FAIRWAY

Farm System Management and Governance for Good Water Quality and Drinking Water Supplies

FAIRWAY REPORT series

Identification of most promising measures and practices

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SUMMARY

Access to sufficient amounts of safe drinking water is vital for human health, public welfare and an important driver of a healthy economy. Many drinking water resources run an increasing risk of pollution by nitrates (NO_3) and pesticides, resulting from the intensification of agricultural production. 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 case study sites across the EU-28, analyses of governance approaches and upscaling activities.

The aim of Task 4.3, presented in the current report, was to identify and assess the most promising measures and practices to decrease nitrate and pesticide pollution of drinking water supplies. For both pesticides and nitrates, the assessment was based on a combination of (i) a synthesis of existing review papers, (ii) a meta-analysis of available data from literature, and (iii) practice-based knowledge from case studies of FAIRWAY across Europe. Questionnaires were sent to partners and actors of the multiple-actor platforms to derived input from the case studies.

The driving factors for diffuse pesticide pollution are (i) the amount and type of used pesticides, (ii) water facilitated transport through or over the soil, (iii) erosion of sediment that causes transport of sorbed particles, and (iv) spray drift during application. Vegetated filter strips are the most clear measure to reduce overland transport and pollution by pesticides. Models are available to calculate dimensions and predict effectiveness for pesticide reduction. Tillage practices are extensively studied in relation to off-site transport of pesticides. The analysis shows that no-till does not provide less off-site transport than conventional tillage, and even suggests higher pollution in no-till systems under specific circumstances. On-site measures against diffuse pollution comprise only a small part of the available approaches to reduce pesticide pollution. To obtain a sustainable system, input reduction, farm system redesign, point source mitigation and policy measures are essential to be taken into account. Beside on-site measures, reduced input of pesticide is a key factor to decrease pollution of water resources. We conclude that the reduction of pesticide transport is of vital importance to protect both groundwater and surface water resources. This involves on-site measures, farm system redesign and regional or national approaches to facilitate a sustainable farming system.

A review of existing meta-analyses and quantitative reviews showed that there is a lot of information available on the effectiveness of measures to reduce NO_3 losses to ground- and surface waters. In particular the use of cover crops, (nitrification) inhibitors, and biochar has been well documented, often in relationship with other N parameters, such as nitrous oxide (N_2O) emissions or soil N transformations. The use of non-legume cover crops appears an effective way to reduce NO_3 losses. This effect is often diminished when legumes are included. Application of nitrification inhibitor DCD also seems to be effective as a measure and cost-benefit analyses show that this can be profitable. For other measures, such as biochar and changes in tillage practices, the results differ. The success of the implementation of a measure often varies per farm and per location. It is subject to differences in topography, climate, and other farm management practices. Farm-tailored solutions are therefore likely to yield result. This is illustrated by the large variety of measures proposed by the case study experts and the differences in applicability. Implementation of measures to reduce NO_3 losses should not only consider the effectiveness, and costs, but also the adoptability and possible (unwanted) side-effects. While some measures may for example decrease NO_3 and N_2O losses, they could increase ammonia volatilization. These effects of the measures on the N cycle and possibly those of other nutrients should be considered. This is true for measures at both the field and farm scales.

GENERAL INTRODUCTION

Access to sufficient amounts of 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. In the European Union, about 65 million people are exposed to drinking water resources of which the quality cannot be guaranteed. Further, many drinking water resources run an increased risk 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 of pollution, and have invested in various purification steps or in the closure of wells when contamination was unacceptably high. In addition, from the early 1990s onwards various policy measures have been implemented in the European Union to decrease the pollution of drinking water resources. The current view is that not all measures are equally effective, and that the protection of drinking water resources needs 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 case study sites across the EU-28, analyses of governance approaches and upscaling activities.

The main objective of WP4 of FAIRWAY is to review and assess measures and practices aimed at maintaining and/or improving water quality of drinking water supplies. Specific objectives are:

- To review and assess measures and practices aimed at decreasing nitrate pollution of drinking water supplies,
- To review and assess measures and practices aimed at decreasing pesticides pollution of drinking water supplies,
- To identify and assess most promising measures and practices to decrease nitrate and pesticide pollution of drinking water supplies

In Tasks 4.1 and 4.2, a review of measures to decrease nitrate and pesticide pollution of drinking water sources has been carried out. Based on the results of these tasks, in Task 4.3 an assessment of the most promising measures and practices to decrease nitrate and pesticide pollution of drinking water supplies was carried out. For both pesticides (Chapter 1) and nitrates (Chapter 2) the assessment was based on a combination of (i) a synthesis of existing review papers, (ii) a meta-analysis of available data from literature and (iii) practice based knowledge from the case studies of FAIRWAY across Europe. Questionnaires were sent to partners and actors of the multiple-actor platforms to derive input about measures that are applied in the case studies (Annexes 1 and 2). The partners and actors were asked about (i) the willingness of farmers to adopt the measures, (ii) the applicability and ease of implementation and operation of the measures, (iii) the effectiveness of the practices and measures, and (iv) the efficiency of the measures in terms of effort (costs) needed, as well as possible side-effects.

1. REDUCTION OF DIFFUSE PESTICIDE TRANSPORT FROM AGRICULTURAL LAND TO GROUNDWATER AND SURFACE WATERS BY MANAGEMENT PRACTISES

Meindert Commelin, Shaun Coutts, Jantiene Baartman, Isobel Wright, Antonio Ferreira, Gerard Velthof, Oene Oenema and Violette Geissen

1.1 INTRODUCTION

The use of pesticides in agriculture increased rapidly during the second half of the 20th century. Pesticides are a key part of monoculture cropping systems that suppress weeds, pathogens and insect pests, and increase yields (Aktar, Sengupta, toxicology, & 2009, n.d.; Y. Liu, Pan, & Li, 2015). The widespread use of pesticides has led to their dispersal into the environment, including drinking water resources (Hildebrandt, Guillamón, Lacorte, Tauler, & Barceló, 2008), and food. Several studies on food safety reported mixtures of pesticide residues in food (Jardim & Caldas, 2012; Szpyrka, 2015), and indicated threats to aquatic plants, animals, and human health (Aktar et al., n.d.; Schinasi & Leon, 2014). Further, international monitoring programs on water quality show that pesticides are present in surface water and groundwater bodies with increasing concentrations (Folch, Carles-Brangarı, & Carrera, 2016; Hildebrandt et al., 2008; Larson, Capel, & Majewski, 1997; H. Wang et al., 2016).

Within the EU a precautionary boundary is set at 0.1 µg/L for contamination of water sources with any single pesticide to prevent harmful effects for humans and the environment. The EU has a strong monitoring program on water safety and before a pesticide is permitted to be used, it is tested and checked for safety by the European Food Safety Agency (EFSA).

However, there is a debate about the safety of permitted pesticides, for example recently concerns about glyphosate as a potential carcinogen have been raised (Samsel & Seneff, 2013). There are also concerns about the impacts of pesticides on human health and the environment at off-site locations (i.e. away from the field where the pesticide is applied), including ground and surface waters (Hildebrandt et al., 2008).

If a pesticide is not transported anywhere after application there is no risk of pollution of groundwater or surface water. However, water flow dynamics, infiltration and runoff after rainfall events often transport pesticides off-site after their application (Borggaard & Gimsing, 2008; Flury, 1996; Rittenburg et al., 2015; Tang, Zhu, & Katou, 2012; Vereecken, 2005; Wauchope, 1978). Three main pathways have been identified; leaching to groundwater, subsurface flow to surface waters and overland runoff (Rittenburg et al., 2015). Local soil and climatic conditions influence which pathways are dominant within a field (Borggaard & Gimsing, 2008; Reichenberger, Sur, Kley, Sittig, & Multsch, 2019). The most important characteristics of the pesticide that influence its potential transport are their solubility, sorbtivity and half-life time (Rittenburg et al., 2015; Wauchope, 1978).

To reduce the transport of pesticides from agricultural fields, measures and good agricultural practices have been developed and implemented at farm level. Several reviews focusing on how to reduce pesticide pollution using land management include Fawcett et al. (1994), Krutz et al. (2005), Reichenberger et al. (2007), Alletto et al. (2010), Felsot et al. (2010), Rittenburg et al. (2015) and Vymazal and Brezinova,(2015).

The objective of this paper is to investigate the effectiveness of on-field management measures for reducing diffuse pesticide pollution by transport to ground- and surface water resources. We combined (i) a synthesis of existing review papers, (ii) a meta-analysis of available data from literature and (iii) practice based knowledge from nine case studies across Europe.

1.2 MATERIALS AND METHODS

As a starting point for the literature synthesis and meta-analysis, initial data sources and literature were collected in two ways. A systematic search was performed through online databases, and a local/expert based search was done throughout Europe. The purpose of the local search was to find studies containing valuable data which were not easily accessible through online databases. The selection criteria for this search were; (1) well documented (peer reviewed or reports), (2) the study should be about a measure to decrease pesticide transport/pollution, (3) the study must be an experiment, with quantitative data presented in the source. For the online systematic search three online databases were used; Scopus, Ovid and Web of Science, and the following search formula was used:

IN TITLE: (pesticid* OR herbicid*) AND (leaching OR runof* OR overland flow OR drift OR spray drift OR infiltration) AND (effect* OR impact OR influence OR reduc* OR decreas*)) NOT (model* OR industr*)) AND **IN ABSTRACT:** (agricult* OR farm* OR field* OR crop*)

In Web of Science the formula was slightly different, 'IN ABSTRACT' was not available and 'TOPIC' was used, which includes abstract, title and keywords.

The local and online search, combined with an added 'snowball' search in relevant reviews resulted in 270 unique titles (figure 1.1). These papers included four meta-analysis papers and seventeen reviews. The results of these papers were summarized and combined with the results of the meta-analysis. The reviews were analyzed by abstracting the answers to several questions, for both transport to ground and surface water:

- How effective is the described measure to reduce transport of pesticides to ground and surface water?
- What is the influence of explanatory variables, like climate, type of agriculture and soil type?
- Are there known side effects of the measure which might influence the effectiveness on the long term or cause different problems?

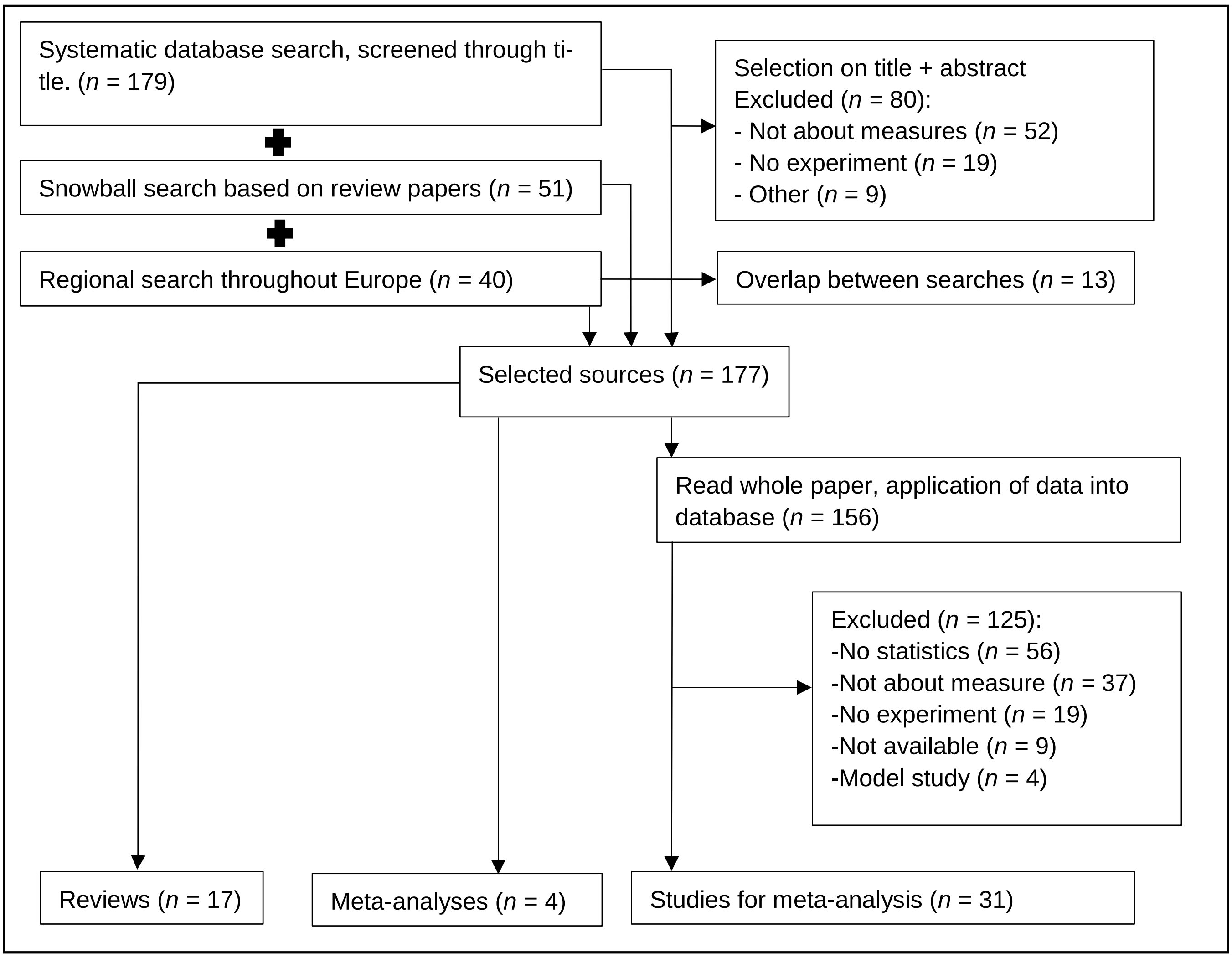

Figure 1.1: Flow chart showing the data search and selection process.

Within the collected sources for the meta-analysis there was a lot of heterogeneity between studies in terms of experimental design and measured data. For the meta-analysis, only sources were included that presented sufficient statistical data (sample size, standard deviation and clear treatment and control). Based on this criteria 31 papers were included in the database for further analysis (Figure 1.1).

1.2.1 Data description

The collected data for meta-analysis mainly covered four measures; soil tillage practices, vegetative filter strips (VFS), application management and drift reduction. The most extensive data set was available for tillage practices. Within most studies multiple comparisons or treatments were done, leading to a total of 141 experiments in the database (Table 1.1).

For tillage practices 41 experimental comparisons were used for the analysis. Because there is a high diversity in tillage practices, the dataset was homogenized by selecting all data comparing no-till (NT) with conventional (plow) tillage (CT). Other measures in the dataset included disc tillage and mulch tillage, however the number of studies was too low to perform a proper statistical analysis. For the general analysis the data is separated into two groups; pesticide transport to groundwater and to surface waters. In the dataset 38 comparisons were found. Recent papers used more data (Reichenberger et al., 2019), however the statistical constraints of the meta-analysis strongly reduced the available data.

Of the included studies eighteen were conducted in the United States, twelve in Europe and one in China. The studies covered a variety in climates including humid continental, Mediterranean and oceanic climates. The main soil types were clay and loam (including silt clay loam, silty clay, clay loam and silt loam) two studies were conducted on sandy.

Table 1.1: Measures included in the dataset

Measure	Number of experiments	Number of papers
Tillage	47	8
VFS	40	10
Application rate	19	5
Drift	18	3
Other	17	5
Total	141	31

Eighteen different pesticides were included in the studies, fifteen of these were herbicides and three insecticides. Of the 141 experiments 127 used herbicides and three studied insecticides (eleven spray drift studies did not specify pesticide type). Most studies covered pesticides that are no longer approved in Europe (83), while 47 studies did use currently approved pesticides. The main reason for this is that many older (pre-2000) studies are included. However, these studies are still valuable for understanding how different measures affect the of transport pesticides with different characteristics.

The risk of pesticide transport is mainly influenced by three characteristics of each pesticide; water solubility (Sw), adsorption coefficient (Koc) and half-life time (DT50). Table 1.2 shows the value ranges related to each parameter (Lefrancq, Jadas-Hécart, La Jeunesse, Landry, & Payraudeau, 2017; Tang et al., 2012; Young & Fry, 2019).

Half of the studies had a block design with a comparison over the same time period (spatial replication). The other studies were time-split where the effect of a measure was studied over time (temporal replication). The duration of most studies was between 1 and 5 years, but one study run for eleven years. A few studies (drift or VFS related) covered several days. Pesticide transport was described by the load, or mass per area per year in runoff. However if total loads were not available, concentrations of pesticides were used. Locations of measurements varied from soils, runoff water and lysimeter leachates to concentrations in larger water bodies like rivers or groundwater inlet points.

