectiveness	NO3 leaching loss reduction of 30-60% are typical in the year of establishment
	High: >25% decrease in concentration/load
Expected implementation costs	100 - 3,300 £/farm, depending on the farm system
cost class:	Moderate: 1000 - 5000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	This method is most applicable to tillage land, particularly light soils, where there are significant areas of spring crops
quantified (classes):	Unknown
Adoptability of the measure	Low-moderate; will depend on the crop rotation and soil type.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite losses to water, and indirect N2O emissions would also be reduced by a small amount.
(Phosphorous)	Particulate P and associated sediment losses would be reduced; typically in the range 20-80%;
(Carbon / CH4)	CO2 emissions would be increased by a small amount through cover crop establishment.
Disadvantages	unknown
References	DEFRA report

Type of measure	Land use and management
Measure	Early harvesting and establishment of crops in the autumn (Harvest crops such as potatoes and maize early; Establish autumn sown crops earlier)
Targetted pollutant	nitrate
Mode of action	By harvesting/establishing crops early, compaction at harvest would be reduced and the crop would be better established in the autumn to take up N and reduce NO3 leaching losses.
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by up to 30% through early winter cereal establishment and associated indirect N2O emissions.
	High: >25% decrease in concentration/load
Expected implementation costs	0 - 14,800 £/farm, depending on the farm system
cost class:	Unknown
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	The method is most applicable to (main crop) potato and maize crops, and maybe applicable to some sugar beet crops
quantified (classes):	Unknown
Adoptability of the measure	Low-moderate. The main disincentive is that harvesting can clash with other harvesting and drilling activities, and potential yield losses due to earlier harvesting
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	Particulate P and associated sediment losses would typically be reduced in surface runoff by 20-50%.
(Carbon / CH4)	
Disadvantages	Yes, decreases crop yield
References	DEFRA report

Type of measure	Land use and management
Measure	Cultivate arable land for spring crops in spring rather than the autumn; Plough out grassland in spring rather than the autumn
Targetted pollutant	nitrate
Mode of action	Cultivation in spring is better for NO3 and particulate P losses, because bare soil is not exposed during the over-winter period, and an actively growing crop is established soon after cultivation to take up N and provide surface cover.
Target of measure	
Expected effectiveness	NO3 leaching losses would typically be reduced by 20-50%
	High: >25% decrease in concentration/load
Expected implementation costs	100 - 3,600 £/farm, depending on the farm system
cost class:	Moderate: 1000 - 5000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	This method is mainly applicable to cultivations on light/medium soils prior to the drilling of spring crops or where there is a switch from winter to spring cereal cropping. The method is also applicable to grassland systems where grass leys are ploughed out and re-seeded
quantified (classes):	Unknown
Adoptability of the measure	Low-moderate on light/medium soils.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Indirect N2O emissions would be reduced by a small amount.
(Phosphorous)	Particulate P and associated sediment losses in surface runoff would typically by reduced by 20-50%.
(Carbon / CH4)	
Disadvantages	Yes, decreases crop yield
References	DEFRA report

Type of measure	Soil management
Measure	Reduced cultivations, using discs or tines, to cultivate the soil surface as the primary cultivation in seedbed preparation (typically 10-15cm cultivation depth); Direct drilling or broadcasting of seed (i.e. no-till).
Targetted pollutant	nitrate
Mode of action	Maintaining good soil structure and improving water infiltration rates reduces soil erosion risks large reductions in surface runoff can be achieved where a mulch of crop residues is left on the surface. NO3 leaching is generally decreased as there is less soil disturbance and hence less organic matter mineralisation
Target of measure	
Expected effectiveness	NO3 (plus ammonium and nitrite) leaching loss reductions can be up to 20%;
	Moderate: 10-25% decrease in concentration/load
Expected implementation costs	-4,300 - -150 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	This method has already been adopted; It is most commonly used on medium/heavy soils, although reduced cultivations are increasingly being carried out on light soils. It is less likely to be adopted in wetter parts of the country
quantified (classes):	Unknown
Adoptability of the measure	The largest barrier to uptake is likely to be the purchase of new machinery (in addition to those outlined above) and so is most likely to be adopted on larger combinable crop farms.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Indirect N2O emissions would also be reduced, however, there is some evidence of higher direct N2O emissions from reduced/no-till land;
(Phosphorous)	Particulate P and associated sediment loss reductions can be up to 60% on medium/heavy soils and up to 90% on light soils.
(Carbon / CH4)	CO2 emissions would be reduced as a result of the lower power requirements of reduced/no-till cultivation; Soil carbon storage would be increased by a small amount typically 0.57 tCO2e/ha/year for reduced tillage and 1.14 tCO2e/ha/year for no-till
Disadvantages	unknown
References	DEFRA report

Type of measure	Soil management
Measure	Cultivate compacted tillage soils to increase aeration and water infiltration rates; Endeavour to establish a vegetative cover from a drilled crop, through natural regeneration or broadcast (barley) seed.
Targetted pollutant	Nitrate and other nutrients
Mode of action	The method reduces surface runoff and soil erosion.Cultivation of the soil surface (during dry conditions) will increase surface roughness, which will enhance water infiltration rates into the soil and reduce surface runoff volumes.
Target of measure	
Expected effectiveness	-
	unknown
Expected implementation costs	50 - 1,600 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	The method is applicable to all tillage land where soils are compacted, and particularly sloping land in high rainfall areas.
quantified (classes):	Unknown
Adoptability of the measure	If compaction is identified as an issue it is likely to be alleviated by farmers
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	There may be a small reduction in direct N_2O emissions, as a result of increased soil aeration.
(Phosphorous)	Particulate P and associated sediment loss reductions would typically be in the range 10 and 50%.
(Carbon / CH4)	CO_2 emissions would be increased by a small amount from the additional cultivation.
(Other)	
Disadvantages	unknown
References	DEFRA report

Type of measure	Soil management
Measure	Cultivate and drill land along the slope (contour) to reduce the risk of developing surface runoff
Targetted pollutant	Nitrate and other nutrients
Mode of action	Cultivate and drill land along the slope (contour) to reduce the risk of developing surface runoff. The ridges created across the slope increase down-slope surface roughness and provide a barrier to surface runoff. As a result, particulate P and associated sediment losses will be reduced
Target of measure	
Expected effectiveness	-
	unknown
Expected implementation costs	20 - 500 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	applicable to all cultivated soils where fields have simple slope patterns
quantified (classes):	Unknown
Adoptability of the measure	Uptake is most likely on fields with gentle/moderate slopes and simple slope patterns, and that are longer across slope than in the upslope direction
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	-
(Phosphorous)	Limited evidence indicates that cultivating/drilling across the slope can reduce particulate P and associated sediment losses by 40-80%.
(Carbon / CH4)	-
Disadvantages	unknown
References	DEFRA report

Type of measure	Soil management
Measure	Leave autumn seedbeds rough (Avoid creating a fine autumn seedbed that will 'slump' and run together)
Targetted pollutant	Nitrate and other nutrients
Mode of action	Avoid creating a fine autumn seedbed that will 'slump' and run together; Leaving the autumn seedbed rough encourages surface water infiltration and reduces the risk of surface runoff, thereby reducing particulate P and associated sediment loss risks
Target of measure	
Expected effectiveness	-
	unknown
Expected implementation costs	100 - 2,500 £/farm, depending on the farm system
cost class:	Moderate: 1000 - 5000 £/farm
Underpinning of the measure	No (≤ 1 report)
Applicability of the measure: qualitative	applicable to the establishment of 'large' seeded crops on tillage land (particularly on light soils). It is most applicable to winter cereal crops that can establish well in coarse seedbeds
quantified (classes):	Unknown
Adoptability of the measure	Low, due to pest (particularly slug) and weed control issues.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	-
(Phosphorous)	Limited field evidence indicates that particulate P and associated sediment losses can be reduced by up to 20%.
(Carbon / CH4)	CO2 emissions would be reduced by a small amount from less cultivation.
Disadvantages	Yes, decreases crop quality and contributes to (more) pest and diseases
References	DEFRA report

Type of measure	Soil management
Measure	Use tines to disrupt tramlines or delay their establishment until the spring
Targetted pollutant	Nitrate and other nutrients
Mode of action	Avoiding the use of over-winter tramlines helps prevent surface runoff and associated sediment mobilisation, as 'compacted' tramlines can act as concentrated flow pathways during periods of increased surface runoff
Target of measure	
Expected effectiveness	-
	unknown
Expected implementation costs	10 - 750 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	is method (either avoiding or disrupting tramlines) is applicable to winter cereal cropped land, particularly on light/medium textured soils on sloping land in higher rainfall areas
quantified (classes):	Unknown
Adoptability of the measure	Low-moderate
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	-
(Phosphorous)	Limited field evidence indicates that tramline disruption can reduce particulate P and associated sediment losses by 30-50% on winter cereal cropped land.
(Carbon / CH4)	CO2 emissions would be increased by a small amount from the additional tine cultivation.
Disadvantages	unknown
References	DEFRA report

Type of measure	Soil management
Measure	Maintain and enhance soil organic matter levels by the regular addition of organic materials (e.g. livestock manures, biosolids, compost, digestate) and retention of crop residues.
Targetted pollutant	nitrate
Mode of action	Maintaining and enhancing soil organic matter levels helps to reduce the risks of surface runoff and erosion, enables improved water retention and the efficient use of soil and added nutrients. The long-term benefits of improved soil structure etc. should be effective in reducing particulate P and associated sediment losses
Target of measure	
Expected effectiveness	NO_3 leaching losses would be increased, particularly where high readily available manures are applied in the autumn period (by up to 20% of total N applied).
	Unknown
Expected implementation costs	-6,800 - 850 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	This method is applicable to all arable farming systems; particularly on low organic matter soils that are structurally unstable.
quantified (classes):	Unknown
Adoptability of the measure	Moderate-high, due to the increasing cost of manufactured fertilisers and importance of organic matter supply to arable soils.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	direct and indirect N_2O emissions and NH_3 emissions would be increased. However, manufactured fertiliser N inputs would be reduced.
(Phosphorous)	Particulate P and associated sediment loss reductions would be expected through building up organic matter reserves and better soil structure over a period of years.
(Carbon / CH4)	CO_2 emissions would be increased by a small amount through transporting and applying the organic materials
Disadvantages	unknown
References	DEFRA report

Type of measure	Soil management
Measure	On sloping tillage fields and outdoor pig land, establish (unfertilised) grass buffer strips along the land contour, in valley bottoms or on upper slopes to reduce and slow down surface runoff.
Targetted pollutant	nitrate
Mode of action	Establish in-field grass areas to prevent surface runoff and erosion. Buffer strips can also act as a sediment-trap, helping to reduce nutrient and other associated losses in surface runoff.
Target of measure	
Expected effectiveness	NO_3 leaching loss reductions from the strip area would be similar to that from ungrazed/zero-N grassland i.e. around a 90% reduction; annual losses from converted land would typically by <5 kg N/ha
	unknown
Expected implementation costs	50 - 3,500 £/farm, depending on the farm system
cost class:	Moderate: 1000 - 5000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	In-field buffer strips are applicable to all arable farming systems, particularly on sloping land. They are particularly suited to fields with long slopes where high volumes of surface runoff can be generated.
quantified (classes):	Unknown
Adoptability of the measure	Low-moderate; 'poor' patches are ideal for buffer strips .Farmers are less likely to establish buffers along the midslope contour, unless financial incentives are available
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite losses would also be reduced by a small amount. Similarly, direct and indirect N_2O emissions would be reduced;
(Phosphorous)	Particulate P and associated sediment losses reductions would typically be in the range 20-80%.
(Carbon / CH4)	CO_2 emissions would be reduced from the un-farmed strips and soil carbon storage increased.
Disadvantages	Yes, decreases crop yield
References	DEFRA report