Table 1.2: Characteristics of pesticides in the dataset

Characteristic	Value	Classification	Occurrence in dataset (total n = 130)
Water solubility (Sw) – mg L^{-1}	<50	Low	53
	50 - 500	Moderate	30
	> 500	High	47
Adsorption coefficient (Koc)	< 75	Low	4
	75 – 500	Moderate	107
	> 500	High	9
	Unknown		10
Half-life time (DT50) – days	<30	Non persistent	98
	30 - 100	Moderately persistent	31
	100 – 365	Persistent	1
	> 365	Very persistent	0

1.2.2 Meta-analysis

To perform the meta-analysis the R-package ‘metafor’ was used (Viechtbauer, 2010). The goal of a meta-analysis is to combine all quantitative data from the collected studies and draw an overall conclusion on the effectiveness of a specific measure. In the reviewed studies the effect of a treatment was shown with different values and units. For a meta-analysis these different designs, units and approaches have to be normalized so they can be compared. To be able to compare effect sizes between studies all data was recalculated to the response ratio (*R*):

$$R = \frac{\overline{X_T}}{\overline{X_C}} \quad (1)$$

Where $\overline{X_T}$ represents the means of the treatment group and $\overline{X_C}$ the means of the control (Borenstein, Hedges, Higgins, & Rothstein, 2009). For each study the mean, standard deviation and sample size was recorded. On several occasions statistical recalculations were done to obtain comparable statistics from each study (Lajeunesse, 2011). The distribution of *R* cannot be assumed to be normal, so to do statistical analyses it is preferable to use the natural logarithm of *R* (Borenstein et al., 2009; Hedges, Gurevitch, & Curtis, 1999). The variance of *ln*(*R)*, needed to derive the uncertainty of a study, is calculated with:

$$v_R = \frac{(SD_T)^2}{n_T(\overline{X_T})^2} + \frac{(SD_C)^2}{n_C(\overline{X_C})^2} \quad (2)$$

with SD_T and SD_C the standard deviations for the treatment and control groups respectively, and n_T and n_C the sample sizes of the groups.

A random effects model was used to combine the estimated effect sizes for all studies within one group (e.g. tillage measures). The model accounted for within study effects when multiple treatments from one study were used. The resulting weighted means and summary effect sizes were transformed back to percentage response effects. A 95% confidence interval (CI) was calculated, and the effectiveness of a measure is considered significant when there is no overlap with a response effect of 0%, indicating ‘no effect’. To understand mechanisms of effectiveness better sub group analysis is done based on pesticide characteristics as presented in table 2.

1.2.3 Case studies

We also utilize insights from nine ongoing case studies of the EU H2020 FAIRWAY project (2017 – 2021) across Europe that are investigating measures to minimize pollution of ground- and surface drinking water resources by pesticides. The case studies reflect different pedo-climatic zones and assess the effectiveness of different measures, their cost, adoptability and applicability for farmers. We collected data from all case study leaders through a questionnaire (Annex 1). The respondents were experts who are in close contact with land managers who apply the measures. The collected data include (i) the measures in the region, and (ii) the evaluation of the measure in terms of effectiveness, cost and applicability by farmers.

1.3 RESULTS

To categorize the measures and to evaluate their effectiveness, the first aspect that needs to be taken into account is the main transport pathway of the pollution process (Rittenburg et al., 2015). Pesticides are mainly transported by air, water and soil. The main transport agent is water, and in some cases also soil particles can transport pesticides, when these in turn are carried by water (Reichenberger, Bach, Skitschak, & Frede, 2007). Reducing diffuse pollutant transport is linked to the transport routes shown in figure 2. Pesticide transport to water bodies can be reduced by either decreasing the input of pesticides into the system (e.g. less or no application) or by influencing the hydrological flow paths and thus reduce the off-site transport of the pesticides. The pathways that are identified as main transport routes to groundwater and surface water are: overland flow, subsurface flow and drainage, leaching and drift.

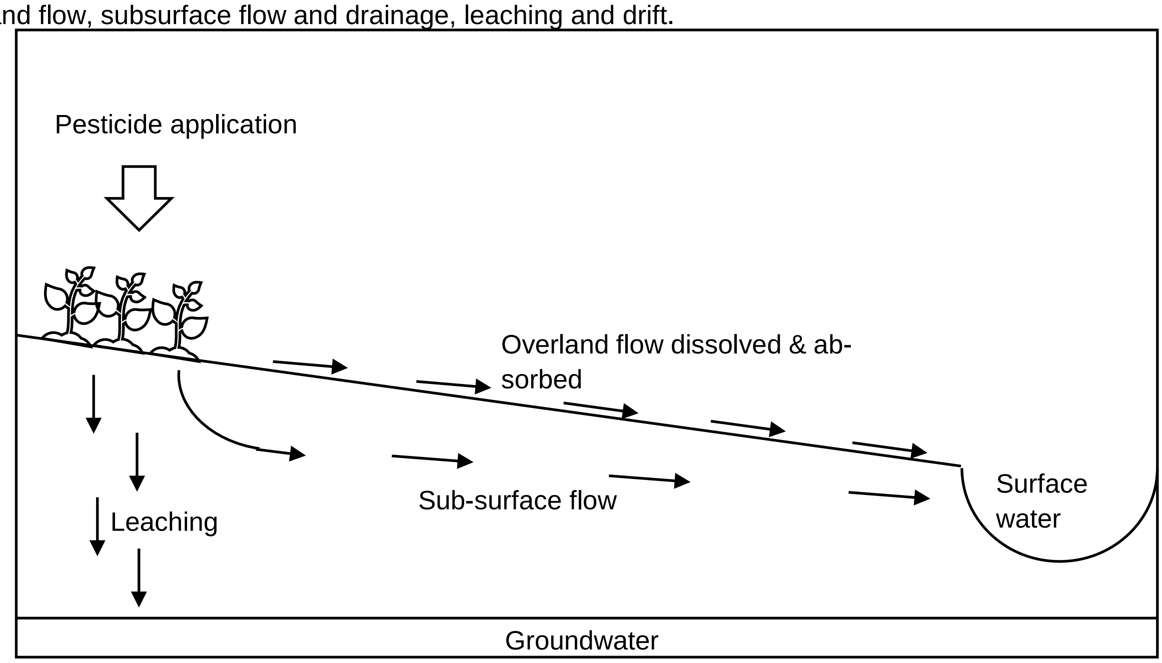

Figure 1.2: Main transport pathways facilitating pesticide pollution from diffuse sources

1.3.1 Literature synthesis

Results from major reviews since 2000 until present were synthesized (Y. Liu et al., 2015; Reichenberger et al., 2007; Rittenburg et al., 2015; Tang et al., 2012; Wauchope, 1978), including the reviews about specific measures in relation to pesticide pollution (Alletto, Coquet, Benoit, Heddadj, & Barriuso, 2010; Felsot et al., 2017; Krutz, Senseman, Zablotowicz, & Matocha, 2005). From these reviews and extra literature that was collected for the meta-analysis, a qualitative overview is made of the most used and studied measures to reduce pesticide pollution of groundwater and surface waters (Table 1.3).

Table 1.3: Synthesis of literature results: effectiveness and costs of key measures. Symbols are explained below the table

Measure [source]	Effectiveness		Costs	Notes [source]
	Groundwater	Surface water		
1. Vegetated filter strips	+	+++	€€	Effectiveness depends on design, added ecological value (Arora, S. K. Mickelson, & J. L. Baker, 2003; Krutz et al., 2005; Rafael Muñoz-Carpena, Ritter, & Fox, 2019; Reichenberger et al., 2019)
2. Constructed wetlands	+	+++	€€€	Effectiveness depends on local design. (Moore, Schulz, Cooper, Smith, & Rodgers, 2002; Stehle et al., 2011; Tournebize, Chaumont, & Mander, 2017; Vymazal & Březinová, 2015)
3. Erosion reduction	-	+/-	?	(Fawcett, Christensen, & Tierney, 1994; Sadeghi & Isensee, 2001)
4. Tillage intensity	+/-	+/-	€	Effectiveness depends on local design (Alletto et al., 2010; Elias, Wang, & Jacinthe, 2018; Tang et al., 2012)
5. Drainage optimization	?	+	€	(Flury, 1996)
6. Residue management/ Mulching	?	+	€	(Alletto et al., 2010)
7. Drift reduction	na*	++	€€	High ecological value (Al Heidary, Douzals, Sinfort, & Vallet, 2014; De Snoo & De Wit, 1998; Felsot et al., 2017; Hilz & Vermeer, 2013; Otto, Loddo, Baldoin, & Zanin, 2015)
8. Crop rotations	++	++	€€	(Brown & Van Beinum, 2009; Rittenburg et al., 2015)
9. Application rate reduction	+	+	€	(Reichenberger et al., 2007)
10. Alternative pesticide	?	?	?	Depends on choice (Reichenberger et al., 2007)
11. Integrated Pest management	++	++	€€€	(Gentz, Murdoch, & King, 2010; Reichenberger et al., 2007)

NOTE: Symbols in the table indicate a scale from negative to positive with – is negative, +/- is neutral and +++ is very positive, this is a qualitative overview since quantitative data is not generally presented in the reviews. For the cost three categories were made, as follows: low (€), moderate (€€) and high (€€€). An ? indicates that no clear data is available and the evaluation of the measure is still unknown. * not available: this transport route does not exist.

1.3.1.1 Tillage practices

Runoff and infiltration processes on the field are strongly related to tillage practices, and thus tillage practices influence the transport pathways of pesticides. Alletto et al. (Alletto et al., 2010) extensively reviewed the effectiveness of tillage practices on both overland and leaching transport of pesticides. For both overland and leaching transport, changes in tillage practices were effective, but local design and application were very important for success (Alletto et al., 2010). Ghidey et al (2005) found that incorporation of applied pesticides below the upper 2-5 cm of the soil is one of the most effective ways to reduce overland flow of pesticides. A meta-analysis of papers after 1985 showed that no-till practices have a higher overland transport of pesticides compared to conventional tillage, including plowing (Elias et al., 2018).

The costs of changing tillage practices are generally low and practicability and feasibility of changing to other tillage practices is good (Reichenberger et al., 2007). However there is a risk that tillage practices will not remediate total pesticide pollution but only change the transport route, because infiltration (leaching) and overland transport are mutually exclusive (Rittenburg et al., 2015). Tillage alters the soil hydraulic properties and thereby the transport pathways of water and related solutes such as pesticides (Alletto et al., 2010). Conservation tillage (i.e. no-tillage or reduced tillage) increases retention/sorption of pesticides in the topsoil (Elias et al., 2018), particularly because of retarded degradation of soil organic matter compared to tillage, this decreases the availability of pesticides for biological degradation, leading to enhanced persistence in soils (Alletto et al., 2010).

1.3.1.2 Vegetated filter strips

A widely used measure to reduce pesticide pollution by overland transport are VFS. They are used to reduce the negative effects of overland flow, and are initially designed as erosion reduction measures. However they also affect pesticide transport. Most filter strips are located at the downstream end of a field, were runoff water leaves the field. VFS have been shown to be effective in reducing overland flow and soil erosion (Krutz et al., 2005; Lerch, Lin, Goyne, Kremer, & Anderson, 2017). They reduce pesticide loss by (1) facilitating the deposition of particles which sorb pesticides, (2) enhancing pesticide retention / sorption by increasing the time available for infiltration, (3) sorbing dissolved-phase herbicides to the grass, grass thatch and soil surface, and (4) reducing the volume of overland flow containing dissolved and particulate-associated pesticides [12,23,39]. Performance of the vegetated filter strips for pesticide trapping depends on the hydrological conditions (e.g. precipitation, infiltration and overland flow), the strip design; strip width, area ratio and type of vegetation cover (Krutz et al., 2005) and characteristics of the particles and pesticides (Tang et al., 2012). The effect of a buffer strip on ground water pollution by pesticides is mentioned as a potential risk of increased leaching, however no data was found during the search for this study. In the past two decades several models, both empirical and mechanistic, have been developed to predict the retention capacity of a VFS. The VFSMOD model by Munoz-Carpena (1999) is further developed and shows to perform well in combination with either empirical or mechanistic pesticide retention equations (Reichenberger et al., 2019). The empirical, revised Sabbagh equation (Sabbagh, Fox, Kamanzi, Roepke, & Tang, 2009) is based on an extensive dataset with experiments from the last decades:

$$\Delta\mathrm{P} = -11.5 + 0.59\Delta\mathrm{Q} + 0.49\Delta\mathrm{E} - 0.38\ln\left(\mathrm{F_{ph}} + 1\right) + 0.20\mathrm{C} \quad (3)$$

with $\Delta\mathrm{P}$the pesticide trapping efficiency (%) , $\Delta\mathrm{Q}$ the infiltration in the buffer (% of total inflow), $\Delta\mathrm{E}$ the sediment trapping in the buffer (% of total inflow), $\mathrm{F_{ph}}$ the solid-dissolved distribution (%) of the pesticide and C the percentage organic matter in the incoming sediment. The equation performs well (R^2 of 0.82) (Reichenberger et al., 2019).

However, while the empirical model performed well, it does not really explain the process of VFS effectiveness. Therefore, Reichenberger (2019) proposed a mass-balance equation as a more mechanistic approach:

$$\frac{\Delta\mathrm{P}}{100} = \frac{\min\left[(\mathrm{V_i} + \mathrm{K_d}\mathrm{E_i}), \frac{\Delta\mathrm{Q}}{100}\mathrm{V_i} + \frac{\Delta\mathrm{E}}{100}\mathrm{K_d}\mathrm{E_i}\right]}{\mathrm{V_i} + \mathrm{K_d}\mathrm{E_i}} \quad (4)$$

Where $\mathrm{V_i}$ is the incoming water (L), $\mathrm{E_i}$ the incoming sediment (kg) and $\mathrm{K_d}$ (L/kg) the sorption coefficient. This model also performs well against empirical data ($\mathrm{R}^2 = 0.77$), and it is regarded as a good predictor for the effectiveness of a VFS.

If well designed and adjusted to local conditions, vegetated buffers are very effective measures, as indicated by the above formula (Reichenberger et al., 2019). The costs are estimated to be moderate, including implementation and maintenance costs and loss of productivity on the area of the field that is used as buffer (Rittenburg et al., 2015).

1.3.1.3 Constructed wetlands

Constructed wetlands are less studied than vegetative filter strips but if well designed, maintained and implemented they can be very effective with rates of pesticide reduction up to 100% (Tournebize et al., 2017; Vymazal & Březinová, 2015). A meta-analysis of the existing data until 2011 showed that the main influential parameters for effectiveness are pesticide characteristics, vegetation type and coverage (Stehle et al., 2011). However the costs are high, and they can take a relatively large surface of productive land to be installed.

1.3.1.4 Subsurface flow and leaching

For situations/locations with mainly subsurface flow, reduction of pesticide loss to surface and groundwater is challenging because altering the pathway of water flow is difficult. Source input management (i.e. Integrated Pest Management) is possible and pipe drainage may decrease the overland flow volume. However, drains may create subsurface flow paths and do not necessarily reduce overall pollutant transport (Rittenburg et al., 2015). Locations with deeply drained soils and thus a risk of leaching to groundwater benefit most from input control measures and increased residence time in the mixing layer (0-5 cm from the soil surface) to enhance degradation of the pollutant (Alletto et al., 2010).

1.3.1.5 Spray drift reduction

Spray drift is a pollution pathway that is different from the other pathways in the sense that no water (flow) is involved. Preventing drift is mainly done by reducing the transport route from the spraying device to offsite areas including open water bodies. Input control is the most effective measure to reduce drift pollution, because if less or no pesticide is sprayed there is less potential pollution. Buffer zones and application technology are effective measures to reduce drift after spraying (Felsot et al., 2017; Hilz & Vermeer, 2013). In addition, no spray zones and windbreaks often have a high ecological value, and within the EU are rewarded within the Common Agriculture Policy (Reichenberger et al., 2007). Optimizing droplet size and speed, in combination with applications during the correct meteorological conditions, greatly reduce drift risk (Al Heidary et al., 2014; De Cock, Massinon, Salah, & Lebeau, 2017). Mechanical drift reduction consists of a broad spectrum of technologies to reduce drift by changing spraying nozzles (Al Heidary et al., 2014) or ventilator design (Otto et al., 2015).

1.3.2 Meta-analysis

The quantitative dataset collected for this paper was sufficient for a meta-analysis on two different tillage practices; tillage and vegetated filter strips (VFS). For VFS a more detailed analysis was conducted, to understand which variables influence effectiveness.