Type of measure	Soil management
Measure	Establish riparian buffer strips (vegetated (and unfertilised) grass/woodland buffer strips alongside watercourses).
Targetted pollutant	nitrate
Mode of action	Riparian buffer strips can reduce pollution delivery in two ways. They distance agricultural activity from watercourses and therefore reduce direct pollution from fertiliser and organic manure additions, and can restrict direct livestock access to watercourses
Target of measure	
Expected effectiveness	NO3 leaching loss reductions from the strip area would be the same as from ungrazed/zero–N grassland i.e. around a 90% reduction; annual losses from converted land would typically be <5 kg N/ha
	unknown
Expected implementation costs	650 - 10,600 £/farm, depending on the farm system
cost class:	Unknown
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	Riparian buffer strips are most effective at retaining sediment when overland flow is shallow and slow; they are particularly suited to low-lying and gently undulating landscapes where the topography does not concentrate the flow into channels.
quantified (classes):	Unknown
Adoptability of the measure	Medium; ‘poor’ field area at the waters edge are ideal. The establishment of riparian areas is less likely on ‘better’ land, unless financial incentives are available.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite losses would also be reduced by a small amount. Similarly, direct and indirect N2O emissions would be reduced, as manufactured fertiliser N would not be applied to the riparian strips.
(Phosphorous)	Particulate P and associated sediment losses would typically be reduced by 20-80%.
(Carbon / CH4)	CO2 emissions would be reduced from the un-farmed strip and soil carbon storage increased
Disadvantages	unknown
References	DEFRA report

Type of measure	Soil management
Measure	Reduce surface runoff from grassland fields by loosening to disrupt compacted soil layers, as required in relation to the depth of soil compaction.
Targetted pollutant	nitrate
Mode of action	Topsoil loosening and shallow spiking/slitting can break up compacted layers and allow more rapid rainwater and slurry infiltration, thus reducing surface runoff. In addition, soil aeration can be improved and result in roots being able to penetrate deeper into the soil, which will increase nutrient uptake from deeper soil layers
Target of measure	
Expected effectiveness	Effects on NO3 leaching losses are likely to be minimal
	Insignificant: <5% decrease in concentration/load
Expected implementation costs	1,000 - 1,500 £/farm, depending on the farm system
cost class:	Moderate: 1000 - 5000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	The method is potentially applicable to all grassland farms, but particularly those with high stocking rates.
quantified (classes):	Unknown
Adoptability of the measure	Moderate to high on fields where soil compaction has been identified.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	N2O emissions are likely to be reduced, and as a result of improved soil infiltration rates NH3 emissions are likely to be reduced following slurry application.
(Phosphorous)	Particulate P and associated sediment losses would typically be reduced by 10-50%.
(Carbon / CH4)	CO2 emissions would be increased by a small amount through the loosening operation.
Disadvantages	unknown
References	DEFRA report

Type of measure	Water management

Measure	Allow existing (old) drainage systems to naturally deteriorate i.e. cease to maintain them;
Targetted pollutant	nitrate
Mode of action	increases the opportunity for the retention (or transformation) of potential pollutants through physical filtration and biological activity in the soil; a higher water table being maintained, thereby reducing N mineralisation from soil organic matter and NO3 leaching,
Target of measure	
Expected effectiveness	NO3 leaching loss reductions would typically be in the range of 10-50%,
	Unknown
Expected implementation costs	450 - 2,500 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	most applicable to the grassland sector on medium/heavy soils
quantified (classes):	Unknown
Adoptability of the measure	Low, without financial incentives. It is highly unlikely that farmers would deliberately allow drainage systems to deteriorate, due to the large impact this can have on production
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite losses would also be reduced, and indirect N2O losses as a result of lower NO3 leaching losses. Direct N2O emissions would be increased as a result of greater soil wetness and associated denitrification losses.
(Phosphorous)	Particulate P and associated sediment losses would typically be reduced by up to 10%
(Carbon / CH4)	-
Disadvantages	Yes, decreases crop yield
References	DEFRA report

Type of measure	Water management
Measure	Actively maintain field drainage systems through jetting, re-installation and renewed moling.
Targetted pollutant	nitrate
Mode of action	The method reduces the period when soils are at risk from compaction and poaching, and reduces the risk of surface runoff and associated particulate P/sediment losses. However, drainflow losses of nutrients (particularly NO3 and P) are likely to be increased
Target of measure	0
Expected effectiveness	O3 leaching losses would typically be increased by 10-50% compared with drainage deterioration
	Negative effect
Expected implementation costs	50 - 1,600 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	The method is applicable to all drained fields, particularly on medium/heavy soils types and in grassland farming systems.
quantified (classes):	Unknown
Adoptability of the measure	High, mainly due to the impact that poor drainage can have on crop production and management versatility of the land.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite losses would also be increased and indirect N2O losses as a result of higher NO3 leaching losses. Direct N2O emissions would be decreased as a result of more aerobic soils.
(Phosphorous)	Particulate P and associated sediment losses would typically be increased by up to 10%, as a result of greater drainflow lossesconditions and lower denitrification losses
(Carbon / CH4)	-
Disadvantages	unknown
References	DEFRA report

Type of measure	Water management
Measure	Clear out ditches on a regular basis to ensure field drainage systems are able to function. This may include cutting vegetation in the bottom of the ditch to prevent flooding.
Targetted pollutant	nitrate
Mode of action	This method will allow field drainage systems to function thereby reducing the risk of waterlogging, soil compaction, poaching and surface runoff
Target of measure	
Expected effectiveness	NO3 leaching losses would typically be increased by up to 20%.
	Negative effect
Expected implementation costs	50 - 600 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	No (≤ 1 report)
Applicability of the measure: qualitative	The method is applicable to all farms with ditches and a drainage system.
quantified (classes):	Unknown
Adoptability of the measure	High, mainly due to the impact that poor drainage (and localised flooding) can have on crop production and the management versatility of land.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite losses would also be increased and indirect N2O losses as a result of higher NO3 leaching losses. However, direct N2O emissions would be decreased as a result of more aerobic soil conditions and lower denitrification losses.
(Phosphorous)	Particulate P and associated sediment losses would typically be increased by up to 10%, and as a result of increased drainflow losses.
(Carbon / CH4)	CO2 emissions would increase by a small amount as a result of the ditch cleaning operation
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Use genetic resources to improve lifetime efficiency of livestock systems
Targetted pollutant	nitrate
Mode of action	Increasing the longevity of cows will decrease CH4 emissions and increase lifetime N use efficiency.
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by up to 10%
	Low: 5-10% decrease in concentration/load
Expected implementation costs	-8,500 - -20,000 £/farm, depending on the farm system
cost class:	Unknown
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	The method is applicable to all livestock systems, but the greatest gains are expected in the beef and sheep sectors.
quantified (classes):	Unknown
Adoptability of the measure	Moderate-high, it will take time for widespread adoption in the beef and sheep sectors.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite) leaching losses and direct and indirect N2O losses and NH3 emissions would be reduced by up to 10%
(Phosphorous)	P: Losses would be reduced by up to 10%
(Carbon / CH4)	Methane: Losses could potentially be reduced by up to 10%.
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Develop new plant varieties with improved genetic traits for the capture of soil N
Targetted pollutant	nitrate
Mode of action	Plants remove more mineral N from the soil and so reduce the amount that can be lost to water and air
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by up to 10%
	Low: 5-10% decrease in concentration/load
Expected implementation costs	-3,000 - -100 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	Can be applied (in principle) to all sectors of agricultural crop production, but has most potential for arable crops.
quantified (classes):	Unknown
Adoptability of the measure	Depends on the increase in cost vs. the reduction in crop N requirement. If this ratio is positive, then uptake is likely to be high.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite) leaching losses and direct and indirect N2O losses and NH3 emissions would be reduced by up to 10%
(Phosphorous)	-
(Carbon / CH4)	CO2 emissions would be reduced by a small amount as a result lower fertiliser N use (and production).
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Improve the accuracy and spread pattern of fertiliser spreaders.
Targetted pollutant	nitrate
Mode of action	A low CV (less than 10%) ensures that fertiliser is spread evenly and all parts of the field receive the recommended rate. This optimises the uptake of soil and fertiliser nutrients, and reduces the amount of residual (autumn) mineral N available for leaching over-winter
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by up to 5%
	unknown
Expected implementation costs	50 - 200 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	The method is applicable to all farm types where manufactured fertiliser is used.
quantified (classes):	Unknown
Adoptability of the measure	Moderate -high. A low cost method which will improve crop growth, as well as reducing diffuse pollution.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite) leaching losses and direct and indirect N2O losses and NH3 emissions would be reduced by up to 5%
(Phosphorous)	-
(Carbon / CH4)	-
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Use a recognised fertiliser recommendation system to plan manufactured fertiliser applications to all crops
Targetted pollutant	nitrate
Mode of action	Use of a fertiliser recommendation system will reduce the risk of applying more nutrients than the crop needs and will minimise the risks of causing diffuse water and air pollution.
Target of measure	
Expected effectiveness	NO_3 leaching losses would be reduced by up to 5%
	unknown
Expected implementation costs	-3,800 - -400 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	Fertiliser recommendation systems can be used in all farming systems, but are particularly useful in high output grassland, arable and horticultural systems. The method would have less impact in extensive grassland systems, as manufactured fertiliser addition rates are low/moderate.
quantified (classes):	Unknown
Adoptability of the measure	Moderate/high. As long as fertiliser prices are 'high' relative to the value of the crop farmers will want to optimise nutrient inputs. Improvements are most likely when organic manures are used.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite) leaching losses and direct and indirect N_2O losses and NH_3 emissions would be reduced by up to 5%
(Phosphorous)	P losses would be reduced by up to 5% (from applied fertilisers).
(Carbon / CH_4)	CO_2 emissions would be reduced by a small amount as a result of lower fertiliser use (and production).
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Use a recognised fertiliser recommendation system make full allowance of the nutrients applied in organic manures and reduce manufactured fertiliser inputs accordingly.
Targetted pollutant	nitrate
Mode of action	Manufactured fertiliser application rates are reduced to no more than required for optimum economic production levels and to maintain adequate nutrient levels in the soil.
Target of measure	
Expected effectiveness	NO_3 leaching losses would be reduced by up to 10%
	unknown
Expected implementation costs	-7,600 - -800 £/farm, depending on the farm system
cost class:	Unknown
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	Most applicable to arable and high output grassland systems (including maize). The method is effective wherever manufactured fertilisers are used to 'top-up' the nutrients supplied by organic manures.
quantified (classes):	Unknown
Adoptability of the measure	Moderate-high, mainly as a result of the increasing cost of manufactured fertilisers, meaning the nutrient inputs from manures are more likely to be taken into account in order to reduce costs.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite) leaching losses and direct and indirect N_2O losses and NH_3 emissions would be reduced by up to 10%
(Phosphorous)	P: Losses would be reduced by up to 10%
(Carbon / CH_4)	CO_2 emissions would be reduced by a small amount as a result of lower fertiliser use (and production).
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Reduce the amount of manufactured N and P fertiliser applied to crops below the economic optimum rate.
Targetted pollutant	nitrate
Mode of action	There will be a reduction in the amount of residual soil NO3 available for leaching in the autumn, however, there will be no effect on the amount of NO3 mineralised from soil organic matter that will also be available for leaching over-winter.
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by up to 10% (from a 20% reduction in N fertiliser rates)
	Low: 5-10% decrease in concentration/load
Expected implementation costs	1,100 - 54,000 £/farm, depending on the farm system
cost class:	Unknown
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	The method is applicable to all farming systems where fertiliser is used.
quantified (classes):	Unknown
Adoptability of the measure	Low, due to impact on yields and farm income. Small reductions in yield can have a (disproportionately) large effect on the economic viability of a farm business. Financial incentives would be required to encourage uptake.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	ammonium and nitrite leaching losses would be reduced by up to 10% (from a 20% reduction in N fertiliser rates) and associated direct and indirect N2O emissions, and NH3 emissions
(Phosphorous)	Soluble P losses would be reduced by up to 10% (from a 20% reduction in P fertiliser rates) plus longer-term reductions through reduced soil P status.
(Carbon / CH4)	CO2 emissions would be reduced by a small amount as a result of lower fertiliser use (and production).
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Do not apply manufactured fertiliser at any time to field areas where there are direct flow paths to watercourses.
Targetted pollutant	nitrate
Mode of action	Avoiding fertiliser spreading to hydrologically well connected areas helps prevent the transfer of pollutants to water.
Target of measure	
Expected effectiveness	Nitrate leaching losses would be reduced by a small amount (up to 2%)
	Insignificant: <5% decrease in concentration/load
Expected implementation costs	20 - 3,600 £/farm, depending on the farm system
cost class:	Unknown
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	This method is potentially applicable to all farming systems, but is probably most applicable to the grassland sector, where open drains and waterlogged areas are most common. It is also applicable to all fields with ditches and areas close to road culverts.
quantified (classes):	Unknown
Adoptability of the measure	Moderate to high. A no fertiliser spreading buffer of 2 m from surface waters is mandatory in Nitrate Vulnerable Zones.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite leaching losses would be reduced by a small amount (up to 2%) and there would be associated small reductions in direct and indirect N2O emissions, and NH3 emissions.
(Phosphorous)	Soluble P losses would be reduced by up to 10%, as hydrologically well connected areas can make a large contribution to P losses
(Carbon / CH4)	CO2 emissions would be reduced by a small amount as a result of lower fertiliser use (and production).
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Do not spread manufactured fertiliser at times when there is a high-risk of surface runoff or rapid movement to field drains i.e. when soils are 'wet
Targetted pollutant	nitrate
Mode of action	This method aims to prevent nutrients being added at times when there is potential for rapid transfer to water. Avoiding N fertiliser application in the autumn/winter reduces the amount of NO3 available for leaching by over-winter rainfall
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by up to 5%
	Low: 5-10% decrease in concentration/load
Expected implementation costs	30 - 850 £/farm, depending on the farm system
cost class:	Unknown
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	The method is potentially applicable to all farming systems, which use fertilisers.
quantified (classes):	Unknown
Adoptability of the measure	Moderate to high. However, farmers may be reluctant not to apply fertiliser N to 'wet' soils in spring to support early season crop growth.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite) leaching losses and direct and indirect N2O losses and NH3 emissions would be reduced by up to 5%
(Phosphorous)	Soluble P losses would be reduced by up to 10%, as hydrologically well connected areas can make a large contribution to P losses.
(Carbon / CH4)	-
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Place nutrients close to germinating or established crops to increase fertiliser N and/or P recovery.
Targetted pollutant	nitrate
Mode of action	Fertiliser placement can be particularly useful in low P status soils to increase uptake efficiency and can also enable reductions in fertiliser application rates through improved nutrient recovery (without any impact on yield).
Target of measure	
Expected effectiveness	Nitrate leaching losses would be reduced by a small amount (up to 2%)
	Insignificant: <5% decrease in concentration/load
Expected implementation costs	20 - 50 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	Fertiliser placement technology is applicable to a wide range of vegetable and potato (and maize) crops; where the method is already widely used.
quantified (classes):	Unknown
Adoptability of the measure	Moderate to high. Uptake of fertiliser placement technology may increase further as manufactured fertiliser prices continue to rise over the longer-term.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite leaching losses would be reduced by a small (up to 2%) amount and direct and indirect N2O emissions, and NH3 emissions (through reduced volatilisation losses from urea).
(Phosphorous)	Soluble P losses would be reduced by up to 5% (through reduced surface runoff risks).
(Carbon / CH4)	-
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Addition of nitrification inhibitors (NIs) to applied manufactured N fertilisers, organic manures and to grazed pastures.
Targetted pollutant	nitrate
Mode of action	NI compounds such as dicyandiamide (DCD), nitrapyrin and 3,4-dimethylpyrazole phosphate (DMPP) have been shown to be effective in reducing N2O emissions and NO3 leaching losses from fertiliser/animal manure additions and grazed pastures, and to improve crop N use efficiency.
Target of measure	
Expected effectiveness	NO3 leaching loss reductions of up to 35%
	High: >25% decrease in concentration/load
Expected implementation costs	300 - 3,200 £/farm, depending on the farm system
cost class:	Moderate: 1000 - 5000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	NIs can be included in manufactured N fertiliser formulations, added to manures, applied to grazed pastures and to animals
quantified (classes):	Unknown
Adoptability of the measure	Low-moderate. NIs are relatively expensive, which is likely to reduce uptake by farmers.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Indirect N2O emissions and direct N2O emission reduction of up to 70%; H3 emissions to air and ammonium/nitrite losses to water may be increased by a small amount.
(Phosphorous)	-
(Carbon / CH4)	O2 emissions would be increased by a small amount through NI use (and production).
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Replace urea or urea-based (e.g. urea ammonium nitrate - UAN) fertiliser, with another form of manufactured fertiliser N (e.g. ammonium nitrate - AN).
Targetted pollutant	nitrate
Mode of action	fertiliser forms such as ammonium nitrate, where NH4 (and dissolved NH3) will be in equilibrium at a much lower pH, greatly reducing the potential for NH3 emissions.
Target of measure	
Expected effectiveness	NO3 leaching losses are likely to be increased by a small amount (up to 5%)
	Insignificant: <5% decrease in concentration/load
Expected implementation costs	-900 - -100 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	All currently used urea and urea-based fertilisers could be replaced with AN or other form of N (e.g. AN, ammonium phosphate, ammonium sulphate).
quantified (classes):	Unknown
Adoptability of the measure	Low, the main reason urea is used is due to the lower cost per unit of N.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	indirect N2O emissions, and direct N2O emissions (c.20%) as more mineral N is retained in the soil through reduced NH3 emissions to air (c.20% of total N applied). Ammonium and nitrite losses to water maybe decreased by a small amount.
(Phosphorous)	-
(Carbon / CH4)	-
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Incorporate a urease inhibitor into solid urea, liquid urea/ammonium nitrate (UAN) solutions etc.
Targetted pollutant	nitrate
Mode of action	Slowing urea hydrolysis allows more time for urea to be 'washed' into the soil and reduces the soil pH increase in close proximity to the applied urea and thereby the potential for NH3 emissions.
Target of measure	
Expected effectiveness	There would be associated small increases in NO3 leaching losses to water as more mineral N is retained in the soil.
	unknown
Expected implementation costs	No net cost; as ammonia emission reductions are likely to be 'balanced' by the cost of the urease inhibitor.
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	A urease inhibitor could potentially be incorporated into solid urea and UAN solutions.
quantified (classes):	Unknown
Adoptability of the measure	Low-moderate. The main issue would be justifying the cost-benefit of use, as many farmers are 'unaware'/don't 'recognise' the potential for elevated NH3 emissions and associated yield losses from urea use.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	NH3 emissions would be reduced by around 70% from solid urea and around 40% for UAN; small increases in ammonium and nitrite leaching losses to water and direct and indirect N2O emissions to air
(Phosphorous)	-
(Carbon / CH4)	-
Disadvantages	unknown
References	DEFRA report