1.3.2.1 Tillage practices

Conventional tillage uses cultivation as the major means of seedbed preparation and weed control. It typically includes a sequence of soil tillage, such as ploughing and harrowing, to produce a fine seedbed, and to incorporate the plant residue from the previous crop into the soil.

In case of no-till the soil is often only disturbed once, where the new crop is sown directly into the harvested field. No-till management is associated with higher amounts of organic matter on the soil surface (Alletto et al., 2010).

For the general analysis the data is separated into two groups; pesticide transport to groundwater and to surface waters, indicated by “leaching” and “overland” in figure 1.4, respectively.

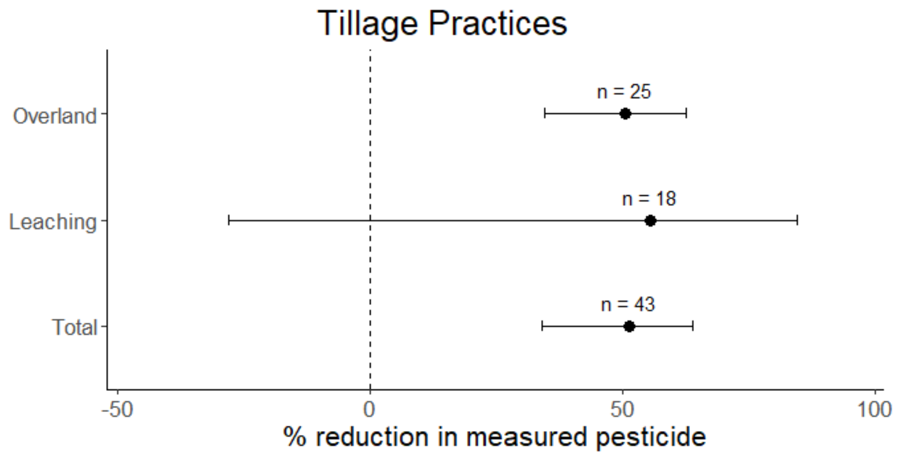

Figure 1.4: Summary effect for reduction of pesticide pollution by conventional tillage compared to no-till. n = # of included studies, error bars represent 95% confidence interval (there is a significant difference when error bars do not overlap with 0). Pesticide transport to groundwater and to surface waters is indicated by “leaching” and “overland”, respectively.

It was expected that no-till management would reduce pesticide transport, because on its performance in terms of erosion. However, the results show for both transport pathways that conventional tillage results in less pesticide pollution. Overall, the effect of tillage was significant with a reduction of 51%. The effectiveness is higher for leaching to groundwater than for overland transport; 55% and 50% pollution respectively. However the effect was not significant for leaching due to the high variation in the dataset.

A meta-regression analysis was done, to evaluate the effect of pesticide adsorption coefficient (K_{oc}) on the effect size. However all studies reported data for pesticides in the moderate class ($K_{oc} = 75 - 500$). The meta-regression did not give any significant effect, but this might be strongly related to the absence of low or high sorbing pesticides in the dataset.

1.3.2.2 Vegetated filter strips

VFS are a measure to reduce overland transport of pesticides. In the dataset 38 comparisons were found. Recent papers used more data (Reichenberger et al., 2019), however the statistical constraints of the meta-analysis strongly reduced the available data.

The general effectiveness of VFS is good with all data points showing a reduction of pesticide transport (figure 1.5). On average the reduction of pollution is 53%, with a 95% confidence interval of 39% - 65%. Variables that might influence the effectiveness of VFS are pesticide type, strip dimension and area to buffer ratio. Buffer area to source area classes are; low >0.08, moderate 0.08 – 0.04 and high <0.04. Figure 5 shows no significant effect between buffer to upstream area ratio. This is in accordance with the empirical and mechanistic models presented by Sabbagh (5) and Reichenberger (6) where VFS pesticide removal is influenced by the reduction of water and sediment in the strip and the chemical adsorption properties of the pesticide involved. Based on this relation, there are optimal dimension for a certain location (Rafael Muñoz-Carpena et al., 2019).

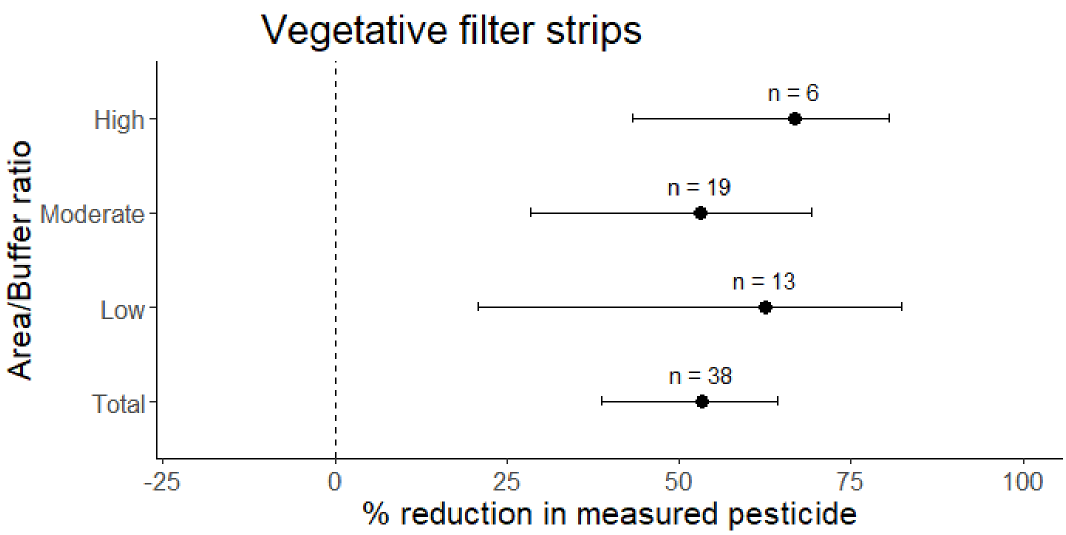

Figure 1.5: Reduction of pesticide pollution through overland flow by VFS. n = # of included studies, error bars represent 95% confidence interval (there is a significant difference when error bars do not overlap with 0). Area/Buffer ratio classes are; low >0.08, moderate 0.08 – 0.04 and high <0.04

Figure 1.6 shows the response ratios for a subgroup analysis on characteristics of involved pesticides. The data is categorized based on the K_{oc} and solubility values of the pesticides in three groups, according to the values presented in table 2. In the lowest category for adsorption (K_{oc}) only one study was included, so no statistics can be shown for this group. Although the visualized trend is not significant the data suggests that a higher sorbtivity will result in the most effective trapping of pesticides by VFS. For solubility there does not seem to be a clear relation. This is expected because VFS tend to reduce the sediment concentration in runoff water by trapping the sediment. The larger the fraction of pesticide connected to sediment, the more effective the measure will be. This result corresponds with the mechanistic and empirical models by Sabbagh and Reichenberger (Reichenberger et al., 2019), where the relation between trapping of pesticide and K_d is in the same direction.

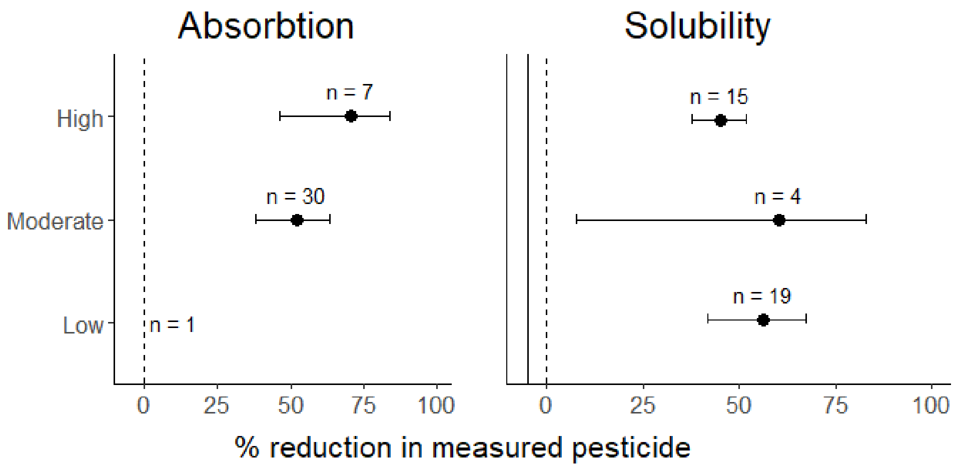

Figure 1.6: subgroup analysis for the relation of K_{oc} and solubility on VFS effectiveness. n = # of included studies, error bars represent 95% confidence interval, (there is a significant difference when error bars do not overlap with 0). The class 'Low' for absorption contains only 1 study, no statistics are calculated for this group.

1.3.3 Case studies

Table 1.5 shows the implemented measures in the case studies including evaluation factors as graded by local experts. The measures have been evaluated for the costs and effectiveness for reducing pollution of groundwater and surface water.

There is a clear distinction between cases where groundwater or surface water is the main area of pollution. No clear mechanical measures are available to reduce leaching risk of pesticides to groundwater. In these cases (Denmark, United Kingdom, Slovenia and Portugal) the main approach is to reduce the input into the system, or the change to an alternative pesticide with lower pollution risks. The reduced input is often enforced by laws or policy, and sometimes subsidies are used to make implementation feasible. This type of measure will reach many land managers because they are enforced at a national or sub-national level.

Reducing input of pesticides often requires a broader 'redesign' of the farming system. The effectiveness of crop rotation and integrated pest management (IPM) depends a lot on the design and on climatic and farm specific conditions, so this type of measure can be effective but has a low adoptability because it needs changes in farming system (Balderacchi & Guardo, 2008).

In cases of overland transport and surface water pollution there is beside diffuse sources, also a lot of attention for point source pesticide pollution, in these cases pesticides will reach surface waters by drainage from the storage/cleaning areas or from accidental spills away from the handling area. This can lead to high concentration in surface waters and there are good working measures to reduce yard associated problems. Examples are wash and load basins (Northern-Ireland and the Netherlands) or biobeds/filters that degrade the pesticides before it reaches the surface water.

Diffuse source measures implemented in the cases in Europe are vegetated filter strip (VFS) for sloping agricultural areas (France and Slovenia) and drift reducing measures (NL). Both measures are well studied and also discussed in earlier sections.

In terms of costs and application by farmers the general trend is that measures are not cost effective, so they are either enforced or subsidized to stimulate implementation. One exception are drift reducing measures, which can be cost effective due to decreased pesticide use (NL).

Table 1.5: Particular applied measures studied within the FAIRWAY case studies, with indicated properties based on expert judgement by experts working in the case study.

Measure	Involved Countries	Effectiveness		Costs
		Groundwater	Surface water	
Safe pesticide cleaning and storage facilities	NL, NIR[5]	+/-	+	?
Safe storage unit for pesticides	NIR	?	+	?
Vegetated filter strips	FR, SL	?	+++	€€
Crop rotation improvement	FR	++	?	€€€
Input reduction	FR, UK	++	++	€€€
Network engagement[1]	UK	?	+	?
Alternative (pesticide or mechanical)	UK, NIR	?	+	?
Integrated Pest Management[2]	UK, DK	+++	+	€€
Obligatory reduced input	PT, DK, SL	+++	+++	€
Bio filters/beds	NIR	?	++	?
Economic/Tax management[3]	DK	+++	?	€€
Drift reduction	NL	?	++	€[4]

NOTE: Symbols in the table indicate a scale from negative to positive with – is negative, +/- is neutral and +++ is very positive. Costs are categorized as; low (€), moderate (€€) and high (€€€). No data as '?'.

[1]Network engagement: embedding information and communication at all levels stimulate change of practice.

[2]Intergrated Pest Management, is a holistic method to reduce pesticide use, by using alternative mechanical and biologic pest management in combination with adjusted cropping and resource management.

[3]These measure increase the price of pesticides, as an extra incentive to look for alternative crop management methods.

[4]Low cost or on the long term even benefits due to reduced use of pesticides

[5]Abbreviations of countries are: NL, The Netherlands; NIR, Northern Ireland; FR, France; SL, Slovenia; UK, United Kingdom; DK, Denmark; PT, Portugal.

1.4 DISCUSSION

This study combines several approaches to review the effectiveness of agronomical measures to reduce pesticide pollution to water resources. The combination of literature synthesis, meta-analysis and evaluation by experts gives a unique overview of the performance of selected measures.

The meta-analysis performed agrees with the results of measure specific analyses (Elias et al., 2018; Reichenberger et al., 2019). Across a wide range of studies vegetative buffer strips and conventional tillage significantly reduced the transport of pesticides into water resources. This study reinforces the meta-analysis by combining them with a literature synthesis and specific case studies. These additional approaches also provide extra context and an unique overview of the effectiveness of agronomical measures to reduce pesticide pollution in water resources.

In the literature synthesis and the meta-analysis we focused on on-site measures to reduce pesticide transport, the case studies did implement some of these measures, but also other regulatory and system wide measures are used in these cases. In countries where leaching of pesticides to groundwater is the main threat (e.g. DK, NL, SL) reducing the pesticide input is the most used measure. This can be applied through regulations of changing the farm system. The results from the literature synthesis and the data-collection are in agreement with this finding, because these studies show no effective on-site measures to reduce leaching. The on-site measures that were presented in the literature are only scarcely applied in practice. For example VFS are suitable for use in France and Slovenia, but not much applied there. The questionnaire results point out that this can mainly be explained by a lack of enforcement (Annex 1). The case studies show that point source pollution management is an important measure to reduce pesticide pollution. In several case-studies, reduction of point source pollution is promoted, with clearly defined measures, and positive results for surface water pollution. The contribution of point source pollution to total pesticide pollution of surface and groundwater sources is unclear. A modelling study in Germany estimated it to be very low (Bach, Huber, & Frede, 2001), while estimates from UK are much higher with contributions up to 40% (CPA, 2010).

The main goal of the meta-analysis is to understand the transport potential of pesticides on agricultural land and the effectiveness of measures to decrease this. Covering the entire spectrum of possible pesticide types and important physical characteristics related to transport is important. However, the studies in the dataset do not cover this entire spectrum. For example, for sorbtivity of pesticides, the systematic search resulted in sufficient data only on both ends of the range, very mobile and very immobile. In addition, mainly pesticides with a short half-life time were studied, which will persist in the system for a shorter period, leaving a knowledge gap at the transport and movement of more persistent pesticides.

The current analysis is carried out using mainly load (mass per area per year) as indicator for pollution. However, the concentration is used as indicator for many regulations. As also shown by Elias (2018) results can differ substantially when using concentrations instead of loads. Especially for event based transport, a concentration might become too high with still an overall low load on annual basis. For this analysis the choice for loads was made, because it represents better how much pesticide is lost in total.

When comparing the results of the literature synthesis with the meta-analysis many similarities emerge. Literature is clear about the potential effectiveness of vegetative filter strips (VFS) (Krutz et al., 2005; R Muñoz-Carpena, Fox, Ritter, Perez-Ovilla, & Rodea-Palomares, 2018; Reichenberger et al., 2019), although they have to be designed to match local conditions. The calculated pollution reduction of VFS is high (53% - 39 – 64 CI 95%), indicating that these are very effective measures to decrease pesticide pollution. For VFS recent model developments show that adapting the dimensions to local conditions is possible (Rafael Muñoz-Carpena et al., 2019).

Tillage practices are clearly related to transport pathways of pesticides and are therefore extensively studied (Alletto et al., 2010). A recent meta-analysis on tillage effects on pesticide pollution has created more insight into this relation (Elias et al., 2018). Where earlier sources expected that erosion reduction would also reduce pesticide pollution (Alletto et al., 2010; Reichenberger et al., 2007; Rittenburg et al., 2015), it is shown by Elias et al. (2018) that no-till systems do not reduce pesticide loads, and may make them worse. Our study, comes to the same conclusion, showing that conventional tillage often leads to less pesticide transport, using a slightly different set of papers for the meta-analysis. This reinforces the result and shows it is general enough to be replicated by an independent study. Substances with higher solubility and lower sorbtivity tend to be transported more under no till management. This process is linked to the influence of no-till management on soil properties like organic matter and pH (Alletto et al., 2010). The relation between organic matter content and pH and the phase distribution of pesticides influences the transport by overland runoff. Under no-till management the soil mixing layer is more shallow than in cultivated soils, which might result in more potential transport during overland flow. To prevent this, incorporating pesticides into the 2 – 5 cm layer will enhance their degradation (Ghidey et al., 2005) thereby reducing the risk on overland transport.

An effective way of reducing pollution by pesticides is by input control or by redesigning the farming system. Input control and redesigning farming systems are farm level measures. In the reviewed literature the main focus is on diffuse pollution, or pesticide transport from the field. Although point source pollution also occurs it is identified as less complex to control (Bach et al., 2001). Reduced input and redesigning the farming system is often referred to as 'Good Agricultural Practices' (GAPs) or 'Best Management Practices' (Rittenburg et al., 2015), which are agricultural management practices aiming at minimizing off site movement of pesticides to surface waters. Examples of such practices include band spraying on row crops, application restrictions for vulnerable soils and/or wet climates and keeping a certain distance from adjacent water bodies when spraying (Tang et al., 2012). Also the timing of pesticide application (with regards to e.g. forecast of heavy rainfall) or an integrated approach to pest management is important to reduce pesticide pollution (Gentz et al., 2010).

The systematic search for articles resulted in only a limited amount of usable data sources. This is mainly due to the requirement of statistical data (mean, SD and *n*) to be able use statistical models for the analysis. This problem with quality of presented data is commonly mentioned in recent meta-analysis studies (Elias et al., 2018; Valkama, Usva, Saarinen, & Uusi-Kämppä, 2019). For most measures within the data set, the amount of data was not sufficient for a thorough meta-analysis. Based on this, we would like to stress the need to always present the mean, SD and sample size of data with experimental results.

Within the case studies examples are given of national laws or regulations which restrict or prohibit the use of pesticides. Such measures are effective on higher policy levels and not reviewed or studied in detail in this study. However, this might be a promising approach to reduce pesticide pollution of drinking water sources. It is evident that there is no single strategy to reduce pesticide losses. When aiming at transport reduction, site-specific plans that are well managed may provide greatest success (Rittenburg et al., 2015).

In the context of preserving the quality of water resources, both surface and ground water, the reduction of pesticide transport is of vital importance (Hildebrandt et al., 2008; Rittenburg et al., 2015). In this study we show that proper management on the field can contribute to reduced pollution from overland transport, but that for transport to groundwater no readily usable agronomical measures are available. To achieve reduction of pesticide pollution in water sources, measures should also include farm system redesign, reduced inputs and regional or national approaches to facilitate a sustainable farming system.

For overland transport well-studied measures are available, such as vegetated filter strips. These measures can strongly decrease pesticide transport. However, to study the effectiveness of these measures, or of agricultural management in general in more detail, high quality and well documented experimental studies are of great value. While this paper discussed the effectiveness of single measures, the contribution of each flow path to total pollution is not specified. This needs further attention in the future, to provide the possibilities for optimal strategies and management to reduce pesticide pollution to ground and surface water resources.

1.5 CONCLUSIONS

The main conclusions of our study are

- The driving factors for diffuse pesticide pollution are (i) the amount and type of used pesticides, (ii) water facilitated transport through or over the soil, (iii) erosion of sediment that causes transport of sorbed particles, and (iv) spray drift during application.
- Vegetated filter strips are the most clear measure to reduce overland transport and pollution by pesticides. Models are available to calculate dimensions and predict effectiveness for pesticide reduction.
- Tillage practices are extensively studied in relation to off-site transport of pesticides. The analysis shows that no-till does not provide less off-site transport than conventional tillage, and suggests even higher pollution in no-till systems under specific circumstances.
- On-site measures against diffuse pollution comprise only a small part of the available approaches to reduce pesticide pollution. To obtain a sustainable system, input reduction, farm system redesign, point source mitigation and policy measures are essential to be taken into account.

2. REDUCTION OF NITRATE TRANSPORT FROM AGRICULTURAL LAND TO GROUNDWATER AND SURFACE WATERS BY MANAGEMENT MEASURES

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2.1 INTRODUCTION

The health effects of nitrate (NO_3) and nitrite (NO_2) in drinking water have long been debated (Bryan & van Grinsven, 2013; L'Hirondel, 2001). The 1958 WHO International Standards for drinking water stated that the ingestion of water containing nitrates in excess of 50–100 mg/l (as NO_3) may give rise to methaemoglobinaemia in infants under 1 year of age (Schullehner, Hansen, Thygesen, Pedersen, & Sigsgaard, 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 of 50 mg/l for NO_3 ion and 3 mg/l for nitrite 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 NO_3 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, Bouwman, Harrison, & Knoop, 2009). Global losses from fertilizers and manures are a factor 2 to 4 larger (Beusen, Bouwman, Van Beek, Mogollón, & Middelburg, 2016). Nitrogen that is not taken up from soil by plants may be lost to surface waters and groundwater as NO_3 via surface runoff and leaching (Burt, Heathwaite, & Trudgill, 1993). This makes the nitrogen unavailable to crops and increases the NO_3 concentration in groundwater and surface waters (Sutton et al., 2011).

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 NO_3 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 NO_3 (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 NO_3 and NO_2.

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 NO_3 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 NO_3 from agriculture (e.g., Addiscott et al., 1991; Burt et al., 1993; Mosier et al., 2004; Goulding, 2006; Sutton et al., 2011).

The overall objective of the FAIRWAY project is to review current approaches and measures for protection of drinking water resources against pollution caused by NO_3 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 objective of this report is to review the effectiveness of management measures for reducing NO_3 losses to ground- and surface water resources. We combined (i) a synthesis of existing review papers, (ii) a meta-analysis of available data from literature and (iii) practice based knowledge from nine case studies across Europe.

2.2 MATERIALS AND METHODS

2.2.1 Literature review

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 NO_3 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

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

In addition, University and Institute libraries were examined in Member States of the European Union, because a significant fraction of the research on measures to reduce NO_3 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 categorized according to Table 2.1 and collected in Excel spreadsheets in a uniform manner. The Excel spreadsheets were subsequently transferred to a database for meta-analysis.

To extend the literature study, we searched Google Scholar for additional review papers and meta-analyses, using the search query: (“Nitrate” OR “Nitrogen”) AND (“Mitigation” OR “Measure”) AND (“Meta-analysis” OR “Review”) AND “Agriculture”.

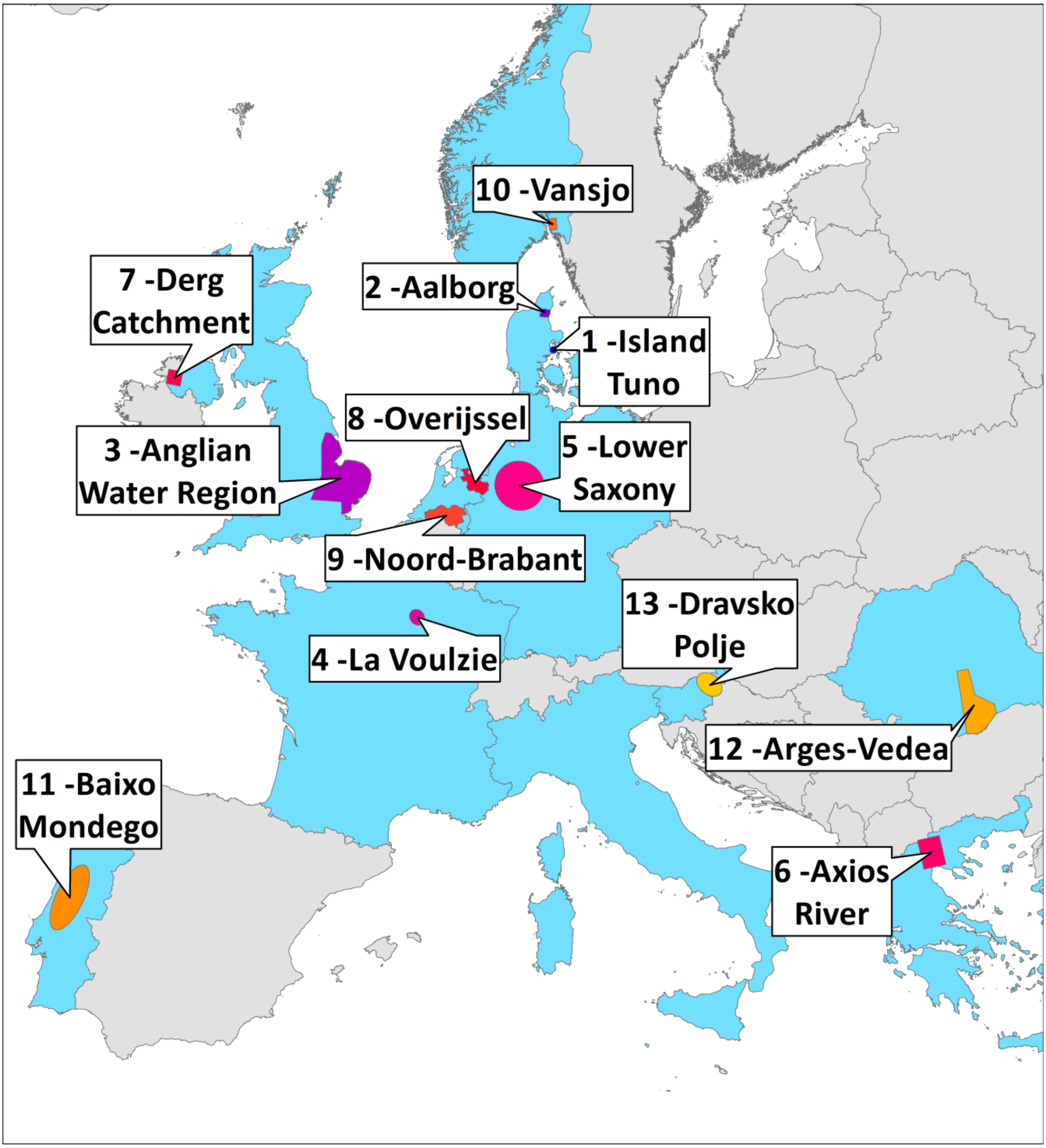

Figure 2.1: Locations of the various case-studies on NO_3 and/or pesticide losses in the FAIRWAY project.

2.2.2 Meta-analysis

We used the R-package ‘metafor’ to conduct the meta-analysis (Viechtbauer, 2010). The goal of a meta-analysis is to combine all quantitative data from the collected studies and draw an overall conclusion on the effectiveness of a specific measure. In the reviewed studies the effect of a treatment was shown with different values and units. For a meta-analysis these different designs, units and approaches have to be normalized so they can be compared. To be able to compare effect sizes between studies all data was recalculated to the response ratio (*R*):

$$R = \frac{\overline{X_T}}{\overline{X_C}}$$

Where $\overline{X_T}$ represents the means of the treatment group and $\overline{X_C}$ the means of the control (Borenstein et al., 2009). For each study the mean, standard deviation and sample size was recorded. The distribution of *R* cannot be assumed to be normal, so the values for *R* were log-transformed before statistical analyses using the natural logarithm (Borenstein et al., 2009; Hedges et al., 1999). Commonly, the variance of each pairwise observation is calculated to weigh the individual observations. Records with a smaller error margin are then assigned a heavier weight when the average and confidence intervals are calculated However, as a large part of the observations in our database were missing a measure of variance, we performed an unweighted analysis of the data.

A random effects model was used to assess the effect of the different measures on combined observations of NO_3 fluxes to drainage or surface water and NO_3 concentrations in soil and water. Study was included in the model as a random factor, to account for different studies contributing a different amount of data points to the database. The resulting means per measure were presented. A 95% confidence interval (CI) was calculated, and the effectiveness of a measure is considered significant when there is no overlap with a response effect of 0%, indicating 'no effect'.

2.2.3 Case studies

Expert knowledge from nine ongoing case studies (Fig. 2.1) of the EU H2020 FAIRWAY project (2017 – 2021) across Europe was used to assess the effectivity, cost-effectiveness of measures, as well as the willingness to adopt them. These case studies are investigating measures to minimize pollution of ground- and surface drinking water resources by nitrates. Questionnaires were sent out and experts were asked (i) which measures were applicable in the region of their case study, and (ii) to evaluate the measures in terms of effectiveness, cost, and applicability (Annex 2). Table 2.2 gives a summary of the questions asked and the information that was provided. All experts are in close contact with land managers who apply the measures.

Table 2.1: Categories of measures to reduce nitrate losses.

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.
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.
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).
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.
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.
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.

Nr	Name of the measure	Characterization of the measures
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.

Table 2.2: Format for the description of measures used in the case study areas.

Name of the measure	Explain the measure in one sentence
Description	Brief characterization of the measure in maximal three sentences; what is (are) the action(s) of the land manager/farmer/citizen
Mode of action	Brief description of the mechanism(s) 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

2.3 RESULTS AND DISCUSSION

2.3.1 Review of existing meta-analyses

Results from reviews and meta-analyses that assessed the effects of different measures on NO_3 losses and soil NO_3 concentrations were summarized and are organized below. The amount of literature available greatly differed for the various practices: several reviews on cover crops and biochar have been published, but for other measures (e.g. adaptations in soil drainage or irrigation management) hardly any (quantitative) reviews were found. Most reviews did not include a cost-benefit analysis, but in two cases (both for nitrification inhibitors) they were reported.

Overall, assessment of these literature reviews showed that most included measures were effective to some extent at reducing the risk of NO_3 losses to water bodies. There is overwhelming evidence that the use of non-legume cover crops is an efficient practice, with reductions in NO_3 leaching from 35% to 98%. The effect does however diminish when legumes are used. Besides cover crops, the use of (nitrification) inhibitors is also effective. In particular for dicyandiamide (DCD), a lot of studies reported a reduction in NO_3 leaching. For biochar, the effect differs from none at all, to considerable reductions in NO_3 leaching. The success of biochar applications seem to depend on soil and environmental conditions, as well as the nature of the biochar used. For changes in tillage systems (switching from conventional to no-till), the reviewed study did not show a significant reduction in NO_3 losses. Rather, for losses through leaching a significant increase was even reported. Switching to organic farming often includes no-till practices and did seem to reduce NO_3 losses. However, there was considerable variation in the results, and when losses were expressed per unit of produce, losses were often increased due to lower yields by organically managed farms.

Table 2.3 gives a summary on the studies and effects of the various measures in the reviews. Below, reviews on the various measures will be discussed per measure.

Table 2.3: Summary of the measures and main effects found in the literature search.

Study	Measure	Response variable	Observ.	Overall effect[1]	Comments
Basche et al. 2014	Cover crops	NO_3 leaching	11	-98%	
Borchard et al. 2019	Biochar	NO_3 leaching	688	N.S.	Long-term studies show greater effect. No effect in grasslands.
Cai and Akiyama 2017	Inhibitors	NO_3 leaching	45	-46%	DCD application
Daryanto et al. 2017	No-till	NO_3 leaching	180	+13%	NO_3 concentrations in leaching samples were similar.
Daryanto et al. 2017	No-till	NO_3 runoff	61	N.S.	NO_3 concentrations in runoff increased significantly.
Liu et al. 2018	Biochar	N leaching	156	-26%	
Liu et al. 2018	Biochar	Soil NO_3 concentration	350	-12%	
Mayer et al. 2007	Buffers	N leaching/runoff	89	-68%	
Mondelaers et al. 2009	Organic farming	NO_3 leaching	?	-32%	Considerable variation
Nguyen et al. 2017	Biochar	Soil NO_3 concentration	862	-11%	
Qiao et al. 2015	Inhibitors	NO_3 leaching	102	-47%	Cost-benefit analysis: DCD - \$162.70 ha^{-1} y^{-1}
Quemada et al. 2013	Fertilizer management	NO_3 leaching	106	-40%	
Quemada et al. 2013	Cover crops	NO_3 leaching	59	-35%	Includes both legume and non-legume crops
Quemada et al. 2013	Improved irrigation	NO_3 leaching	82	-58%	Average of several practices
Thapa et al. 2018	Cover crops	NO_3 leaching	216	-56%	Non-legume crops only
Tonitto et al. 2006	Cover crops	NO_3 leaching	?	-70%	Non-legume crops only
Tonitto et al. 2006	Cover crops	NO_3 leaching	?	-40%	Legume crops only
Tuomisto et al. 2012	Organic farming	N leaching	48	-31%	But an increase in N leaching per unit of produce.
Valkama et al. 2015	Cover crops	N leaching	27	-50%	Non-legume crops only
Valkama et al. 2015	Cover crops	Soill N concentration	29	-35%	Non-legume crops only
Yang et al. 2016	Inhibitors	NO_3 leaching	298	-55%	Both DCD and DMPP Cost-benefit analysis: DCD - \$109.49 ha^{-1} y^{-1} DMPP - \$15.67 ha^{-1} y^{-1}

[1] Negative numbers indicate a reduction in NO_3 losses/concentrations

[2] Not significant

2.3.1.1 Cover crops

Basche et al. (2014) did a meta-analysis that focuses on the effect of cover crops on nitrous oxide (N_2O) emissions, but also includes a few studies with data on NO_3 leaching (3 studies, 11 data points; Fig. 2.2). They only included studies in which the cover crop was not harvested. The authors argue that, while cover crops may not reduce (and sometimes even increase) N_2O emissions from agricultural fields, the N that is prevented from leaching as NO_3 represents a reduction of subsequent N_2O emissions from leachate once it has been transported outside field boundaries. Therefore, reducing NO_3 leaching to ground and surface waters may also benefit N_2O emissions from agricultural sources.