Type of measure	Land use and management
Measure	Use clover in place of fertiliser N to fix nitrogen from the air, resulting in lower manufactured fertiliser N use.
Targetted pollutant	nitrate
Mode of action	Rhizobium trifolii present in root nodules of the host clover plant fix di-nitrogen gas, which is then nitrified within the plant system. However, fixation by legumes can be repressed through the application of fertiliser N.
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by up to 20%
	Moderate: 10-25% decrease in concentration/load
Expected implementation costs	No net cost; we have assumed that the cost of establishing clover was offset by savings in fertiliser N use
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	This method is applicable to most grassland systems, but may entail a reduction in stocking rates where high rates of manufactured N fertiliser have previously been used.
quantified (classes):	Unknown
Adoptability of the measure	Moderate; with little uptake on high N fertiliser systems.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite leaching losses would be reduced by up to 20%; There would be associated reduction in direct (up to 50%) and indirect (up to 20%) N2O emissions, and NH3 emissions
(Phosphorous)	-
(Carbon / CH4)	-
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Do not apply manufactured N and P fertilisers to soils when soil fertility levels are high
Targetted pollutant	other pollutants
Mode of action	the amount of N and P lost with eroded soil particles and in solution will be reduced.
Target of measure	
Expected effectiveness	-
	unknown
Expected implementation costs	-900 - -100 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	The method is potentially applicable to all farming systems, but would most likely be applied to high output grassland, arable and horticultural farms.
quantified (classes):	Unknown
Adoptability of the measure	Moderate. 'High' P fertiliser prices mean that there is an increasing tendency for farmers to run-down high P status soils
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	-
(Phosphorous)	Soluble P losses would be reduced (over the longer-term) by up to 50% and particulate P losses by up to 30% (over the longer-term).
(Carbon / CH4)	-
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Adjust the composition of livestock diets to reduce the total intake of N and P per unit of production.
Targetted pollutant	nitrate
Mode of action	Restricting diets to recommended levels of N and P will limit the amounts excreted.
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by up to 10%
	Low: 5-10% decrease in concentration/load
Expected implementation costs	600 - 6,250 £/farm, depending on the farm system
cost class:	Moderate: 1000 - 5000 £/farm
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	Benefits are likely to be greatest on dairy, pig and poultry units, and least on beef/sheep units that feed a largely forage-based diet
quantified (classes):	Unknown
Adoptability of the measure	Low-moderate in dairy sector. In the pig sector, uptake for P is already high and uptake for N would be higher with stronger economic incentives. In the poultry sector, uptake for N and P is already high, although there is potential to increase phytase use in the broiler industry.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite leaching losses would be reduced by up to 10% and direct and indirect N2O emissions, and NH3 emissions (by up to 10%).
(Phosphorous)	Soluble P losses would be reduced by up to 10% and in the longer-term particulate P losses
(Carbon / CH4)	CH4 emissions would be reduced by a small amount if dairy cow N intake was reduced by maize use in place of grass silage.
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Manage livestock in smaller groups, divided on the basis of their individual feed requirements
Targetted pollutant	nitrate
Mode of action	Greater division and grouping of livestock on the basis of their feed requirements allows more precise formulation of individual rations. This will reduce N and P surpluses in the diet and reduce the amounts excreted.
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by up to 5%
	Insignificant: <5% decrease in concentration/load
Expected implementation costs	350 - 1,800 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	This method is applicable to all livestock systems, except those primarily based on grazing.
quantified (classes):	Unknown
Adoptability of the measure	Low in the pig sector, without financial incentives. Uptake is already moderate-high in the dairy sector.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite leaching losses would be reduced by up to 5%, and direct and indirect N2O emissions, and NH3 emissions (by up to 5%).
(Phosphorous)	Soluble P losses would be reduced by up to 10% and in the longer-term particulate P losses.
(Carbon / CH4)	There may be a decrease in CH4 emissions from ruminants (depending on the diet formulation).
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Reduce the length of time livestock graze in the fields, either by keeping stock inside during the night or by shortening the length of the grazing season.
Targetted pollutant	nitrate
Mode of action	Urine deposited later in the season, when there is little opportunity for the grass sward to utilise the added N, make the greatest contribution to NO3 leaching losses.
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by up to 20%
	Moderate: 10-25% decrease in concentration/load
Expected implementation costs	1000 - 5,250 £/farm, depending on the farm system
cost class:	Unknown
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	The method is applicable to livestock farms where animals graze outside between spring and autumn, and where there is suitable housing
quantified (classes):	Unknown
Adoptability of the measure	Low-moderate, due to additional labour and associated costs
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite leaching losses would be reduced by up to 20% and direct and indirect N2O emissions.However, NH3 emissions would be increased by up to 20% through greater housing, storage and land spreading emissions.
(Phosphorous)	Particulate/soluble P and associated sediment losses would be reduced by up to 10%, as a result of lower amounts of poaching damage
(Carbon / CH4)	CH4 emissions would increase as greater amounts of manure are stored. CO2 emissions would increase as a result of greater forage production and manure management activities.
Disadvantages	unknown
References	DEFRA report

Type of measure	Improve efficiency
Measure	Where soil conditions allow, the grazing season is extended (either earlier in the spring or later in the autumn).
Targetted pollutant	nitrate
Mode of action	excreta returns (urine and faeces) are deposited directly in the field. NH3 emissions derive predominantly from the urea content of the urine, which must first be hydrolysed to ammonium carbonate before NH3 emissions can occur.
Target of measure	
Expected effectiveness	NO3 leaching losses would be increased by up to 20%,
	unknown
Expected implementation costs	-1,300 - -250 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	No (≤ 1 report)
Applicability of the measure: qualitative	This method can be applied to all farms where cattle are housed, however, soil conditions are likely to limit the potential of the method on many farms because of unacceptable soil damage through poaching.
quantified (classes):	Unknown
Adoptability of the measure	Low, limited by suitable soil types and climate.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite leaching losses would be increased by up to 20%, and direct and indirect N2O emissions. However, NH3 emissions would be reduced by up to 20%, through lower emissions at grazing.
(Phosphorous)	Particulate/soluble P and associated sediment losses would be increased by up to 10%, as a result of greater poaching damage.
(Carbon / CH4)	CH4 emissions would reduce as smaller amounts of manure are stored. CO2 emissions would reduce as a result of lower forage production and manure management activities.
Disadvantages	unknown
References	DEFRA report