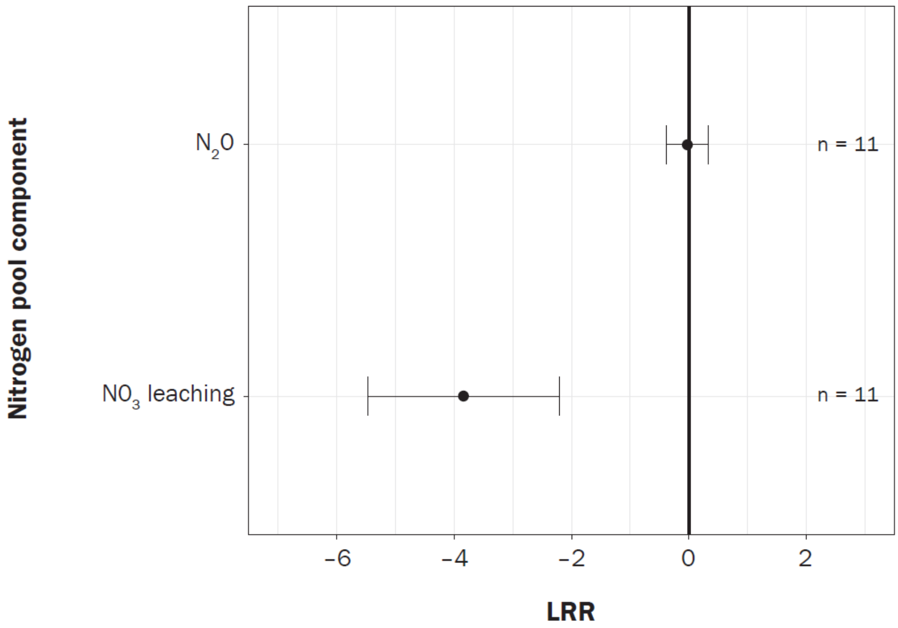

Figure 2.2: The mean NO_3 leaching response ratios (LRR; natural log of the NO_3 leaching with a cover crop divided by the NO_3 leaching without a cover crop) and 95% confidence intervals compared to the mean N_2O response ratios from the same studies. From Bassche et al. (2014).

Thapa et al. (2018)also did a meta-analysis on the effect of cover crops on NO_3 leaching (28 studies, 238 observations). They reported a 56% reduction of NO_3 leaching by non-legume cover crops. Mixtures of legumes and non-legumes showed a response similar to the non-legume crops and both were more effective than legumes on their own. These results were obtained when one study was omitted from the results due to high variation. Results were affected by planting date, shoot biomass, and precipitation, but the lack of statistical information in the used studies prevented a deep analysis of contributing factors.

Tonitto et al. (2006) conducted a study on cash crop yields and N retention in systems with and without cover crops. They found that non-legume cover crops decreased NO_3 leaching by 70%, but there was no difference in cash crop yields between systems with and without a cover crop. Legume-based systems reduced NO_3 leaching by 40% on average. There was an overall 10% yield penalty when using legumes, rather than mineral fertilizer to provide N to the cash crops, but no negative effect was observed when legumes provided more than 110 kg N ha^{-1}. There were no differences in soil N status of conventional and green manure systems after harvest, suggesting that NO_3 leaching losses were mainly reduced by avoiding bare fallow throughout the cropping rotation.

Valkama et al. (2015) studied the effects of catch crops on nitrogen (either NO_3 or total N) leaching and yield of spring cereals in the Nordic countries (Denmark, Sweden, Finland, and Norway). In their meta-analysis, non-leguminous catch crops reduced N leaching by 50% (27 observations; Fig. 2.3a) and soil NO_3/inorganic N by 35% in fall (29 observations; Fig. 2.3b). For the effect on soil N, there were differences among species used: annual ryegrass was more effective (60% reduction) than perennial ryegrass and Westerwolds ryegrass (25% reduction). Legumes, on the other hand, did not reduce soil N. Studies with non-legume catch crops also reported a slight (3%) yield reduction, whereas the ones with legume or mixed (legume + non-legume) catch crops reported increases for yield and crop N content (6%).

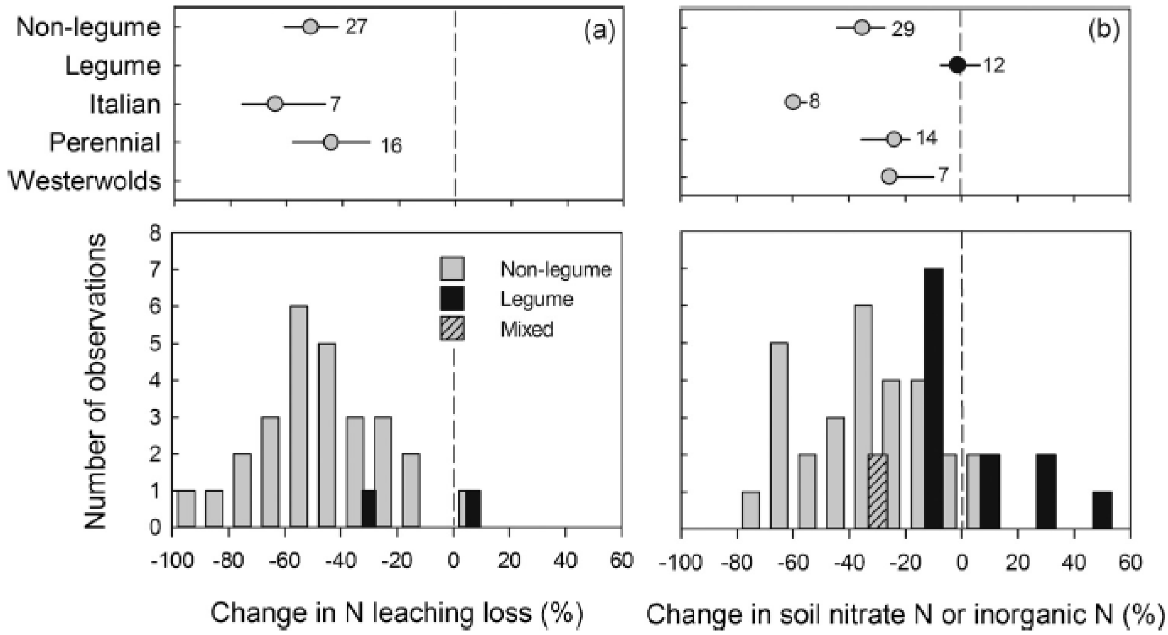

Figure 2.3: Distribution of the percentage changes in (a) N leaching loss and (b) soil nitrate N or inorganic N in autumn due to undersown catch crops (non-legumes, legumes, mixed) compared to the controls with no catch crops. The symbols indicate weighted average responses with 95% Cis for all non-legumes and legumes, as well as Italian (annual), perennial and Westerwolds ryegrasses. The dashed line indicates the control groups. The numbers indicate the number of observations. From Valkama et al. (2015).

2.3.1.2 Biochar

Borchard et al. (2019) investigated the effect of biochar additions on N_2O emissions, soil NO_3 concentrations, and NO_3 leaching. Their main findings show that, overall, soil NO_3 concentrations remained unaffected and the use of biochar did not significantly reduce NO_3 leaching (13% reduction, not significant). However, in studies that lasted longer than 30 days (shorter studies showed an increase in NO_3 losses) the effect was significant (26-32% reduction). Biochar decreased both N_2O and NO_3 losses in annual arable crops and horticulture, but no effect was found for grasslands or perennial crops. Besides this, addition of large additional N (> 150 kg/ha) as (mineral) fertilizer diminished the effect of biochar on NO_3 leaching. Although biochar addition may suppress soil N losses as N_2O emissions and NO_3 leaching, there is a higher risk of NH_3 volatilization when applying biochar.

Liu et al. (2018) assessed the effect of biochar additions on the soil N cycle. Aside from N leaching losses, they summarized effects on gaseous losses and soil N pools. On average, biochar reduced N leaching by 26% (22% for NH_4 and 29% for NO_3) and soil NO_3 concentrations with 12%. NH_3 volatilization, on the other hand, was increased by 19% (this effect was larger in soils with a low buffering capacity). Wood-based biochars were the most effective, whereas manure-based biochars did not seem to have a significant effect. There was no effect of pyrolysis temperature on the effect size (with biochar/no biochar), but the effectiveness in reducing N leaching increased with higher biochar application rates.

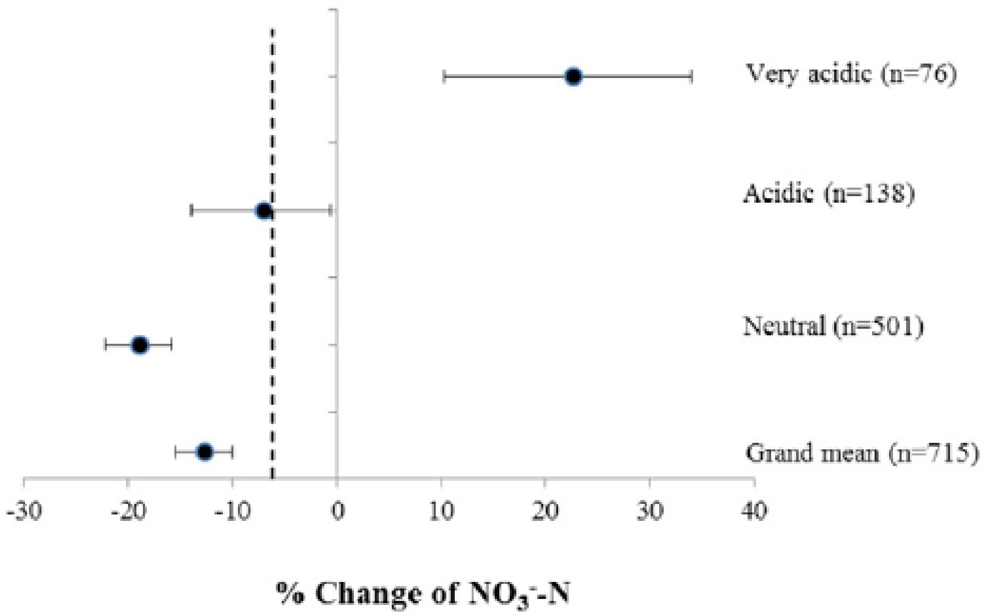

Figure 2.4: Influence of soil pH on NO_3 availability in soil. Symbols represent mean effect sizes with 95% confidence intervals. The numbers correspond to observations in each class. The dotted line indicates the mean effect for all pH ranges when biochar is co-applied to soil. From Nguyen et al. (2017).

Nguyen et al. (2017) reported a meta-analysis on the effect of biochar on soil inorganic N (56 studies, 1080 observations). They found that biochar applications reduced soil inorganic N (-11% for NH_4 and -10% for NO_3). Most of their studies were shorter than a year. They found plant-derived biochars and biochars pyrolyzed at lower temperatures (< 401 °C) to be more effective at reducing soil N concentrations than woody biochars. Higher biochar application rates were more effective, but application of urea alongside biochar decreased the biochar's effect of lowering soil NO_3 concentrations and even increased them compared to the control. Biochar worked best to reduce soil NO_3 concentrations on neutral soils (Fig. 2.4). Very acidic soils showed increased NO_3 levels when biochar was applied. Generally, time between application and observation had little effect on soil NO_3 concentrations. Climatic conditions may affect the effect of biochar on reducing nitrate leaching, but an assessment of climatic conditions was not included in the meta-analysis paper.

2.3.1.3 Inhibitors

Cai and Akiyama (2017) reviewed the effect of inhibitors and biochar on N_2O and NO_3 losses in urine patches on grasslands. Studies originated predominantly from temperate areas (UK and New Zealand). They reported a decrease of 46% in NO_3 losses when the nitrification inhibitor DCD was applied. When used in combination with the urease inhibitor n-butyl thiophosphoric triamide (NBPT) NO_3 losses were reduced by 42%. Effectiveness increased with higher doses of DCD. There was no significant difference between coated and liquid forms of DCD and study type or duration did not affect the results. Although there was no difference between the effects of DCD and those of DCD+NBPT, the authors state that if NH_3 large losses are expected, a combination of DCD and NBPT would be the more logical option.

Qiao et al. (2015) collected 62 field studies of nitrogen enriched studies to summarize the effect of nitrification inhibitors on the nitrogen cycle. They found that the use of inhibitors decreased NO_3 leaching by 47%. Besides this, N_2O emissions were decreased by 44%, NO emissions by 24%, but NH_3 emissions were increased by 20%. They also conducted cost-benefit analysis and calculated that applications of nitrification inhibitors could increase the revenue of a maize farm by \$162.70 ha^{-1} y^{-1} which would correspond to a 8.95% in financial gain (Table 2.4).

Yang et al. (2016) investigated the effect of dicyandiamide (DCD) and 3,4-dimethypyrazole phosphate (DMPP) on soil nitrogen transformations and plant productivity. They found that both nitrification inhibitors were equally effective at altering soil N transformations. Both inhibitors increased soil NH_4 content (DCD: 25.3% and DMPP: 41.1%) and decreased NO_3 content (DCD: 17.0% and DMPP: 20.7%). DCD and DMPP were equally effective at reducing NO_3 leaching (~55%, n=298), but NH_4 leaching was increased for DMPP, but decreased for DCD. Also, in neutral soils or when urea was applied, DMPP seemed more effective than DCD. Total N leached did not differ between the two inhibitors. For plant production, DCD was more effective than DMPP in increasing yields. These authors also conducted a cost-benefit analysis and concluded applying fertilizer N in combination with DCD had a benefit of \$109.49 ha^{-1} y^{-1}, whereas for DMPP this was only \$15.67 ha^{-1} y^{-1} (Table 2.5). The authors do note that DCD has a higher toxicity to plants and human health than DMPP (although toxicity for both products is relatively low) and that this may change the cost-benefit analysis over a longer time.

Table 2.4: Cost-benefit analysis for a maize farm applying nitrification inhibitors (NI) with fertilizer rate of 125 kg N/ha/yr. For change in N loss under NI, positive values indicate that NI increases N losses, and negative ones indicate N reduces N loss. For the monetary response, the positive numbers indicate the amount of the economic benefit, whereas the negative ones indicate the amount of the economic cost. From Qiao et al. (2015).

Variables	Assessed impacts	Cost (data source)	Change in N loss under NI (kg N^{-1} ha^{-1})*	Monetary response (\$$ha^{-1}$)
NH_3 emission	The cost of human health damage	\$1.30 kg^{-1} N (Compton *et al.*, 2011)	3.52	−4.58
N_2O emission	The cost of climate change	\$1.24 kg^{-1} N (Kusiima & Powers, 2010)	−0.55	0.69
NO emission	The cost human health damage	\$23.00 kg^{-1} N (Compton *et al.*, 2011)	−0.18	4.18
Dissolved inorganic N leaching	The abatement cost of reducing N from agricultural drainage water	\$2.71 kg^{-1} N (Jaynes *et al.*, 2010)	−9.17	24.84
Sum of the environmental impacts				**25.16**
Variables	Assessed impacts	Unit price (data source)	Changes in yield (ton ha^{-1})#	Monetary response (\$ ha^{-1})
Maize production	The benefit of increase in yield	\$197.00 ton^{-1} (USDA, 2013)	0.83	**163.83**
Variables	Assessed impacts	Unit price	Application rate (kg ha^{-1})†	Monetary response (\$ ha^{-1})
Dicyandiamide (DCD)	The cost of purchasing DCD	\$1.75 kg^{-1}¶	15.00	−26.25
Sum of the monetary responses				**162.70**

*Changes in N loss under NI = 125 kg N ha^{-1} × (F_{N+NI} − F_N). The positive value indicated an increase in N loss under NI, and the negative values indicated a decrease in N loss under NI.

#The change in maize production was calculated by multiplying the mean maize production in US (9.24 ton ha^{-1}, USDA, 2012) with mean response ratio of maize yield (1.09) estimated by the current study (Table S6).

†The recommended DCD application rate (15 kg ha^{-1} yr^{-1}) was from Di & Cameron (2003).

¶The price of DCD was the mean of the market price of DCD from the website of Alibaba.

Table 2.5: Cost-benefit analysis of nitrification inhibitor (NI) application in a maize farm with fertilizer N rate of 125 kg N/ha/yr. For change in N loss under NI, positive values indicate that NI increases N losses, and negative ones indicate N reduces N loss. For the monetary response, the positive numbers indicate the amount of the economic benefit, whereas the negative ones indicate the amount of the economic cost. From Yang et al. (2016)

	Assessed impacts	Cost[1]	Change in N loss under NI ($kg\,N^{-1}\,ha^{-1}$)*		Monetary response ($\$ha^{-1}$)		
			DCD	DMPP	DCD	DMPP	
NH_3 emission	The cost of human healthdamage	$\$1.30\,kg^{-1}N$	2.24(n.s)	−0.90(n.s)	−2.91	1.17	
N_2O emission	The cost of climate change	$\$1.24\,kg^{-1}\,N$	−0.56	−0.59	0.69	0.74	
NO emission	The cost of human healthdamage	$\$23.00\,kg^{-1}N$	–	−0.07(n.s)	–	1.67	
Dissolved inorganic N leaching	The abatement cost of reducing N from agricultural drainage water	$\$2.71\,kg^{-1}\,N$	−7.32	−9.06	19.82	24.55	
Sum of the environmental impacts					**17.61**	**28.12**	
			Changes in yield ($ton\,ha^{-1}$)#		Monetary response ($\$\,ha^{-1}$)		
Variables	**Assessed impacts**	**Unit price**[4,5]	DCD	DMPP	DCD	DMPP	
Maize production	The benefit of increase in yield	$\$197.00\,ton^{-1}$	0.60	0.11(n.s)	**118.14**	**21.30**	
		Unit price§		Application rates ($kg\,ha^{-1}$)†		Monetary response ($\$\,ha^{-1}$)	
Variables	**Assessed impacts**	DCD	DMPP	DCD	DMPP	DCD	DMPP
DCD, DMPP	The cost of purchasing DCD or DMPP	$\$1.75kg^{-1}$	$\$27kg^{-1}$	15.00	1.25	−26.25	−33.75
Sum of the monetary responses						**109.49**	**15.67**

2.3.1.4 No tillage systems

Daryanto et al. (2017) compared no-till systems to conventional tillage systems in their NO_3 losses through leaching and runoff processes for several field crops. They compared both NO_3 load and concentrations (Fig. 2.5). No-till provided no overall reduction in either concentration or load than conventional tillage systems. No-till systems had higher NO_3 concentrations in runoff, but due to lower runoff volumes the load was similar. Leaching NO_3 losses were significantly higher in no-till systems. Soil drainage characteristics (texture, artificial drainage) are likely to play an important role in the effects of no-till on NO_3 losses. Fertilizer type (organic vs. inorganic vs. no fertilizer) had no effect on the NO_3 concentrations in runoff and leaching samples.

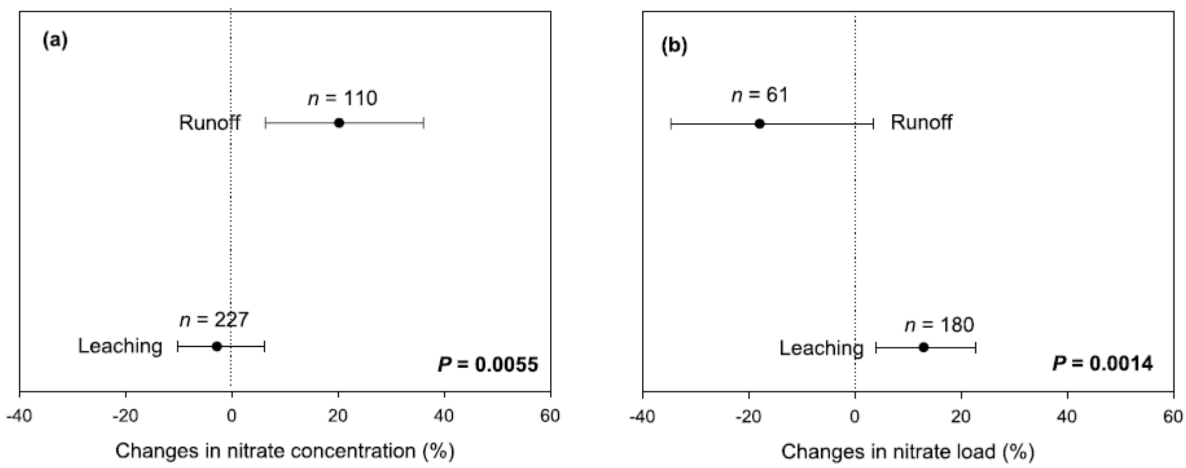

Figure 2.5: The overall percentage change in concentration (a) and load (b) of nitrate with no-till in comparison to conventional tillage. Black dots represent the mean of the response ratio with error bars representing the 95% confidence intervals. A negative value indicates a reduction due to no-till adoption in comparison to conventional tillage. Numbers represent the number of observations. From Daryanto et al. (2017).

2.3.1.5 Vegetative buffers

Mayer et al. (2007) reviewed the effect of riparian buffers on nitrogen concentrations in streams and tried to link the effects of buffers to the buffer width (45 studies; 89 observations). Overall, buffers were very effective at removing N from streams (67.5%). Buffers were particularly effective at removing subsurface N. They found a wide variation in effectiveness and a small part could be explained by buffer width. Buffers > 50 m were more effective at removing N than were those <25 m. This was particularly true for horizontally transferred N removal, but not for vertical transferred N removal. No effect of buffer vegetation was observed, but buffers with herbaceous or herbaceous/forest vegetation became increasingly effective as they got wider.

2.3.1.6 Organic farming

Tuomisto et al. (2012) studied the effect of organic farming on the environment. Their main conclusion is that, while organic farming may have environmental benefits and may reduce N leaching per land unit, this is not necessarily true per unit of produce. This is a result from both the lower inputs and outputs of organic farming. Over 48 observations, they found a 31% reduction of N leaching in organic systems when expressed per land unit, but a 49% increase of leaching losses per unit of product. The lower leaching losses (and lower yields) were likely a result of reduced N inputs in organic farming systems. In addition to the effect on N leaching, Tuomisto et al. (2012) show a reduction in N_2O emissions (per land unit) and an increase in soil organic matter content. Losses of ammonia and P were not significantly different between conventional and organic systems.

Mondelaers et al. (2009) did a meta-analysis on the differences in environmental impacts between organic and conventional farming. They assessed NO_3 losses among other parameters. Their analysis showed that NO_3 leaching was 32% lower in organic farming systems. However, the variability between studies was considerable.

2.3.1.7 Other

Quemada et al. (2013) conducted a meta-analysis (44 studies, 279 observations) on the effects of water and fertilizer management, cover crops, and fertilizer technology on NO_3 leaching and crop yield. They found that proper water application management can reduce NO_3 leaching by up to 80% without lowering crop yields. Improving fertilizer management reduced leaching by 40% (Fig. 2.6), and the best results were obtained if fertilization occurred at the recommended rate. Cover crops reduced NO_3 leaching by 50% compared to fallow land, but only if the cover crops were not leguminous. Legume cover crops had no significant effect.

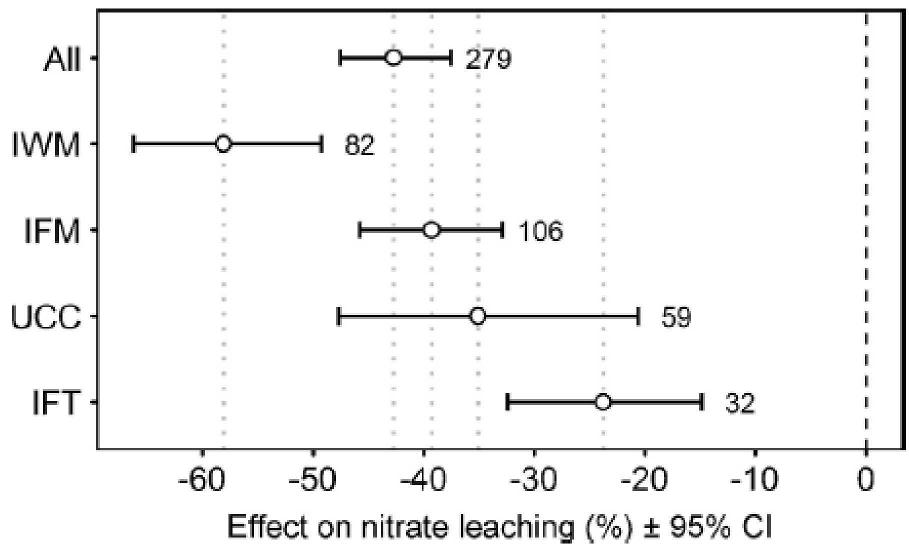

Figure 2.6: Overall effect off management strategies (All) and the effect of management strategy groups on NO_3 leaching in units of percent change from the control. Mean values and 95% confidence intervals are shown. IWM: improved water management; IFM: improved fertilizer management; UCC: use of cover crops; IFT: improved fertilizer technologies. Numbers represent numbers of observations. From Quemada et al. (2013).

Wang et al. (2019) used meta-analysis (86 studies, 324 observations) to construct a model to describe the emission factor for NO_3 leaching from N fertilizer additions. They show that NO_3 leaching from N additions do not remain constant (as a set fraction of the added N), but increase with higher N additions according to a quadratic relationship. Their conclusion is that the emission factor for NO_3 leaching set by the IPCC (30% of N input) overestimates NO_3 leaching.

Zhou and Butterbach-Bahl (2014) conducted a meta-analysis on the link between NO_3 leaching and crop yields in maize and wheat cropping systems. They showed that maize systems saw NO_3 losses that were about two times higher than those in wheat systems. Due to higher maize yields however, yield-scaled NO_3 losses were comparable between the two systems. They further conclude that NO_3 losses can be reduced by fertilizing close to the optimal N rate, as NO_3 leaching increased with N application rate.

2.3.2 Meta-analysis

In the meta-analysis we included 53 studies and 278 observations that compared a variety of measures to reduce NO_3 losses (Table 2.6). Because of a lack of studies and the absence of a solid, uniform type of pairwise comparisons (treatment group vs. control group), it was impossible to incorporate studies covering measures like implementation of balanced N fertilization, adaptations of N application timing or rate, restricted grazing, changes in crop rotations, and mulching (see Table 2.1). It was also necessary to combine studies with different indicators, and so the effect on N or NO_3 concentrations in soil and water is assessed jointly with reported results on NO_3 flux from soil (field) to water. This implies a significant generalization of the data and the results should thus be viewed with some caution.

Table 2.6: Comprehensive list of studies included in the meta-analysis, including the NO_3 indicator and the type of measure described in the studies.

Study	Indicator	Measure type
Adams and Jan, 2006	NO_3 flux	Cover crops
Asing et al., 2008	NO_3 concentration	Inhibitor
Askegaard et al., 2006	NO_3 flux	Cover crops
Benham et al., 2007	NO_3 flux	Tillage
Besnard, 2004	NO_3 flux + NO_3 concentration	Cover crops
Besnard and Kerveillant, 2006	NO_3 flux	Cover crops
Bock et al., 2015	NO_3 concentration	Biochar
Bonaiti and Borin, 2010	NO_3 flux + NO_3 concentration	Controlled drainage
Bosch et al., 2015	NO_3 flux + NO_3 concentration	Tillage
Dennis et al., 2010	NO_3 flux	Inhibitor
Di and Cameron, 2012	NO_3 concentration	Inhibitor
Drury et al., 2009	NO_3 flux + NO_3 concentration	Controlled drainage
Dunn et al., 2011	NO_3 concentration	Vegetative buffer
Eykelbosh et al., 2015	NO_3 concentration	Biochar
Francis et al., 1995	NO_3 flux + N content	Cover crops
García-González et al., 2018	N content	Cover crops
Gordon et al., 2011	?	Tillage
Goss et al., 1993	NO_3 flux	Tillage
Guardia et al., 2018	N content	Inhibitor
Hill et al., 2015	NO_3 flux	Biochar + Inhibitor

Huang et al., 2015	NO_3 flux	Tillage
Jabro et al., 2016	NO_3 concentration	Tillage
Johnson and Smith, 1996	NO_3 flux	Tillage
Jouni et al., 2018	?	Controlled drainage
Kaspar et al., 2012	NO_3 flux	Cover crops
Krueger et al., 2011	NO_3 concentration	Cover crops
Macdonald et al., 2005	NO_3 flux	Cover crops
Martinez and Guiraud, 1990	NO_3 concentration	Cover crops
Mehdi and Madramootoo, 1999	NO_3 concentration	Tillage
Menneer et al., 2008	NO_3 concentration	Inhibitor
Monaghan et al., 2009	NO_3 concentration	Inhibitor
Nicholson et al., 2016	NO_3 flux	Application method
O'Connor et al., 2016	NO_3 flux	Inhibitor
Parkin et al., 2016	NO_3 concentration	Cover crops
Pisani et al., 2017	NO_3 concentration	Tillage
Premrov et al., 2014	NO_3 flux	Cover crops + Tillage
Ritter et al., 1998	NO_3 content	Cover crops + Tillage
Saarnio et al., 2018	N content	Biochar
Sanz-Cobena et al., 2012	NO_3 concentration	Inhibitor
Schipper and Vojvodić-Vuković, 2000	NO_3 concentration	Vegetative buffer
Schmidt and Clark, 2012	NO_3 concentration	Vegetative buffer
Shepherd, 2006	NO_3 flux	Cover crops
Shepherd et al., 2017	NO_3 concentration	Inhibitor
Smith et al., 2002	N concentration	Inhibitor
Stolzenburg, 2010	NO_3 flux + NO_3 concentration	Cover crops
Tauchnitz et al., 2018	NO_3 concentration	Inhibitor
Thorman et al., 2016	NO_3 flux	Application method
Ventura et al., 2013	NO_3 flux	Biochar
Vos et al., 1994	NO_3 concentration	Cover crops
Welten et al., 2014	NO_3 concentration	Inhibitor
Wesström and Messing, 2007	NO_3 flux	Controlled drainage
Yamulki and Misselbrook, 2016	NO_3 flux	Application method
Zaman and Blennerhassett, 2010	NO_3 concentration	Inhibitor

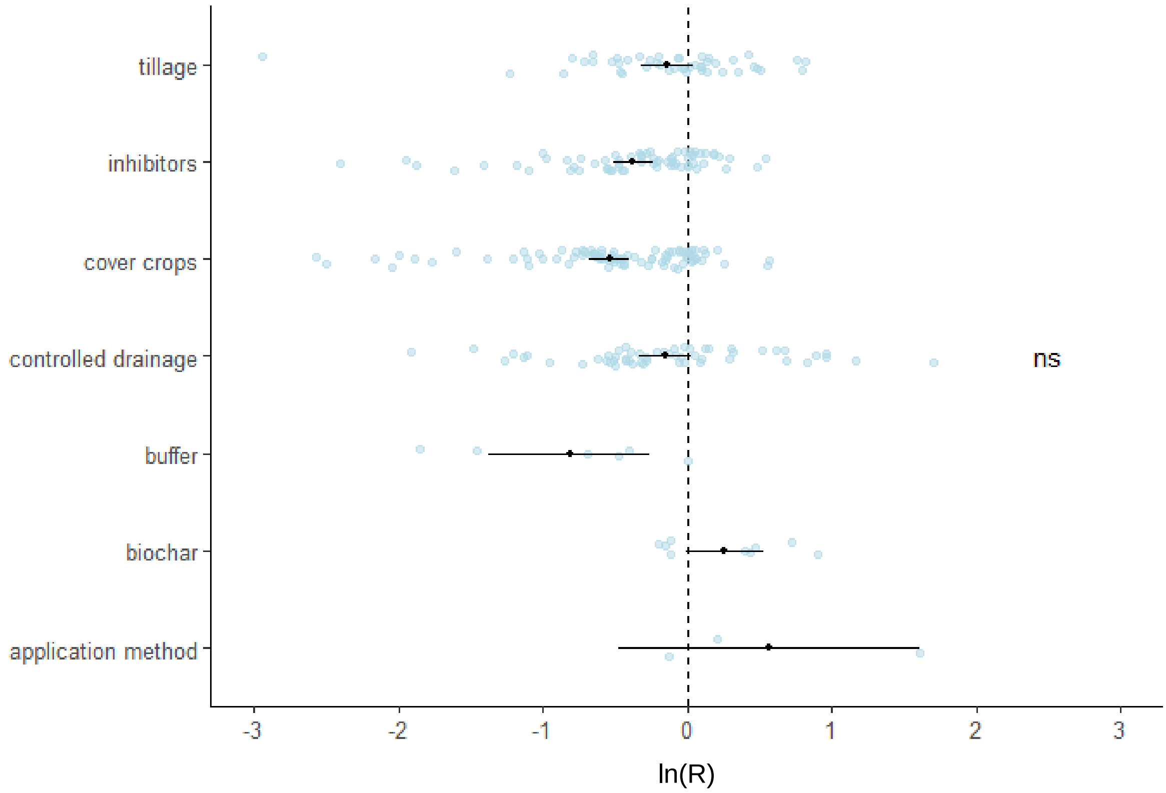

Figure 2.7: Results of a meta-analysis on the effect of various measures on nitrate losses. Black dots represent the average of the natural logarithm of the response ratio (R). Blue dots represent individual observations and error bars show the 95% confidence interval.