Type of measure	Land use management
Measure	When soils are 'wet', the number of livestock per unit area and/or the time stock spend in the field is reduced to avoid (severe) poaching and compaction of the soil.
Targetted pollutant	nitrate
Mode of action	Poaching/compaction reduces soil water infiltration rates and increases the risk of surface runoff. Lower stocking rates will also reduce the amount of excreta deposited and pollutant amounts available for loss.
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by up to 20%
	Moderate: 10-25% decrease in concentration/load
Expected implementation costs	1000 - 5,200 £/farm, depending on the farm system
cost class:	Unknown
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	his method is applicable to all livestock farms where animals are kept outside and is particular to those with high stocking rates, where extended grazing is practised or where stock are wintered outdoors.
quantified (classes):	Unknown
Adoptability of the measure	Low-moderate, due to added labour and associated forage production/manure costs.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite) leaching losses would be reduced by up to 20% and direct and indirect N2O emissions. However, NH3 emissions would be increased by up to 20% through greater housing, storage and land spreading emissions.
(Phosphorous)	Particulate/soluble P and associated sediment losses would be reduced by up to 10%, as a result of lower amounts of poaching damage.
(Carbon / CH4)	CH4 emissions would increase as greater amounts of manure are stored. CO2 emissions would also increase as a result of greater forage production and manure management activities.
Disadvantages	unknown
References	DEFRA report

Type of measure	Land use management

Measure	Move feeders at frequent intervals
Targetted pollutant	nitrate
Mode of action	Moving feeders frequently prevents the accumulation of elevated nutrients and FIOs in localised areas, and reduces the severity of poaching.
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by a small amount (<2%).
	Insignificant: <5% decrease in concentration/load
Expected implementation costs	100 - 450 £/farm, depending on the farm system
cost class:	Unknown
Underpinning of the measure	No (≤ 1 report)
Applicability of the measure: qualitative	The method is most applicable to beef/sheep systems (particularly where livestock are wintered outside) and outdoor pigs.
quantified (classes):	Unknown
Adoptability of the measure	Moderate-high. A simple method, though regular management is needed to be effective.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite leaching losses would be reduced by a small amount (<2%). Direct and indirect N2O emissions and NH3 emissions would also be reduced, as a result of less soil compaction/poaching.
(Phosphorous)	Particulate/soluble P and associated sediment losses would be reduced by up to 10%, as a result of lower amounts of 'severe' poaching damage.
(Carbon / CH4)	CH4 emissions would be reduced from lower amounts of compaction/poaching damage. CO2 emissions would increase by a small amount as a result of greater feeding trough movements.
Disadvantages	unknown
References	DEFRA report

Type of measure	Soil management
Measure	Construct water troughs with a firm base to reduce poaching damage to the soil.
Targetted pollutant	nitrate
Mode of action	Water troughs, with a firm yet permeable base, reduce poaching and allow the rapid infiltration of urine, reducing the risks of surface runoff and transfer of pollutants to watercourses.
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by a small amount (<2%).
	Insignificant: <5% decrease in concentration/load
Expected implementation costs	200 -700 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	No (≤ 1 report)
Applicability of the measure: qualitative	This method is applicable to all beef/sheep/dairy systems where livestock are grazed.
quantified (classes):	Unknown
Adoptability of the measure	Moderate.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite leaching losses would be reduced by a small amount (<2%). Direct and indirect N2O emissions and NH3 emissions would also be reduced, as a result of less soil compaction/poaching.
(Phosphorous)	Particulate/soluble P and associated sediment losses would be reduced by up to 10%, as a result of lower amounts of 'severe' poaching damage.
(Carbon / CH4)	CH4 emissions would be reduced due to lower amounts of compaction/poaching damage. CO2 emissions would increase by a small amount as a result of base construction.
Disadvantages	unknown
References	DEFRA report

Type of measure	Land use and management
Measure	Reduce the total number of livestock on the farm i.e. the number of stock per unit of land area.
Targetted pollutant	nitrate
Mode of action	reducing the number of stock will reduce the amounts of excreta and manure produced per unit area. As a result of lower stocking rates on cattle/outdoor pig farms, there will be fewer urine patches and less NO3 available for loss by leaching or N2O emission, and poaching risks will be reduced.
Target of measure	
Expected effectiveness	NO3 leaching losses would be reduced by up to 20%
	Moderate: 10-25% decrease in concentration/load
Expected implementation costs	5,000 - 33,000 £/farm, depending on the farm system
cost class:	High: >5000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	The method is potentially applicable to all livestock farms, and in particular more intensively stocked units that produce large quantities of excreta and manure. The method would also apply to indoor pig and poultry units, as less manure would be produced.
quantified (classes):	Unknown
Adoptability of the measure	Very low, due to the large negative impact on overall farm profitability.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	Ammonium and nitrite leaching losses would be reduced by up to 20%
(Phosphorous)	Particulate/soluble P and associated sediment losses would be reduced by up to 30%.
(Carbon / CH4)	CH4 and CO2 emissions would be reduced by up to 20%
Disadvantages	unknown
References	DEFRA report

Type of measure	Land use and management
Measure	Grassed buffer strip
Targetted pollutant	nitrate & pesticides
Mode of action	use of buffer strip to slow down water (and solute) transfer to surface water
Target of measure	quality surface water resources
Expected effectiveness	
	Moderate: 10-25% decrease in concentration/load
Expected implementation costs	
cost class:	Moderate: 10-50 euro per ha
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	Partly - only fits hilly areas.
quantified (classes):	Partly (on 25-75% of the agricultural land)
Adoptability of the measure	
quantified (classes):	No (on <25% of the addressees)
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
(Other)	Yes, contributes to landscape diversity;
Disadvantages	Yes, decreases crop yield
References	1. Reichenberger S et al, 2007; 2. CORPEN, 2007

ANNEX 2. OVERVIEW OF MEASURES TO REDUCE NITRATE POLLUTION OF DRINKING WATER RESOURCES AT THE FAIRWAY CASE-STUDY SITES

Location	Netherlands - Overijssel
Targeted pollutants	nitrate
Target of the measure	quality groundwater resources
Name of measure	crop rotation grass and maize
Description	Crop rotation in which grass and maize alternate
Mode of action	Soil conditionn and soil organic matter content is preserved (avoid contious growing of maize on one parcel) which is favourable for retention of nitrate in soil
Expected effectiveness	Moderate: 10-25% decrease in concentration/load
Expected cost	Low: < 10 euro per ha
Underpinning	Yes (> 5 reports)
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	higher NUE, higher crop yields, less purchase of concentrates, lower pesticides use
Disadvantages	No
References	1. Verloop et al, 2006. Reducing nitrate leaching to groundwater in an intensive dairy farming system
	2. Oenema et al., 2010. Multiscale effects of Management, Environmental Conditions, and Land Use on Nitrate Leaching in Dairy Farms
Additional comments	When fields are located far from the buildings, farmers don't like to destine the fields for grassland (high transport costs/labour associated with grass management)

Location	Netherlands - Overijssel
Targeted pollutants	nitrate
Target of the measure	quality groundwater resources
Name of measure	undersow grass between rows of maize
Description	Undersow Italian Ryegrass in between the rows of maize
Mode of action	Italian rye catches up N that is released in soil after the harvest of maize
Expected effectiveness	Moderate: 10-25% decrease in concentration/load
Expected cost	Low: < 10 euro per ha
Underpinning	Yes (> 5 reports)
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	Yes, contributes to landscape diversity
	higher soil quality (SOM)
Disadvantages	no, but it is not succesfull on all fields
References	Schröder, JJ. 1998. Towards improved nitrogen management in silage maize production on sandy soils. Ph.D. Thesis 0
Additional comments	Sowing of Italian rye directly after harvest of maize is also effective, provided that the maize is not harvested too late in the season (close to winter)

Location	Netherlands - Overijssel
Targeted pollutants	nitrate
Target of the measure	quality groundwater resources
Name of measure	(climate adaptive) timing manure application
Description	Optimizing the timing of manure application (not in autumn)
Mode of action	Manure N is applied early in the growing seasons to synchronize uptake of N by crops and release in soil
Expected effectiveness	Moderate: 10-25% decrease in concentration/load
Expected cost	Moderate: 10-50 euro per ha
Underpinning	Yes (> 5 reports)
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	higher NUE, higher crop yields, less purchase of concentrates
Disadvantages	big manure storage required to keep manure in winter
References	1. Aarts et al., 2000. Groundwater recharge through optimized Intensive dairy farms. J. Environ. Qual. 28:738-743.
	2. Cuttle and Bourne, 1993. Uptkae and leaching of nitrogen from artificial urine applied to grassland on different dates during the growing season. Plant Soil 150: 77-86.
Additional comments	

Location	Norway - Vansjø
Targeted pollutants	nitrate
Target of the measure	quality surface water resources
Name of measure	Reduced tillage
Description	Reduced tillage is the single measure that has the greatest effect with respect to reduced nutrient leakage. It contributes to reduced soil erosion and the loss of nutrients (N,P) and soil particles from the crop land to the river basin.
Mode of action	In Morsa, this measure alone has led to a reduction of nearly four tonnes of phosphorus per year. Reduced tillage also has important additional effects:
Expected effectiveness	Moderate: 10-25% decrease in concentration/load
Expected cost	Moderate: 10-50 euro per ha
Underpinning	Yes (> 5 reports)
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	Plant residues on the soil surface protect the soil from rain and running water Increased content of organic material in the soil layer increases the stability of the soil aggregates Increased biological activity with subsequent improved soil structure in the soil layer Reduced traffic on the areas leads to less risk of packing damage
Disadvantages	Unknown
References	1. Refsgaard, K. and Bechmann, M. 2015. Cost-effectiveness of tillage methods to reduce phosphorus loss from agricultural land. Journal of Environmental Planning and Management. Volume 59, 2016 - Issue 9, pages 1560-1579.
	2.Bechmann, M. 2012. Effect of tillage on sediment and phosphorus losses from a field and a catchment in south eastern Norway. Special Issue on Soil in erosion in Nordic countries. Acta Agriculturae Scandinivica, section B. Plant and soil 62, Suppl. 2, 206 - 216.
Additional comments	Disadvantages or not; is often a consequence of how it is being done in practice.

Location	Norway - Vansjø
Targeted pollutants	nitrate
Target of the measure	quality surface water resources
Name of measure	Reduced (optimal) fertilization
Description	Reduced (or optimal) fertilization is an important measure. The Morsa/Vansjø Sub-River Basin organisation has contributed to changes in the national standards for phosphorus fertilizers for cereals and meadows. These have now been reduced by 25%. This results in reduced phosphorus content in soil over time and consequently reduced amount of phosphorus that is bound to particulate matter, as well as reduction in the amount of alloys available phosphorus.
Mode of action	Requires better planning of farm nutrient balances for individual fields, towards more precision farming. Selection of time, type of fertiliser and method of fertilisation are important. Soil tests should be conducted. Phosphorus index is a tool that helps estimate the risk of phosphorus (P) losses from agricultural fields.
Expected effectiveness	Low: 5-10% decrease in concentration/load
Expected cost	Low: < 10 euro per ha
Underpinning	Yes (> 5 reports)
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Yes (more than 75% of the addressees)
Other benefits	Can increase yield if done in a precision-farming manner. Can reduce costs, in particular if commersial fertilisers are being used.
Disadvantages	None
References	1. Bechmann, M., Blicher-Mathiesen, G., Kyllmar, K., Iital, A., Lagzdins, A., Salo, T., 2014. Nitrogen application, balances and the effect on nitrogen concentrations in runoff from small catchments in the Nordic - Baltic countries. Agriculture, Ecosystems and Environment 198 (2014) 104 - 113.
Additional comments	

Location	Norway - Vansjø
Targeted pollutants	nitrate
Target of the measure	quality surface water resources
Name of measure	Grass covered waterways
Description	Grass covered waterways Relatively small areas on a field can account for a very large part of the soil erosion (and associated nutrient losses), especially when a large amount of surface water seeks it way to lower and narrower parts of the fields .
Mode of action	The measure of grass covered waterways, which involves sowing grass in water-bearing and erosion-induced drops, is a very important measure that is given high priority. Grass covered waterways are established in droughts where the water digs.
Expected effectiveness	High: >25% decrease in concentration/load
Expected cost	Very high: >100 euro per ha
Underpinning	Partly (1-5 reports)
Applicability	No (on <25% of the agricultural land)
Adoptability	No (on <25% of the addressees)
Other benefits	Yes, contributes to landscape diversity
	other, namely substantively reduction in soil erosion.
Disadvantages	None
References	1.Anne-Grete Buseth Blankenberg og Heidi A. Grønsten. Vegetasjonsdekke som tiltak mot tap av jord og fosfor (Vegetation cover as measure against soil and phosphorous losses) .BIOFORSK TEMA vol 9 nr 6 ISBN 978-82-17-01218-4 http://www.bioforsk.no/ikbViewer/Content/109019/Vegetasjonsdekke_AGB.pdf
	2. Peter Fiener and Karl Auerswald . 2017. Grassed Waterways. Ch. in Precision Conservation: Geospatial Techniques for Agricultural and Natural Resources Conservation, J. Delgado, G. Sassenrath and T. Mueller (ed.) ISBN: 978-0-89118-356-3, Published: June 16, 2017
Additional comments	Reduces the amount of cropland.