Overall, the data was spread widely for the different measures assessed. Figure 2.7 shows the average and 95% confidence intervals for the effect size (ln(*R*)) of the different measures. The results from the meta-analysis show that implementation of a vegetative buffer, the use of cover crops, and application of (nitrification) inhibitors lead to a significant decrease in NO_3 losses (95% confidence interval not overlapping 0). For the other analyzed measures (tillage, controlled drainage, biochar, and changes in application method), no significant average effect was recorded in the compiled database. Moreover, although some of the measures had a significant effect on NO_3 losses, including 'measure type' as an explanatory variable in the meta-analysis model did not significantly improve it. This indicates that the variation of the effect explained by the different measures is limited.

For the measures for which enough studies and observations were available, we assessed the effect of the measure more closely. Figure 2.8 shows the effect of the individual cover crops on NO_3 losses (18 studies, 84 observations). Lupins, grass, barley, oat, mustard, and rye were particularly effective in reducing losses. For turnips and wheat the effect was not significant. In our database, we did not observe the large difference in effectiveness between legume and non-legume crops, as observed in other literature reviews. It should be noted, however, that the number of studies included in the current analysis was limited. Moreover, there was no significant effect of including 'cover crop type' as an explanatory variable in the model.

When examining changes in tillage practice (11 studies, 47 observations), we did see a significant improvement when the type of tillage was considered ($p=0.0011$, Fig. 2.9). Whereas studies that reported the effect of reduced tillage and no-till did not significantly affect NO_3 losses, there was one study (Gordon et al., 2011) that used row shaper and basin tillage that did not match with the tillage forms included in the other studies and was therefore kept separate. No-till and reduced tillage had no effect on NO_3 losses however, and this is in line with the results reported in previous meta-analyses.

For research on the use of nitrification inhibitors (14 studies, 67 observations) we were able to distinguish between DCD used alone, or in combination with a urease inhibitor. The analysis shows that by itself, DCD significantly reduced NO_3 losses, but the studies in which it was used in combination with a urease inhibitor showed no significant reduction (Fig. 2.10). Including the differences between these two groups significantly improved the statistical model ($p=0.0224$). Overall, the effectivity of DCD as a measure is in line with the results found in previous meta-analyses.

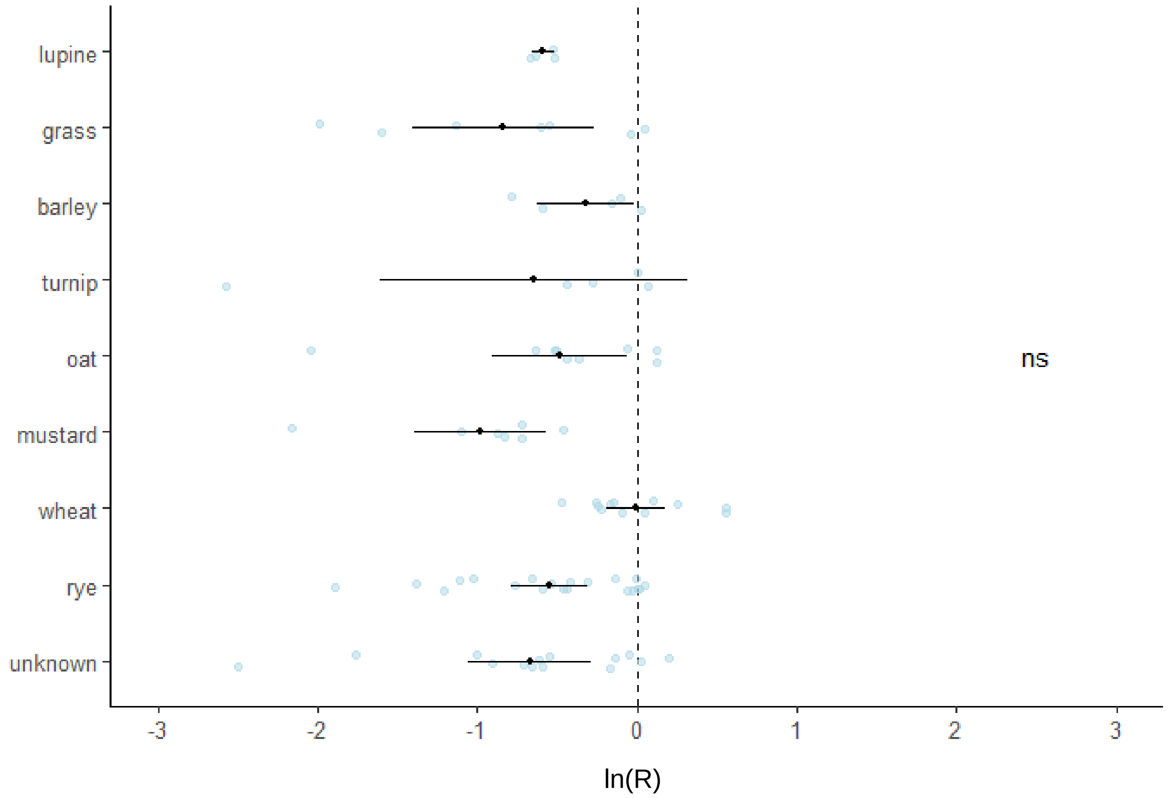

Figure 2.8: Results of a meta-analysis on the effect of various cover crops on nitrate losses. Black dots represent the average of the natural logarithm of the response ratio (R). Blue dots represent individual observations and error bars show the 95% confidence interval.

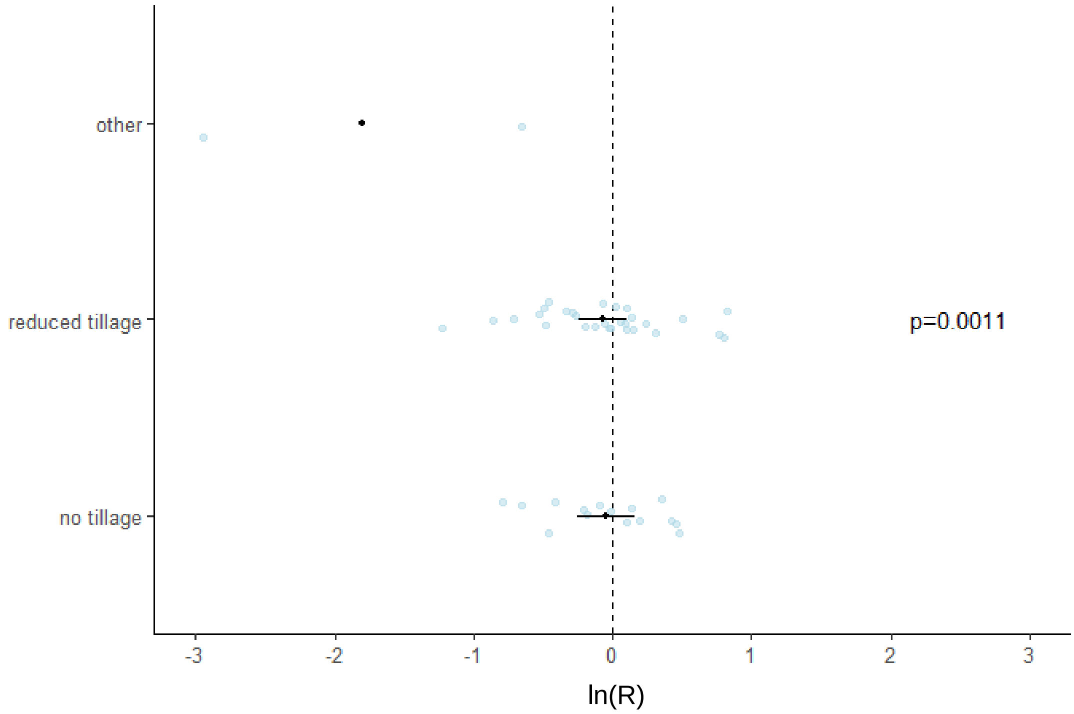

Figure 2.9: Results of a meta-analysis on the effect of tillage practices on nitrate losses. Black dots represent the average of the natural logarithm of the response ratio (R). Blue dots represent individual observations and error bars show the 95% confidence interval.

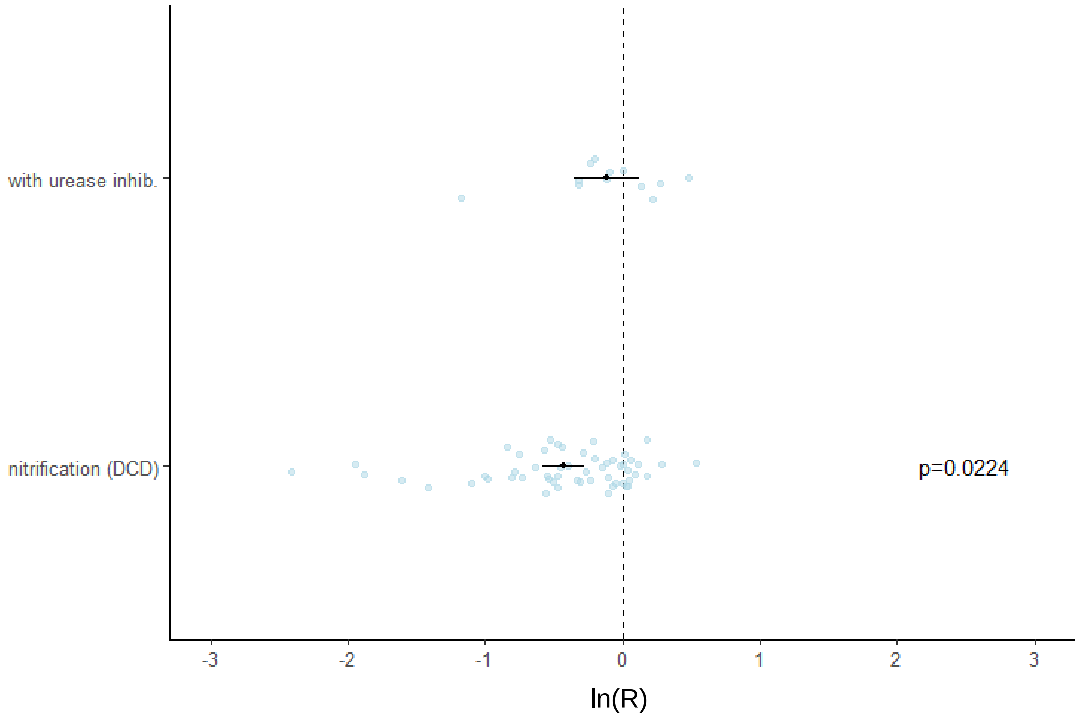

Figure 2.10: Results of a meta-analysis on the effect of application of (nitrification) inhibitors on nitrate losses. Black dots represent the average of the natural logarithm of the response ratio (R). Blue dots represent individual observations and error bars show the 95% confidence interval.

2.3.3 Case studies

Table 2.7 – Overview of the measure types applied and studied within the FAIRWAY case studies, with indications on effectivity, cost, applicability, and adoptability.

Measure type	Country[1]	Target[2]	Effectivity[3]	Cost[4]	Applicability[5]	Adoptability[6]	Notes
Changes in cropping system or crop rotation	NL, SLO	GW/SW/NUE	++	€	++	++	May improve soil health/quality, decrease chance of diseases.
Changes in fertilization timing	NL, DK, GR, ROM, SLO	GW/SW	+++	€	+++	+++	E.G. no manure spreading in the fall or splitting fertilizer applications. Expenses may increase if it demands more labor or requires additional manure storage space.
Changes in application method	GER, DK	GW	++	€	++	++	Effectivity may depend on the farm; may decrease other N losses such as greenhouse gases.
Changes in application dose (reduced input, balanced fertilization, or optimal fertilization)	NOR, POR, GER, DK, GR, SLO	GW/SW/NUE	++	€	+++	+++	May require soil testing. May be mandatory.
Cover crops	DK, GR, ROM, SLO	GW/SW	+++	€€	++	++	May increase soil OM content. Cost varies based on farm type. Less applicable/adoptable in Slovenia.
Reduced tillage	NOR	SW	++	€€	+++	++	May prevent soil erosion.

Buffer strips (either between crops and waterways, or between rows of crops)	NL, FR, GR, ROM, SLO	GW/SW	++	€€	++	+	May contribute to landscape diversity, but decrease crop yields. Implementation costs differ per country.
Grassed waterways	NOR	SW	+++	€€€€	+	+	May reduce erosion and contribute to landscape diversity. Reduces the amount of cropland
Farm-scale nutrient management tools	GER	NUE	*	€	+++	+++	Farmers may be obliged to use these tools.
Outreach and information events	GER	NUE	*	€	++	++	Effectivity depends on farm type and farmer knowledge.
Other	GR	GW/SW	?	?	?	?	Grassland and grazing management; improved fertilizer storage; no data available yet.

[1] Abbreviations for the various participating countries: NL – Netherlands; SLO – Slovenia; DK – Denmark; GR – Greece; ROM – Romania; GER – Germany; FR – France; NOR – Norway.
[2] Target of the measure: groundwater (GW), surface water (SW), nitrogen use efficiency (NUE).
[3] Effectivity is evaluated as Low (+, 5-10% load reduction), Moderate (++, 10-25% load reduction), High (+++, >25% load reduction), Variable (*), or Unknown (?).
[4] Implication costs are evaluated as Low (€, < €10/ha), Moderate (€€, 10-50/ha), High (€€€, €50-100/ha), Very high (€€€€, > €100/ha), or Unknown (?).
[5] Applicability is evaluated as No (+, on < 25% of the land), Partly (++, on 25-75% of the land), Yes (+++, on > 75% of the land), or Unknown (?).
[6] Adoptability is evaluated as No (+, in < 25% of the cases), Partly (++, in 25-75% of the cases), Yes (+++, in > 75% of the cases), or Unknown (?).

The results of the questionnaires sent out to the FAIRWAY case studies were collected and aggregated in a table (see Annex 1). From 8 different case studies, 36 different measures were recorded. They were then aggregated by measure type and the average/overall scores for effectivity, cost, applicability, and adoptability were assessed from the individual records and comments.

In general, there was a wide variety of measures described (Table 2.7). Optimizing the rate and timing of fertilizer and manure applications were measures that were applicable throughout (almost) all of the case studies. With a highly rated effectivity, applicability and adoptability, as well as a relatively low cost these are measures that can be taken easily an may yield quick results. Nevertheless, storage space, weather conditions and labour demand may be limiting factors for implementation of these measures. Additionally, reducing application rates or balancing N fertilization may result in yield losses and potential to implement this may depend on the characteristics of the farm.

From the questionnaire results there was no clear distinction between the type of measures adopted in the different parts of the continent (Annex 1). There were a few measures that were reported by just one or two case studies, but that does not directly imply that these measures are not used elsewhere. From the Greek case study, data on effectivity, cost, applicability, and adoptability was missing, as the case study had not been running for very long.

As reflected in the literature review and meta-analysis, the effectiveness of cover crops was rated as high. While it may not be the cheapest measure to implement, four out of eight case studies mentioned this measure. Buffer strips between crops and water ways (or between rows of crops) was also a frequently reported measure, but the effectivity was evaluated slightly lower and so was the adoptability. Compared to the literature review and the meta-analysis, there were several measures that were absent in the questionnaire results. Implementation of biochar and nitrification inhibitors was not reported by the experts. Measures on drainage or irrigation management were not reported either. The Norwegian case study reported a positive effect of reduced tillage, which in addition to decreasing nutrient transports to surface water, decreases erosion.