Location	France - La Voulzie
Targeted pollutants	nitrate & pesticides
Target of the measure	quality surface water resources
Name of measure	buffer stip, grass strip
Description	buffer stip, grass strip
Mode of action	use of buffer strip to slow down water (and solute) transfert to surface water
Expected effectiveness	Moderate: 10-25% decrease in concentration/load
Expected cost	Moderate: 10-50 euro per ha
Underpinning	Yes (> 5 reports)
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	No (on <25% of the addressees)
Other benefits	Yes, contributes to landscape diversity
Disadvantages	Yes, decreases crop yield
References	1. Reichenberger S et al, 2007
	2. CORPEN, 2007
Additional comments	

Location	Portugal - Baixo Mondego
Targeted pollutants	nitrate & pesticides
Target of the measure	
Name of measure	Control of input through management system approaches.
Description	There is a tight control of the amount of pesticides that a farmer can buy, and each farmer, must make a course and pass na exam to be able to buy pesticides. The level of the course depends on how professional you are and the amount of land you have. Even people with backyards need to have an habilitation to be able to buy pesticides. There is also a control on the amount of fertilizers, either mineral or organic that you can by or dispose in the area they have available.
Mode of action	This is a management system approach, where a documental management system has to be set im place, and where control checks are performed. It requires a database with all the information on farmers, their parcels and crops, which is available to the sellers, that are not allowed to sell more than is needed for the area and crops. The farmer has to maintain a documental system that witnesses what, when and the amount of substances applyed, both pesticides and fertilizers.
Expected effectiveness	High: >25% decrease in concentration/load
Expected cost	Low: < 10 euro per ha
Underpinning	Unknown
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Yes (more than 75% of the addressees)
Other benefits	Yes, decreases energy costs
	There is a more judicious use of production factors.
Disadvantages	No
References	
Additional comments	This has just started to be applied, so no results yet (my father which has a backyard that he farms, needed to make a specific pesticide course to be able to buy the amount of pesticides he needs, and the sellers will cross the information of area and crops before they sell any pesticides). In addition, there are controls to the amount of mineral and organic fertilizers. A document register has to be kept to be monitored by external experts if needed.

Location	Germany - Lower Saxony
Targeted pollutants	nitrate, phosphate
Target of the measure	quality groundwater resources
Name of measure	Farm-holistic fertilization planning with generic software
Description	Farm-holistic planing (including economic scenarios) to better estimate the amount of fertilizer needed
Mode of action	• decrease of total nitrate/phosphate of nutrients applied • improved nutrient efficiency due to optimized plant availability of other nutrients/micronutrients • optimized integration of organic fertilizers • high adoptability by farms (holistic approach, also considers economic and logistic challenges)
Expected effectiveness	depends on individual farm; no effect up to high effect
Expected cost	Low: < 10 euro per ha
Underpinning	Only projects reports exist, no official (scientific) publications available
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Yes (more than 75% of the addressees)
Other benefits	yes, potentially various
Disadvantages	No
References	
Additional comments	

Location	Germany - Lower Saxony
Targeted pollutants	nitrate, phosphate
Target of the measure	quality groundwater resources
Name of measure	Sampling-based (and model-based) fertilization planning
Description	Soil and plant sampling (and modelling of water dynamics in the soil) to better estimate crop nutrients needs and timing of fertilization; e.g. soil mineral nitrogen analysis, humus analysis, analysis of temporal development of nitrate/chlorophyll contents in plant sap, ...
Mode of action	• increase of yield (higher nutrient export from the field) • decrease of total nitrate/phosphate applied • improved timing of fertilization
Expected effectiveness	depends on individual farm; no effect up to high effect
Expected cost	Low: < 10 euro per ha
Underpinning	Only projects reports exist, no official (scientific) publications available
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	Unknown
Disadvantages	No
References	
Additional comments	comment concerning adoptability: depends on respective crop (rotation)

Location	Germany - Lower Saxony
Targeted pollutants	nitrate, phosphate
Target of the measure	quality groundwater resources
Name of measure	Calculation of nutrient balances (different scenarios)
Description	Calculation of nutrient balances both field-based and farm-based
Mode of action	• decrease of total nitrate/phosphate of nutrients applied • identification of critical factors (such as crops, techniques, ..)
Expected effectiveness	depends on individual farm; no effect up to moderate effect
Expected cost	Low: < 10 euro per ha
Underpinning	Only projects reports exist, no official (scientific) publications available
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Yes (more than 75% of the addressees)
Other benefits	Unknown
Disadvantages	No
References	
Additional comments	comment concerning adoptability: farmers are legally obliged to do so

Location	Germany - Lower Saxony
Targeted pollutants	nitrate, phosphate
Target of the measure	quality surface and groundwater
Name of measure	Information events/discussions/ field days concerning relevant topics
Description	Improved information transfer about topics dealing with efficient use of farm manure, e.g. • professional advise ("How much farm manure can be efficiently used by my crops?") • legal framework ("Which amount of farm manure am I allowed to apply legally, e.g. when considering special restrictions in water protected areas?") • economic considerations ("Which economic benefits can I expect using farm manure by substituting mineral fertilizers?") • soil fertility ("Which effect do I see on soil fertility in respect to potentially increased stocks of humus but also due to e.g. soil compaction?") • various effects ("Which other problems may arise when I apply farm manure, e.g. civilians complaing about odours, ...? ")
Mode of action	• development of farm-holistic concept concerning the use of fertilizers --> decrease of nitrate/phosphate • substitution of mineral farm manure with organic fertilizers (and with that supporting farms in the northwest(farm manure surplus region)) • increased yields (higher nutrient export from the field) ---> reduced amounts of nitrate/phosphate being lost to the environment
Expected effectiveness	depends on individual farm; no effect up to high effect
Expected cost	Low: < 10 euro per ha
Underpinning	Only projects reports exist, no official (scientific) publications available
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	Unknown
Disadvantages	No
References	
Additional comments	

Location	Germany - Lower Saxony
Targeted pollutants	nitrate, phosphate
Target of the measure	quality surface and groundwater
Name of measure	Demonstration/use of innovative techniques concerning farm manure application (while avoiding soil compaction)
Description	Improved information transfer and promoting of innovative techniques to enable efficient application of farm manure
Mode of action	• increased nutrient efficiency (minimizing losses to the environment, e.g. less ammonia losses when applying farm manure) • improving/maintaining soil fertility --> increasing/maintaining yield levels --> high(er) nutrient export from the field •motivating farmers to participate in project
Expected effectiveness	depends on individual farm; no effect up to moderate effect
Expected cost	Low: < 10 euro per ha
Underpinning	Only projects reports exist, no official (scientific) publications available
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	Yes, decreases greenhouse gas emissions
	Yes, decreases greenhouse gas emissions
Disadvantages	No
References	
Additional comments	

Location	Denmark - Island Tunø and Aalborg
Targeted pollutants	nitrate & pesticides
Target of the measure	quality groundwater resources
Name of measure	IPM, precision farming and timing
Description	Spatial and temporal targeted nitrate and pesticides application
Mode of action	Reduction and application of the most effective legal pesticides in minimal amounts
Expected effectiveness	High: >25% decrease in concentration/load
Expected cost	Low: < 10 euro per ha
Underpinning	Yes (> 5 reports)
Applicability	Unknown
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	Yes, decreases greenhouse gas emissions
Disadvantages	Labour consuming
References	http://www.endure-network.eu/endure_publications/papers_in_scientific_journals2
Additional comments	References are written in Danish

Location	Denmark - Island Tunø and Aalborg
Targeted pollutants	nitrate
Target of the measure	quality groundwater resources
Name of measure	Legal measures.
Description	Manure is not allowed to be used in the autumn. Combined with quotes on nitrogen application and high utilisation of organic manure.
Mode of action	Reduction of nitrate leaching
Expected effectiveness	High: >25% decrease in concentration/load
Expected cost	Low: < 10 euro per ha
Underpinning	Yes (> 5 reports)
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Yes (more than 75% of the addressees)
Other benefits	Yes, decreases greenhouse gas emissions
	Reduction in energy consumptions
Disadvantages	Increased management requirements
References	
Additional comments	References are written in Danish

Location	Denmark - Island Tunø and Aalborg
Targeted pollutants	nitrate
Target of the measure	quality groundwater resources
Name of measure	Cover crops
Description	Between 10 - 35 % of the farm area must be sowed with cover crops
Mode of action	Modification of pollution pathway
Expected effectiveness	High: >25% decrease in concentration/load
Expected cost	High: 50-100 euro per ha
Underpinning	Yes (> 5 reports)
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	Yes (more than 75% of the addressees)
Other benefits	No
Disadvantages	cost
References	
Additional comments	The cost varies based on the farm types

Location	Denmark - Island Tunø and Aalborg
Targeted pollutants	nitrate & pesticides
Target of the measure	quality groundwater resources
Name of measure	Restriction in farming system
Description	Agreement on no pesticide use and reduction of nitrogen leaching
Mode of action	Reduction
Expected effectiveness	High: >25% decrease in concentration/load
Expected cost	Very high: >100 euro per ha
Underpinning	Unknown
Applicability	No (on <25% of the agricultural land)
Adoptability	No (on <25% of the addressees)
Other benefits	Benefits for the water quality but none for the farmers
Disadvantages	decrease in crop yield, causes problems for the management of the farm
References	
Additional comments	one-off payment

Location	Greece - Axios River
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	Management of meadows and grassland
Description	Management of meadows and grassland
Mode of action	departure of grazing animals as soon as possible, avoid fertilization of meadows with manure or wet manure, grassland seeding early in the autumn, meadows and grasslands should always be crop covered during winter
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	Unknown
Applicability	Unknown
Adoptability	Unknown
Other benefits	Unknown
Disadvantages	Unknown
References	Journal of Government No. 85167/800 (2000) Code of Good Agricultural Practice for the protection of nitrate induced water pollution from agricultural sources
Additional comments	

Location	Greece - Axios River
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	Cover crop during autumn-winter
Description	Cover crop during autumn-winter
Mode of action	soil cultivation with fall-winter crops wherever possible, early sowing (15-30 September), cover crops should be existed even with non-cultivated plants
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	Unknown
Applicability	Unknown
Adoptability	Unknown
Other benefits	Unknown
Disadvantages	Unknown
References	Journal of Government No. 85167/800 (2000) Code of Good Agricultural Practice for the protection of nitrate induced water pollution from agricultural sources
Additional comments	

Location	Greece - Axios River
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	Isolation of well waters from unconfined aquifers
Description	Areas with high geologically nitrate content could lead to high nitrate content of their waters through leaching process.
Mode of action	High nitrate concentrations of the drinking water could be decreased by isolating the well waters from existing unconfined aquifers.
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	Unknown
Applicability	Unknown
Adoptability	Unknown
Other benefits	Unknown
Disadvantages	Unknown
References	1. M. Mitrakas et al., (1989). Nitrate content of surface and ground wters of Northern Greece
Additional comments	

Location	Greece - Axios River
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	Στοραγε οφ φεριλιζερσ
Description	Storage and transport of inorganic fertilizers
Mode of action	fertilizers should be stored in strong bags at least 50 meters away from surface waters, preventative measures should be taken to avoid accidents and risk of spreading during transport
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	Unknown
Applicability	Unknown
Adoptability	Unknown
Other benefits	Unknown
Disadvantages	Unknown
References	Journal of Government No. 85167/800 (2000) Code of Good Agricultural Practice for the protection of nitrate induced water pollution from agricultural sources
Additional comments	

Location	Greece - Axios River
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	Απλιψατιον τιμε
Description	fertilizer application time and quantity
Mode of action	Estimation of the right fertilizer quantity to a given crop, fertilizer should be applied at the high growth rate of plant (spring-summer), fertilization should be avoided from October 15 to February 1, fertilization avoidance on frozen or snow-covered soils, application of legume cover crops on sloping land, fertilization over small distances using spreader machine, avoidance of fertilization during strong winds, use of fertilizers in precise quantities and avoid of spreading in uncultivated land
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	Unknown
Applicability	Unknown
Adoptability	Unknown
Other benefits	Unknown
Disadvantages	Unknown
References	Journal of Government No. 85167/800 (2000) Code of Good Agricultural Practice for the protection of nitrate induced water pollution from agricultural sources
Additional comments	

Location	Greece - Axios River
Targeted pollutants	nitrate
Target of the measure	quality groundwater resources
Name of measure	split fertilization
Description	nitrogen management for Wheat cultivation
Mode of action	split fertilization to a number of doses for each field and rational management of irrigation water for each field
Expected effectiveness	Moderate: 10-25% decrease in concentration/load
Expected cost	Low: < 10 euro per ha
Underpinning	Partly (1-5 reports)
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	nitrogen fertilisation efficiency is increased
Disadvantages	Unknown
References	1. Karyotis et al, 2002. The Greek Action Plan for the mitigation of nitrates in water resources of the vulnerable district of Thessaly
	2.karyotis T., Kosmas C., 2010. Nitrogen leaching, mineralization and uptake in cultivated soils of central Greece
Additional comments	Discouragement of crop production is also suggested in the regions where pollution risk is extremely high

Location	Greece - Axios River
Targeted pollutants	nitrate
Target of the measure	quality groundwater resources
Name of measure	Manure and N-fertilizer application management
Description	nitrogen fertilizers application
Mode of action	manure total nitrogen should not exceed the amount of 170 Kg N/Ha in vegetation covered soil and 150 Kg N/Ha in uncovered soil, N fertilization and application of farm animal wastes during rainy season is forbidden with the exception of basic autumn and winter crop N fertilization, apply of N fertilizer on water-saturated soils is forbidden, fertilization outside of cultivated area is forbidden
Expected effectiveness	Moderate: 10-25% decrease in concentration/load
Expected cost	Unknown
Underpinning	No (≤ 1 report)
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	Unknown
Disadvantages	Unknown
References	1. Joint Ministerial Decision19652/1906/199
	2. Joint Ministerial Decision 20419/2522/2001
Additional comments	

Location	Greece - Axios River
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	Cultivation techniques and constructions around fields
Description	cultivation techniques
Mode of action	construction of stable uncultivated strips at least 1 m near water bodies and trenches, plant cover in sloping parcels to protect erosion sensitive terrain during rainy season and soil
Expected effectiveness	Moderate: 10-25% decrease in concentration/load
Expected cost	Low: < 10 euro per ha
Underpinning	No (≤ 1 report)
Applicability	Unknown
Adoptability	No (on <25% of the addressees)
Other benefits	Yes, contributes to landscape diversity
Disadvantages	Unknown
References	1. Joint Ministerial Decision19652/1906/199
	2. Joint Ministerial Decision 20419/2522/2001
Additional comments	

Location	Romania - Arges-Vedea

Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	crop rotation including cover crops
Description	Part of the agricultural area of farm is cultivated with cover crops for soil protection and fixing nitrogen. The cover crops is incorporated in soil with the main tillage (ploughing) and available for the next crop
Mode of action	Nitrogen is fixed during the periods with high nitrogen leaching. In this way nitrogen is available for the next crop
Expected effectiveness	Moderate: 10-25% decrease in concentration/load
Expected cost	Low: < 10 euro per ha
Underpinning	Partly (1-5 reports)
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	Yes, decreases greenhouse gas emissions
	higher soil quality, higher NUE and SOM
Disadvantages	No
References	1. Borlan, 1985. Guide of accomplishing fertilisation plans for cereals, fruit trees, vineyards, vegetables and grasslands. Romanian version.
	2. Davidescu, 2000. Compendium of Agrochemistry. Romanian version.
	3. Hera and Borlan, 1998. Soil fertilization and fertility. Romanian version.
	4. Ministry of Agriculture and Rural Development, 1989. Methodology of establishing nitrogen rates applied during spring according to soil mineral nitrogen stock. Romanian version.
Additional comments	Usually this measure is applied on flat fields for wind erosion protection and on slopes for soil protection against water erosion

Location	Romania - Arges-Vedea
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	manure application at proper time
Description	Animal manure is applied and incorporated in soil in autumn with the main soil tillage. The manure might be also incorporated in soil with the seedbed operation, in spring season, according to manure quality and its decomposed rate
Mode of action	Manure is properly managed in terms of storage and soil application as fertilizer.
Expected effectiveness	Moderate: 10-25% decrease in concentration/load
Expected cost	High: 50-100 euro per ha
Underpinning	Partly (1-5 reports)
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	Yes (more than 75% of the addressees)
Other benefits	Yes, decreases greenhouse gas emissions
	higher soil quality, higher NUE and SOM
Disadvantages	Cost with manure management (storage, transport, application and incorporation
References	1. Mihail Dumitru et. all, 2015. Code of Good Agricultural Practices for water protection against nitrate pollution from agricultural sources. Romanian version.
	2. Hera and Borlan, 1998. Soil fertilization and fertility. Romanian version.
	3. Davidescu, 2000. Compendium of Agrochemistry. Romanian version.
Additional comments	The animal manure applied in autumn usually is partially decomposed, while in spring, usually, totally decomposed animal manure is applied.

Location	Romania - Arges-Vedea
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	grass strips between fruit trees rows in orchards and vineyard rows
Description	The interval between trees or vineyard rows is sowed with grass-clover and leguminous crops which are resistant to agricultural equipment traffic
Mode of action	The soil is covered and the soil physical quality is maintained at an optimum level. Nitrogen is fixed by grass-clover and leguminous crops. The harvested biomass is used as mulch on trees and vineyard rows, supplying the soil with nitrogen.
Expected effectiveness	High: >25% decrease in concentration/load
Expected cost	High: 50-100 euro per ha
Underpinning	Partly (1-5 reports)
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	Yes, decreases greenhouse gas emissions
	higher soil quality, higher NUE
Disadvantages	No
References	1. Mihail Dumitru et. all, 2015. Code of Good Agricultural Practices for water protection against nitrate pollution from agricultural sources. Romanian version.
	2. ICDP Maracineni, 2015. Guide for trees and shrubs cultivation. Romanian version.
	3. Borlan, 1985. Guide of accomplishing fertilisation plans for cereals, fruit trees, vineyards, vegetables and grasslands. Romanian version.
Additional comments	If the farmer have animal manure , he applies totally decomposed manure on trees and vineyards rows

Location	Slovenia - Dravsko polje
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	Limit on N input
Description	Limits N input from organic fertilisers all over Slovenia to 170 kg/ha and on narrowest water protection zones to 140 from composted organic manure.
Mode of action	a) Reduction / substitution of contaminant input
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	No (≤ 1 report)
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Yes (more than 75% of the addressees)
Other benefits	Yes, decreases ammonia emissions
Disadvantages	No
References	Glavan, M., Pintar, M. and Urbanc, J., 2015. Spatial variation of crop rotations and their impacts on provisioning ecosystem services on the river Drava alluvial plain. Sustainability of Water Quality and Ecology, 5(0): 31-48. https://doi.org/10.1016/j.swaqe.2015.01.004
	Glavan M, Jamšek A, Pintar M. 2017. Modelling Impact of Adjusted Agricultural Practices on Nitrogen Leaching to Groundwater. In Water Quality, Tutu H (ed). InTech: Rijeka, Croatia. https://www.intechopen.com/books/water-quality/modelling-impact-of-adjusted-agricultural-practices-on-nitrogen-leaching-to-groundwater
Additional comments	Monitoring results show that concentrations on Nitrate in groundwater are falling or are stable after the fall. However certain boreholes are still problematic with high concentrations. Expected effectiveness is nitrate below 50 mg/l in groundwater and falling. Costs were never estimated and impacts of measure examined and reported only to the level of state monitoring results. measure is highly applicable and adoptable as it is obligatory for all farmers.
	Scientific literature in Slovene and English language is quite limited for our Case study - practically non-existent.

Location	Slovenia - Dravsko polje
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	Timing manure application
Description	Sets time limits for the application of organic and mineral fertilisers.
Mode of action	a) Reduction / substitution of contaminant input
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	No (≤ 1 report)
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Yes (more than 75% of the addressees)
Other benefits	Yes, decreases ammonia emissions
Disadvantages	No
References	Glavan, M., Pintar, M. and Urbanc, J., 2015. Spatial variation of crop rotations and their impacts on provisioning ecosystem services on the river Drava alluvial plain. Sustainability of Water Quality and Ecology, 5(0): 31-48. https://doi.org/10.1016/j.swaqe.2015.01.004
	Glavan M, Jamšek A, Pintar M. 2017. Modelling Impact of Adjusted Agricultural Practices on Nitrogen Leaching to Groundwater. In Water Quality, Tutu H (ed). InTech: Rijeka, Croatia. https://www.intechopen.com/books/water-quality/modelling-impact-of-adjusted-agricultural-practices-on-nitrogen-leaching-to-groundwater
Additional comments	Study was made from Slovenian Agricultural Institute in 2016/17 ordered by Ministry for Environment. However data to evaluate effectiveness or costs are not available. Not published in scientific literature. Open link (in Slovene): http://www.mediafire.com/folder/iq8wxkyv5qnzc/WP4_-_Measures_results
	Scientific literature in Slovene and English language is quite limited for our Case study - practically non-existent.

Location	Slovenia - Dravsko polje
Targeted pollutants	nitrate & pesticides
Target of the measure	quality surface water resources
Name of measure	Buffer zones
Description	A safe zone used to reduce N entering surface waters and modify pollution pathways.
Mode of action	a) Reduction / substitution of contaminant input; b) Modification of pollution pathway
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	No (≤ 1 report)
Applicability	No (on <25% of the agricultural land)
Adoptability	No (on <25% of the addressees)
Other benefits	No
Disadvantages	Yes, decreases crop yield
References	Glavan, M., Pintar, M. and Urbanc, J., 2015. Spatial variation of crop rotations and their impacts on provisioning ecosystem services on the river Drava alluvial plain. Sustainability of Water Quality and Ecology, 5(0): 31-48. https://doi.org/10.1016/j.swaqe.2015.01.004
	Glavan M, Jamšek A, Pintar M. 2017. Modelling Impact of Adjusted Agricultural Practices on Nitrogen Leaching to Groundwater. In Water Quality, Tutu H (ed). InTech: Rijeka, Croatia. https://www.intechopen.com/books/water-quality/modelling-impact-of-adjusted-agricultural-practices-on-nitrogen-leaching-to-groundwater
Additional comments	Study was made from Slovenian Agricultural Institute in 2016/17 ordered by Ministry for Environment. However data to evaluate effectiveness or costs are not available. Not published in scientific literature. Open link (in Slovene): http://www.mediafire.com/folder/iq8wxkyv5qnzc/WP4_-_Measures_results
	Scientific literature in Slovene and English language is quite limited for our Case study - practically non-existent.

Location	Slovenia - Dravsko polje
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	Five year crop rotation
Description	Used to improve soil health. One of the positive effect is also reduced use of N - introduction of legumes crops (beans/peas/clovers).
Mode of action	a) Reduction / substitution of contaminant input
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	No (≤ 1 report)
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	Partly (on 25-75% of the addressees)
Other benefits	positive for soil health, reduces plant pests and disease
Disadvantages	No
References	Glavan, M., Pintar, M. and Urbanc, J., 2015. Spatial variation of crop rotations and their impacts on provisioning ecosystem services on the river Drava alluvial plain. Sustainability of Water Quality and Ecology, 5(0): 31-48. https://doi.org/10.1016/j.swaqe.2015.01.004
	Glavan M, Jamšek A, Pintar M. 2017. Modelling Impact of Adjusted Agricultural Practices on Nitrogen Leaching to Groundwater. In Water Quality, Tutu H (ed). InTech: Rijeka, Croatia. https://www.intechopen.com/books/water-quality/modelling-impact-of-adjusted-agricultural-practices-on-nitrogen-leaching-to-groundwater
Additional comments	Data to evaluate effectiveness or costs are not available. Detailed applicability and adoptability can be retrieved from national agricultural payments database.
	Scientific literature in Slovene and English language is quite limited for our Case study - practically non-existent.

Location	Slovenia - Dravsko polje
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	Cover crops
Description	Protects soil from weather impacts. Plants prevent erosion and nutrient leaching. They can act as catch-crops and save N in plants biomass.
Mode of action	a) Reduction / substitution of contaminant input
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	No (≤ 1 report)
Applicability	No (on <25% of the agricultural land)
Adoptability	No (on <25% of the addressees)
Other benefits	positive for soil physical properties, organic matter
Disadvantages	No
References	Glavan, M., Pintar, M. and Urbanc, J., 2015. Spatial variation of crop rotations and their impacts on provisioning ecosystem services on the river Drava alluvial plain. Sustainability of Water Quality and Ecology, 5(0): 31-48. https://doi.org/10.1016/j.swaqe.2015.01.004
	Glavan M, Jamšek A, Pintar M. 2017. Modelling Impact of Adjusted Agricultural Practices on Nitrogen Leaching to Groundwater. In Water Quality, Tutu H (ed). InTech: Rijeka, Croatia. https://www.intechopen.com/books/water-quality/modelling-impact-of-adjusted-agricultural-practices-on-nitrogen-leaching-to-groundwater
Additional comments	Data to evaluate effectiveness or costs are not available. Detailed applicability and adoptability can be retrieved from national agricultural payments database.
	Scientific literature in Slovene and English language is quite limited for our Case study - practically non-existent.

Location	Slovenia - Dravsko polje
Targeted pollutants	nitrate
Target of the measure	quality surface and groundwater
Name of measure	Plants for green manure
Description	Protects soil from weather impacts. Plants prevent erosion and nutrient leaching. They can act as catch-crops and save N in plants biomass.
Mode of action	a) Reduction / substitution of contaminant input
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	No (≤ 1 report)
Applicability	No (on <25% of the agricultural land)
Adoptability	No (on <25% of the addressees)
Other benefits	contributes to higher soil organic matter
Disadvantages	No
References	Glavan, M., Pintar, M. and Urbanc, J., 2015. Spatial variation of crop rotations and their impacts on provisioning ecosystem services on the river Drava alluvial plain. Sustainability of Water Quality and Ecology, 5(0): 31-48. https://doi.org/10.1016/j.swaqe.2015.01.004
	Glavan M, Jamšek A, Pintar M. 2017. Modelling Impact of Adjusted Agricultural Practices on Nitrogen Leaching to Groundwater. In Water Quality, Tutu H (ed). InTech: Rijeka, Croatia. https://www.intechopen.com/books/water-quality/modelling-impact-of-adjusted-agricultural-practices-on-nitrogen-leaching-to-groundwater
Additional comments	Data to evaluate effectiveness or costs are not available. Detailed applicability and adoptability can be retrived from national agricultural payments database.
	Scientific literature in Slovene and English language is quite limited for our Case study - practically non-existent.

ANNEX 3. LIST OF REFERENCES OF STUDIES USED IN THE QUANTITATIVE ANALYSIS OF THE EFFECTIVENESS OF MEASURES.

AgroCampus Rennes (2006) AgrocampusRennes citing "Besnard, 2004" (2006) Pratique agricoles, fuites de nitrates et qualité de l'eau dans les bassins versants : Synthèse des références applicables au contexte breton. Agrocampus – Rennes, 65 rue de Saint-brieuc – CS 84215, 35042 Rennes cedex

Appel, T. und Fritsch, F. (2015): Nitratauswaschung nach Körnerraps in Abhängigkeit vom Strohmanagement und der Stoppelbearbeitung. VDLUFA-Schriftenreihe 71, Kongressband 2015, S. 170-177.

Armbruster, M.; Laun, N.; Heger, A. & Wiesler, F. (2013), 'Integrated nitrogen management—A strategy to improve nitrogen efficiency in intensive field vegetable production', Proceedings of NUTRIHORT, Nutrient Management, Innovative Techniques and Nutrient Legislation in Intensive Horticulture for an Improved Water Quality, Ghent, Belgium, 15--18.

Armbruster, M.; Fischer, H.; Wiesler, F. (2017): Pappel-Kurzumtriebsplantage auf leichten Böden im Oberrheingraben - Ergebnisse der ersten Umtriebsphase.VDLUFA-Schriftenreihe Bd. 74/2017, 58-66.

Benoit, M.; Garnier, J.; Beaudoin, N. & Billen, G. (2016), 'A participative network of organic and conventional crop farms in the Seine Basin (France) for evaluating nitrate leaching and yield performance', Agricultural Systems 148, 105--113.

Besnard, A.; Kerveillant, P. (2006) Effet et devenir de l'azote d'un couvert végétal enfoui dans une succession blé-mais. Qualité de l'eau en milieu rural: Savoirs et pratiques dans les bassins versants .in: Merot P. (ed), Qualité de l'eau en milieu ruiral: Savoirs et pratiques daans les bassins versants. INRA, Paris. p145-150.

Bilosovб, H.; Sarapatka, B.; Stbnarovб, M.; Micovб, P. & Svozilovб, M. (2017), 'Nitrogen leaching from grassland ecosystems managed with organic fertilizers at different stocking rates', Archives of Agronomy and Soil Science 63(11), 1535--1545.

Boese, L. (2013) Wirkung ammoniumstabilisierter N-Dünger im Vergleich zu ihren nicht stabilisierten Formen in unterschiedlicher Gabenteilung auf Kornertrag, Rohproteingehalt und N-Saldo von Winterweizen auf Löss-Schwarzerde. Untersuchen, Bewerten, Beraten, Forschen: 125 Jahre VDLUFA im Dienste von Landwirtschaft , Umwelt- und Verbraucherschutz, KONGRESSBAND 2013 BERLIN, p167-173

Brozyna, M. A.; Petersen, S. O.; Chirinda, N. & Olesen, J. E. (2013), 'Effects of grass-clover management and cover crops on nitrogen cycling and nitrous oxide emissions in a stockless organic crop rotation', Agriculture, ecosystems & environment 181, 115--126.

Bucur D.G., Dumitru M., Creangă I., Simota C., Calciu Irina, (2010) "Monitorizarea poluării cu nitrați în județul Argeș ."Editura SITECH, Craiova.

Bucur, D.; Jitareanu, G. & Ailincai, C. (2011), 'Effects of long-term soil and crop management on the yield and on the fertility of eroded soil', Journal of Food, Agriculture & Environment 9(2), 207--209.

Carlton, A. J.; Cameron, K. C.; Di, H. J.; Edwards, G. R. & Clough, T. J. (2018), 'Nitrate leaching losses are lower from ryegrass/white clover forages containing plantain than from ryegrass/white clover forages under different irrigation', New Zealand Journal of Agricultural Research, 1--23.

Carlton, A. J.; Cameron, K. C.; Edwards, G. R.; Di, H. J. & Clough, T. J. (2018), 'Effect of two irrigation rates on nitrate leaching from diverse or standard forages receiving spring deposited urine', New Zealand Journal of Agricultural Research 61(4), 440--453.

Creanga, I., D.G. Bucur, R-D Busu (2008) Evolutia continutului de nitrati din zone vulnerabile la poluarea cu nitrati din surse agricole (ZVN), sub influenta precipitatiilor din anul 2005 (comuna Cosesti, jud. Arges). Lucrarile celei de-a XVIII-a Conferinte Nationale pentru Stiinta Solului.

Defra (2006) Optimising slurry application timings to minimise nitrogen losses Opti-N. Defra. http://sciencesearch.defra.gov.uk/Document.aspx?Document=ES0115_7943_FRP.doc

DEFRA (2001) Effect of cattle slurry application rate and method, to grass and maize, on N losses by leaching, ammonia volatilisation and as nitrous oxide. DEFRA Final Project Report (CSG15) Project code NT1851.

Dennis, S. J.; Cameron, K. C.; Di, H. J.; Moir, J. L. & Richards, K. G. (2010), Dicyandiamide (DCD) reduces nitrate losses from Irish soils, in 'Soil Solutions for a Changing World: Proceedings of the 19th World Congress of Soil Science, Brisbane, Australia', pp. 1--6.

Di, H. J. & Cameron, K. C. (2012), 'How does the application of different nitrification inhibitors affect nitrous oxide emissions and nitrate leaching from cow urine in grazed pastures?', Soil Use and Management 28(1), 54--61.

Djurhuus, J. & Olsen, P. (1997), 'Nitrate leaching after cut grass/clover leys as affected by time of ploughing', Soil Use and Management 13(2), 61--67.

Dumitru, M, C. Simota, I. Calciu (2013) Tehnologie de utilizare agricola a namolului de porc. Managementul Nutrientilor - Directiva Nitrati. Editora SOLNESS. ISBN 978-973-729-381-7

Eriksen, J. (2001). Nitrate leaching and growth of cereal crops following cultivation of contrasting temporary grasslands. The Journal of Agricultural Science, 136(3), 271-281.

Eriksen, J.; Askegaard, M. & Kristensen, K. (2004), 'Nitrate leaching from an organic dairy crop rotation: the effects of manure type, nitrogen input and improved crop rotation', Soil Use and Management 20(1), 48--54.

Eriksen, Jørgen , Poul Nordemann Jensen, Brian H. Jacobsen (eds) (2014) Virkemidler til realisering af 2. Generations vandplaner og målrettet arealregulering. DCA - Nationalt Center for Fødevarer og Jordbrug, Blichers Allé 20, postboks 50, 8830 Tjele. DCA-report 052.

Francis, G. S.; Haynes, R. J. & Williams, P. H. (1995), 'Effects of the timing of ploughing-in temporary leguminous pastures and two winter cover crops on nitrogen mineralization, nitrate leaching and spring wheat growth', The Journal of Agricultural Science 124(1), 1--9.

Froment, M. A.; Chalmers, A. G. & Smith, K. A. (1992), 'Nitrate leaching from autumn and winter application of animal manures to grassland', Aspects of applied biology.

Fucik, P.; Kvitek, T.; Lexa, M.; Novбk, P.; Bilkovб, A. & others (2008), 'Assessing the stream water quality dynamics in connection with land use in agricultural catchments of different scales.', Soil and Water Research 3(3), 98--112.

Fucik, P.; Zajicek, A.; Duffkovб, R. & Kvitek, T. (2015), Water Quality of Agricultural Drainage Systems in the Czech Republic—Options for Its Improvement'Research and practices in water quality', InTech, .

Goss, M. J.; Howse, K. R.; Lane, P. W.; Christian, D. G. & Harris, G. L. (1993), 'Losses of nitrate-nitrogen in water draining from under autumn-sown crops established by direct drilling or mouldboard ploughing', Journal of soil science 44(1), 35--48.

Haberle, J. & Кбs, M. (2012), 'Simulation of nitrogen leaching and nitrate concentration in a long-term field experiment', Journal of Central European Agriculture 13(3), 0--0.

Hansen, E. M.; Djurhuus, J. & Kristensen, K. (2000), 'Nitrate leaching as affected by introduction or discontinuation of cover crop use', Journal of Environmental Quality 29(4), 1110--1116.

Hansen, E. M. & Eriksen, J. (2009), 'Nitratudvaskning fra majs', ICROFSnyt, 3--4.

Hansen, E. M.; Eriksen, J. & Vinther, F. P. (2007), 'Catch crop strategy and nitrate leaching following grazed grass-clover', Soil Use and Management 23(4), 348--358.

Hansen, K.; Rosenqvist, L.; Vesterdal, L. & Gundersen, P. (2007), 'Nitrate leaching from three afforestation chronosequences on former arable land in Denmark', Global Change Biology 13(6), 1250--1264.

Hepperly, P.; Lotter, D.; Ulsh, C. Z.; Seidel, R. & Reider, C. (2009), 'Compost, manure and synthetic fertilizer influences crop yields, soil properties, nitrate leaching and crop nutrient content', Compost Science & Utilization 17(2), 117--126.

Herold, L., S. Wagner, E. Höpfner (2008) Entwicklung der Nmin-Gehalte auf landwirtschaftlich genutzten Böden in Thüringen. Erhöhte Biomassenachfrage – eine neue Herausforderung für die Landwirtschaft und weitere Beiträge aus den öffentlichen Sitzungen und Workshops des 120. VDLUFA-Kongresses vom 16. bis 19. September 2008. Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten KONGRESSBAND 2008 JENA, p476-481

Jakab, G. I.; Karsai, G.; Szalai, Z. & Szaby, J. A. (2017), 'Nitrate loss from fertilized crop fields: does slope steepness matter?', ТБЈЦKOLУGIAI LAPOK 15(2), 77--84.

Johnson, P. A. & Smith, P. N. (1996), 'The effects of nitrogen fertilizer rate, cultivation and straw disposal on the nitrate leaching from a shallow limestone soil cropped with winter barley', Soil use and management 12(2), 67--71.

Jurisić, A.; Zgorelec, Z.; Sestak, I.; Mesić, M. & Mikoc, V. (2014), 'Nitrate-nitrogen content in soil and lysimeter water under different nitrogen fertilization levels in crop production', Agriculturae Conspectus Scientificus 79(1), 45--50.

Klik, A. & Strohmeier, S. (2011), 'Reducing soil erosion by using sustainable soil management systems', Wasserwirtschaft 101(9), 20--24.

Knapp, N., T. Makary, T. Müller (2017) Gabenreduzierte Stickstoffdüngung zu Winterweizen – Realisieren gabenreduzierte N-Düngungsverfahren auf tonhaltigen Böden den gleichen Ertrag wie eine dreigeteilte Stickstoffdüngung? Standortgerechte Landnutzung -umweltverträglich und wirtschaftlich VDLUFA-Schriftenreihe Band 74/2017 VDLUFA-Verlag, Darmstadt, p. 288-294.

Kramer, S. B.; Reganold, J. P.; Glover, J. D.; Bohannan, B. J. M. & Mooney, H. A. (2006), 'Reduced nitrate leaching and enhanced denitrifier activity and efficiency in organically fertilized soils', Proceedings of the National Academy of Sciences 103(12), 4522--4527.

Kubin, E. (1998) Leaching of nitrate nitrogen into the groundwater after clear felling and site preparatio. Boreal Environment Research 3: 3–8.

Lord, E. I. & Mitchell, R. D. J. (1998), 'Effect of nitrogen inputs to cereals on nitrate leaching from sandy soils', Soil Use and Management 14(2), 78--83.

Manevski, K.; Børgesen, C. D.; Andersen, M. N. & Kristensen, I. S. (2015), 'Reduced nitrogen leaching by intercropping maize with red fescue on sandy soils in North Europe: a combined field and modeling study', Plant and soil 388(1-2), 67--85.

Manevski, K.; Jakobsen, M.; Kongsted, A. G.; Georgiadis, P.; Labouriau, R.; Hermansen, J. E. & Jørgensen, U. (2019), 'Effect of poplar trees on nitrogen and water balance in outdoor pig production-A case study in Denmark', Science of the Total Environment 646, 1448--1458.

Marin, N.; Dumitru, M.; Dumitrascu, M.; Lungu, M.; Mihalache, D. & Stanescu, A. M. (2017), 'INFLUENCE OF DIFFERENT FERTILIZERS ON NPK CONTENT IN SOIL, IN CONSERVATION AGRICULTURE SYSTEM', Annals of the University of Craiova-Agriculture, Montanology, Cadastre Series 46(1), 409--413.

Marinov, D.; Querner, E. & Roelsma, J. (2005), 'Simulation of water flow and nitrogen transport for a Bulgarian experimental plot using SWAP and ANIMO models', Journal of contaminant hydrology 77(3), 145--164.

Martinez, J. & Guiraud, G. (1990), 'Alysimeter study of the effects of a ryegrass catch crop, during a winter wheat/maize rotation, on nitrate leaching and on the following crop', Journal of Soil Science 41(1), 5--16.

Nicholson, F.A., M. Bowden, M. Chauhan, R. Cross, D. Munro, K.E. Smith, R.E. Thorman & J.R. Williams (2017): Agricultural Greenhouse Gas Inventory Research Platform - InveN2Ory. Manure experimental site in Norfolk, 2011-12. Version:1. Freshwater Biological Association. doi:10.17865/ghgno667

Nitcheva, O., D. Marinov (2014) Nitrogen pollution in Bulgaria - Characterization and solutions. In"Aloe et al (eds) Managing Nitrogen and Phosphorus Loads to Water Bodies: Characterisation and Solutions. Towards Macro-Regional Integrated Nutrient Management. JRC-Ispra , 14-15 July 2014. JRC Technical report. p26-29

Nováková, K & Nágel, D. (2009). The influence of irrigation on nitrates movement in soil and risk of subsoil contamination. Soil and Water Research. 4. S131-S136. 10.17221/483-SWR

Pavlović, J. B.; Krogstad, T. & Rajić, N. Z. (2017), 'Applicability of zeolites in potassium and nitrate retention in different soil types', J. Serb. Chem. Soc. 82(11), 1303--1314.

Pisani, O.; Strickland, T. C.; Hubbard, R. K.; Bosch, D. D.; Coffin, A. W.; Endale, D. M. & Potter, T. L. (2017), 'Soil nitrogen dynamics and leaching under conservation tillage in the Atlantic Coastal Plain, Georgia, United States', Journal of Soil and Water Conservation 72(5), 519--529.

Premrov, A.; Coxon, C. E.; Hackett, R.; Kirwan, L. & Richards, K. G. (2014), 'Effects of over-winter green cover on soil solution nitrate concentrations beneath tillage land', Science of the Total Environment 470, 967--974.

Pugesgaard, S.; Schelde, K.; Larsen, S. U.; Læerke, P. E. & Jørgensen, U. (2015), 'Comparing annual and perennial crops for bioenergy production-influence on nitrate leaching and energy balance', GCB Bioenergy 7(5), 1136--1149.

Ritter, W. F.; Scarborough, R. W. & Chirnside, A. E. M. (1998), 'Winter cover crops as a best management practice for reducing nitrogen leaching', Journal of Contaminant Hydrology 34(1-2), 1--15.

Romic, D.; Romic, M.; Borosic, J. & Poljak, M. (2003), 'Mulching decreases nitrate leaching in bell pepper (Capsicum annuum L.) cultivation', Agricultural Water Management 60(2), 87--97.

Rusakova, I. & others (2015), 'REDUCING NITRATE LEACHING FROM SODDY-PODZOLIC SANDY LOAM SOIL WHEN APPLYING POULTRY MANURE IN COMBINATION WITH BARLEY STRAW', Scientific Papers: Management, Economic Engineering in Agriculture & Rural Development 15(1).

Sestak, I.; Mesić, M.; Zgorelec, Z.; Kisić, I. & Basić, F. (2014), 'Winter wheat agronomic traits and nitrate leaching under variable nitrogen fertilization', Plant, Soil and Environment 60(9), 394--400.

Shepherd, M. A. (1999), 'The effectiveness of cover crops during eight years of a UK sandland rotation', Soil Use and Management 15(1), 41--48.

Simunic, I.; Mesic, M.; Sraka, M.; Likso, T. & Coga, L. (2011), 'Influence of drainpipe spacing on nitrate leaching and maize yield', Cereal research communications 39(2), 273--282.

Simunić, I.; Tomić, F. & Kricka, T. (2011), 'Leaching nitrate and atrazine on the reclamation test field of different drainpipe spacing', Journal of Environmental Protection and Ecology 12(1), 89.

Smith, K. A.; Beckwith, C. P.; Chalmers, A. G. & Jackson, D. R. (2002), 'Nitrate leaching following autumn and winter application of animal manures to grassland', Soil Use and Management 18(4), 428--434.

Stolzenburg, K., 2010: Anbau von Miscanthus (Miscanthus x giganteus) als nachwachsender Rohstoff auf Acker- und Grünlandflächen unter dem Aspekt der Nitratverlagerung. Pude, R. (Hrsg.). Miscanthus –Umwelt- und Nutzungsaspekte. Tagung vom 24.-26. November 2010 in Ardagger, Österreich. Kurzfassungen der Vorträge. Universität Bonn ILB-Press. ISBN 978-3-941766-04-4.

Sumelius, J.; Mesic, M.; Grgic, Z.; Kisic, I.; Franic, R. & others (2005), 'Marginal abatement costs for reducing leaching of nitrates in Croatian agriculture', Agricultural and Food Science.

Svoboda Z, J. Zahora, I. Mikajlo (2016) Effects of Cereal/Legume Intercropping on Nitrogen Leaching: Lysimetric Field Experiment. MendelNet Conference Proceedings

Tauchnitz, N.; Bischoff, J.; Schrцdter, M.; Ebert, S. & Meissner, R. (2018), 'Nitrogen efficiency of strip-till combined with slurry band injection below the maize seeds', Soil and Tillage Research 181, 11--18.

Tauchnitz, N., Bischoff, J., Schrödter, M., Rupp, H., Meissner, R. (2012) Einfluss von Leguminosen in Maisfruchtfolgen auf die Sickerwassermenge und den Nitrataustrag anhand von Lysimeteruntersuchungen Kongressband 2012 Passau. Vorträge zum Generalthema: Nachhaltigkeitsindikatoren für die Landwirtschaft: Bestimmung und Eignung VDLUFA-Schriftenreihe 68: Verband Deutscher Landwirtschaftlicher ntersuchungs- und Forschungsanstalten (VDLUFA), Darmstadt, S. 245 – 252.

Thomsen, I. K. & Hansen, E. M. (2014), 'Cover crop growth and impact on N leaching as affected by pre-and postharvest sowing and time of incorporation', Soil use and management 30(1), 48--57.

Thomsen, I. K., Hansen, E. M., & Vinther, F. P. (2013). Evaluering af mellemafgrøders effekt i forhold til efterafgrøder. DCA - Nationalt Center for Fødevarer og Jordbrug,. DCA rapport, Nr. 34

Thorman, RE, L. Sagoo, H. Kingston, G. Bennett, B.J. Chambers and J.R. Williams (2016) Integrated Strategies to Minimise Slurry Nitrogen Losses -- Application Rates and Method. Experimental site Devon, 2004. .

Torstensson, G. & Aronsson, H. (2000), 'Nitrogen leaching and crop availability in manured catch crop systems in Sweden', Nutrient cycling in Agroecosystems 56(2), 139--152.

Vögeli Albisser, C. & V. Prasuhn, 2013: Auswirkungen des Klimawandels auf die Schadstoffverfrachtung ins Grundwasser. Projekt-Schlussbericht, BAFU & Agroscope, 107 S

Xie, Y. & Kristensen, H. L. (2016), 'Overwintering grass-clover as intercrop and moderately reduced nitrogen fertilization maintain yield and reduce the risk of nitrate leaching in an organic cauliflower (Brassica oleracea L. var. botrytis) agroecosystem', Scientia horticulturae 206, 71--79.

Tolner, László & Rétháti, Gabriella & Kovács, Attila. (2012). Examination of an alternative way to prevent nitrate leaching in soil by using glycerol as a biodiesel by-product. 11th Alps-Adria Scientific Workshop Smolenice, Slovakia, p.267-270.

Yamulki S., and T.H. Misselbrook (2016) Integrated Strategies to Minimise Slurry Nitrogen Losses -- Application Rates and Method. Experimental site Devon, 2004. .

Zaman, M. & Blennerhassett, J. D. (2010), 'Effects of the different rates of urease and nitrification inhibitors on gaseous emissions of ammonia and nitrous oxide, nitrate leaching and pasture production from urine patches in an intensive grazed pasture system', Agriculture, Ecosystems & Environment 136(3-4), 236--246.

Zupanc, V.; Sturm, M.; Lojen, S.; Marsić-Kacjan, N.; Adu-Gyamfi, J.; Bracic-Zeleznik, B.; Urbanc, J. & Pintar, M. (2011), 'Nitrate leaching under vegetable field above a shallow aquifer in Slovenia', Agriculture, ecosystems & environment 144(1), 167--174.