Another difference between the measures included in the literature review and meta-analysis on one hand, and the response from the case study questionnaires on the other is that the measures from the latter seemed to focus more on the farm-scale. Measures on outreach, information sharing, whole-farm assessments and large-scale N input reductions were reported. Although the effect of management decisions at this level is more difficult to quantify than field-ready measures such as cover crops, buffer zones, or inhibitors, they are relatively cheap to organize and may prove beneficial for reducing other N losses and increasing N use efficiency across the entire farm.

2.4 CONCLUDING REMARKS

The main conclusions of this report are:

- A review of existing meta-analyses and quantitative reviews showed that there is a lot of information available on the effectiveness of measures to reduce NO_3 losses to ground- and surface waters. In particular the use of cover crops, (nitrification) inhibitors, and biochar has been well documented, often in relationship with other N parameters, such as N_2O emissions or soil N transformations.
- The use of non-legume cover crops appears an effective way to reduce NO_3 losses. This effect is often diminished when legumes are included. Application of DCD also seems to be effective as a measure and cost-benefit analyses show that this can be profitable. For other measures, such as biochar and changes in tillage practices, the results differ.
- The success of the implementation of a measure often varies per farm and per location. It is subject to differences in topography, climate, and other farm management practices. Farm-tailored solutions are therefore likely to yield result. This is illustrated by the large variety of measures proposed by the case study experts and the differences in applicability.
- Implementation of measures to reduce NO_3 losses should not only consider the effectiveness, and costs, but also the adoptability and possible (unwanted) side-effects. While some measures may for example decrease NO_3 and N_2O losses, they could increase NH_3 volatilization. These effects of the measures on the N cycle and possibly those of other nutrients should be considered. This is true for measures at both the field and farm scales.

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ANNEX 1. QUESTIONNAIRE PESTICIDE MEASURES

Country	Short description	Full description	Mechanisms	Measure target Ground water (GW) Surface water (SW)	Effectiveness	Costs	Applicability	Adoptability	Other benefits	Disadvantages	Comments
Netherlands	Drift-reducing spray techniques	Adoption of spray techniques (air-supported spraying, Wingssprayer, Low Volume Spraying) that diminish the risk of pesticide spray drift. The effectiveness of spraying increases (more pesticides reaches the targeted plant or weeds). Farmers often opt for lower dosages.	Source reduction: Diminshing contamination of adjecent surface water. Less leaching to groundwater (only if farmers opt for lower dosage through increased effectiveness of spraying).	GS/SW	++	+	++	++	No	No	
Netherlands	Installing a wash basin and processing/purefying contaminated water	Cleaning spray machines (or other machinery that might have come into contact with pesticides) on a fixed spot where waste water is collected and processed or purefied by biological decay (Phytobac, biofilter) or evaporation (Heliosec).	End-of pipe	SW	+	?	+++	+	No	No	

France	buffer stip, grass strip	buffer stip, grass strip	use of buffer strip to slow down water (and solute) transfert to surface water	SW	++	++	++	+	Landscape diversity	De-creases crop yield	
France	Rotation impro-vement	Respect for an an-nual maximal pro-portion of surfaces	Improvement of the crop rotation to minimize the pesticide use	GW	++	+++	++	+	Landscape diversity		
France	Pesticide de-creace	Respect for an maximal IFT fixed for year	Reduction of the maximun pestidide load by the farmer during the cropping sea-son.	GW	++	+++	++	+	No		
England	Network Engage-ment Information events/discus-sions/ field days	'Network engage-ment' embedding information and communication at all levels from sup-ply chain to agron-omist to farmers to stimulate change of practice. This is be-ing done by an An-glian Water agricul-tural adviser. In partnerships with Anglian Wa-ter(AW), UoL is conductiong a farmer survey to review the effec-tiveness of knowledge trans-fer, using AW catchment advi-sors, to promote on farm best pracice for Metal-dehyde use.	Reduction of input thorugh behaviour change	?	?	?	?	?	Unknown	Unknown	Social sci-ence ap-proach, diffi-cult to gauge effectivity

England	Substitute alternative product to Metaldehyde	Ecosystem services' approach involving payment to farmers for product substitution away from metaldehyde has been used. In these areas AW's "Slug It Out" campaign in 2015 secured 100% farmer agreement on over 7,600ha to switch to an alternative method of slug control including ferric phosphate. Water quality has been monitored. In a partnerships with Anglian Water(AW), UoL is conductiong a farmer survey to review the effectiveness/ sustainability providing an alternative product (Ferric Phosphate) to Metaldehyde. Farmers receive a finacial incentives for:- a) Joining the scheme b) Price difference in product price (ferric phosphate is more expensive) c) Bonus if the whole catchment is below the WFD individual pesticide level (0.1µg/l)	Reduction of input thorugh behaviour change Substitution for alternative product	?	?	?	?	+++	Unknown	Unknown	Social science approach, difficult to gauge effectivity

England	limited intervention (control) Metaldehyde best practices	Limited intervention (control) – using the Cringle Brook catchment and historic information. This is the control area, but as part of the H2020 project UoL in conjunction with AW and other support networks are developing a MAP in this area with previous minimum intervention for Metaldehyde best practice. We will monitor the interim progress of the Map as a new process for change.	Reduction of input through behaviour change. Innovative approaches to reduce Metaldehyde use and/or movement to water course	?	?	?	?	?	Unknown	Unknown	Social science approach, difficult to gauge effectivity
Portugal	Control of input through management system aproaches.	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	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	?	+++	+	+++	+++	Decreases energy costs	No	

		can by or dispose in the area they have available.	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.								
Denmark	Legal measures.	Farmers cannot use pesticides which will exceed the treshold of 0,1 µg / l.	Substitution of contaminant input	GW	+++	+	+++	+++	No	No	
Denmark	Economic measure	Variable tax on different pesticides depending on their impact on the environment	Reducing the application of the worst pesticides	GW	+++	++	+++	+++	Environmental effects and human health	High costs	
Denmark	IPM, precision farming and timing	Spatial and temporal targeted nitrate and pesticides application	Reduction and application of the most effective legal pesticides in minimal amounts	GW	+++	+	?	++	Decreases GHG emissions	Labour consuming	
Denmark	Restriction in farming system	Agreement on no pesticide use and reduction of nitrogen leaching	Reduction	GW	+++	++++	+	+	Better water quality	Decreases crop yield	one-off payment

Northern Ireland	Installation of a pesticide sprayer loading area and wash down area	Construction of a concrete pesticide loading, and/or washing area. This item could include; a new bunded concrete loading area, holding tanks, fixed pumps and pipework for removing washings from the holding tank. Site preparation and excavation is included	Source Reduction	SW	?	?	?	?	No	No	
Northern Ireland	Biobeds	A biobed is a lined pit in the ground filled with a mixture of peat free compost, straw and soil turfed over. This provides an area where pesticides can be mixed and handled	Source Reduction	SW	?	?	?	?	No	No	
Northern Ireland	Biofilters	The biofilter system is made up of three Intermediate Bulk Containers (IBCs) in sequence which are filled with biomix. Washings from the pesticide sprayer loading area are pumped into the uppermost tank and filtered through the biomix as it moves through the tanks. The treated washings are then pumped to an irrigation area.	Source Reduction	SW	?	?	?	?	No	No	

Northern Ireland	Pesticide storage unit	The Industry standard Pesticide Storage Cabinet will be resistant to fire, capable of retaining leakages/spillage, dry, frost-free, adequately ventilated and secure against unauthorised access.	Source Reduction	SW	?	?	?	?	No	No	
Northern Ireland	Contractor for Weed Wiping to replace MCPA Use	Using weed wipers to manage grassland weeds like rushes reduces spray drift, uses less pesticide and is applied directly to the plant. Weed wipers will be used with glyphosate which potentially has less impact on water quality than MCPA. Glyphosate translocates through the plant meaning it kills the weed at the root, unlike MCPA	Source Reduction	SW	?	?	?	?	No	No	
Slovenia	Buffer zones	A safe zone used to reduce N entering surface waters and modify pollution pathways.	a) Reduction / substitution of contaminant input; b) Modification of pollution pathway	SW	?	?	+	+	No	Decreases crop yield	
Slovenia	Prohibition of problematic PPP	Prohibits the use for the health and environment harmful PPPs. Has to be scientificly confirmed. In use all over the country	a) Reduction / substitution of contaminant input	GW/SW	?	?	+++	+++	Increases biodiversity	No	Pesticides concentrations have dropped after inplementaion of this measure

		with stricter list of prohibited PPP on drinking water protection zones.									in all groundwaters

ANNEX 2. QUESTIONNAIRE NITRATE MEASURES

Country:	Measure category	Short description	Full description	Mechanisms	Measure target Ground water (GW) Surface water (SW)	Effectivenes	Costs	Applicability	Adoptability	Other benefits	Dis-advantages	Additional comments
Germany	Application method	Demonstration/use of innovative techniques concerning farm manure application (while avoiding soil compaction)	Improved information transfer and promoting of innovative techniques to enable efficient application of farm manure	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		*	+	++	++	Decreases GHG emissions	No	
Denmark	Application method	IPM, precision farming and timing	Spatial and temporal targeted nitrate	Reduction and application of	GW	+++	+	?	++	Decreases GHG emissions	Labour consuming	

			and pesticides application	the most effective legal pesticides in minimal amounts								
Netherlands	Buffer strips	undersow grass between rows of maize	Undersow Italian Ryegrass in between the rows of maize	Italian rye catches up N that is released in soil after the harvest of maize	GW	++	+	++	++	Landscape diversity; higher SOM	no, but it is not succesfull on all fields	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)
France	Buffer strips	buffer stip, grass strip	buffer stip, grass strip	use of buffer strip to slow down water (and solute) transfer to surface water	SW	++	++	++	+	Landscape diversity	Yes, decreases crop yield	
Greece	Buffer strips	Isolation of well waters from unconfined aquifers	Areas with high geologically nitrate content couldlad to high nitrate content of their waters through leaching process.	High nitrate concentrations of the drinking water could be decreased by isolating the well waters from existing unconfined aquifers.	GW/SW	?	?	?	?	Unknown	Unknown	
Greece	Buffer strips	Cultivation techniques and constructions around fields	cultivation techniques	construction of stable uncultivated strips at least 1 m near water bodies and trenches, plant cover in sloping parcels to protect er-	GW/SW	++	+	?	+	Landscape diversity	Unknown	

				rosion sensitive terrain during rainy season and soil								
Romania	Buffer strips	grass strips between fruit trees rows in orchards and vineyard rows	The interval between trees or vineyard rows is sowed with gramineous grass and leguminous crops which are resistant to agricultural equipments traffic	The soil is covered and the soil physical qualiy is maintained at an optimum level. Nitrogen is fixed in the gramineous grass and leguminous crops. The harvested biomass is used as mulch on trees and vineyard rows, supplying the soil with nitrogen.	GW/SW	+++	+++	+++	++	Decreases GHG emissions; higher SOM; higher NUE	No	
Slovenia	Buffer strips	Buffer zones	A safe zone used to reduce N entering surface waters and modify pollution pathways.	a) Reduction / substitution of contaminant input; b) Modification of pollution pathway	SW	?	?	+	+	No	Yes, decreases crop yield	
Denmark	Cover crop	Cover crops	Between 10 - 35 % of the farm area must be sowed with cover crops	Modification of pollution pathway	GW	+++	+++	++	+++	No	cost	The cost varies based on the farm types
Greece	Cover crop	Cover crop during autumn-winter	Cover crop during autumn-winter	soil cultivation with fall-winter crops wherever possible, early sowing (15-30	GW/SW	?	?	?	?	Unknown	Unknown	

				September), cover crops should be existed even with non-cultivated plants								
Romania	Cover crop	crop rotation including cover crops	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	Nitrogen is fixed during the periods with high nitrogen leaching. In this way nitrogen is available for the next crop	GW/SW	++	+	+++	++	Decreases GHG emissions; higher SOM; higher NUE	No	Usually this measure is applied on flat fields for wind erosion protection and on slopes for soil protection against water erosion
Slovenia	Cover crop	Cover crops	Protects soil from weather impacts. Plants prevent erosion and nutrient leaching. They can act as catch-crops and save N in plants biomass.	a) Reduction / substitution of contaminant input	GW/SW	?	?	+	+	Positive for soil physical properties, higher SOM	No	
Slovenia	Cover crop	Plants for green manure	Protects soil from weather impacts. Plants prevent erosion and nutrient leaching. They can act as catch-crops and save N in	a) Reduction / substitution of contaminant input	GW/SW	?	?	+	+	Higher SOM	No	

			plants biomass.									
Norway	Dose	Reduced (optimal) fertilization	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.	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.	SW	+	+	+++	+++	Can increase yield if done in a precision-farming manner. Can reduce costs, in particular if commercial fertilisers are being used.	None	

Portugal	Dose	Control of input through management system aproaches.	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.	This is a management system approach, where a documental management system has to be set in 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.		+++	+	+++	+++	Decreases energy costs, there is a more judicious use of production factors	No	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 additon, there are controls to the amount of mineral and organic fertilizers. A document regist has to be kept to be monitored by external experts if needed.

Germany	Dose	Sampling-based (and model-based) fertilization planning	Soil and plant 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 anaysis, humus analysis, analysis of temporal development of nitrate/chlorophyll contents in plant sap, ...	• increase of yield (higher nutrient export from the field) • decrease of total nitrate/phosphate applied • improved timing of fertilization		*	+	++	++	Unknown	No	comment concerning adoptability: depends on respective crop (rotation)
Denmark	Dose	Restriction in farming system	Agreement on no pesticide use and reduction of nitrogen leaching	Reduction	GW	+++	+++	+	+		Decrease in crop yield, causes problems for the management of the farm	Benefits for the water quality but none for the farmers

Greece	Dose	Application time	fertilizer application time and quantity	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, fertilzation avoidance on frozen or snow-covered soils, application of legume cover crops on sloping land, fertilization over small distances using spreader machine, avoidance of fertlization during strong winds, use of fertilizers in precise quantities and avoid of spreading in uncultivated land	GW/SW	?	?	?	?	Unknown	Unknown	

Greece	Dose	Manure and N-fertilizer application management	nitrogen fertilizers application	manure total nitrogen should not exceed the amount of 170 KgN/Ha in vegetation covered soil and 150 KgN/Ha in uncovered soil, N fertilization and application of farm animal wastes during rainy season is forbiden with the exception of basic autumn and winter crop N fertilization, apply of N fertilizer on water-saturated soils is forbiden, fertilization outside of cultivated area is forbiden	GW	++	?	++	++	Unknown	Unknown	
Slovenia	Dose	Limit on N input	Limits N input from organic fertlisers all over Slovenia to 170 kg/ha and on narrowest water protection zones to 140 from composted organic manure.	a) Reduction / substitution of contaminant input	GW/SW	?	?	+++	+++	Decreases NH3 emissions	No	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 effectivnes is nitrate below 50 mg/l in groudwater and falling. Costs were never estimated and impacts of measure examided and reported only to the level of state monitoring results. measure is highly applicable and adoptable as it is obligatory for all farmers.
Greece	Grasland management	Management of meadows and grassland	Management of meadows and grassland	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	GW/SW	?	?	?	?	Unknown	Unknown	

Greece	Improved storage	Storage of fertilizer	Storage and transport of inorganic fertilizers	fertilizers should be stored in strong bags at least 50 meters away from surface waters, preventative meaasures should be taken to avoid accidents and risk of spreading during transport	GW/SW	?	?	?	?	Unknown	Unknown	
Germany	Outreach	Information events/discussions/ field days concerning relevant topics	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	• 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 north-west(farm manure surplus region)) • increased yields (higher nutrient export from the field) ---> reduced amounts of nitrate/phosphate being		*	+	++	++	Unknown	No	

			("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, ...? ")	lost to the environment								

Norway	Reduced tillage	Reduced tillage	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.	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:	SW	++	++	+++	++	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	Unknown	Disadvantages or not; is often a consequence of how it is being done in practice.
Netherlands	Rotation	crop rotation grass and maize	Crop rotation in which grass and maize alternate	Soil conditionn and soil organic matter content is preserved (avoid contious growing of maize on one parcel) which is favourable for	GW	++	+	++	++	higher NUE, higher crop yields, less purchase of concentrates, lower pesticides use	No	When fields are located far from the buildings, farmers don't like to destine the fields for grassland (high

				retention of nitrate in soil								transport costs/labour associated with grass management)
Slovenia	Rotation	Five year crop rotation	Used to improve soil health. One of the positive effecte is also reduced use of N - inroduction of legumes crops (beans/peas/clovers).	a) Reduction / substitution of contaminant input	GW/SW	?	?	++	++	positive for soil health, reduces plant pests and disease	No	Data to evalute effectivness or costs are not available. Detailed applicabilty and adoptabilty can be retrived from national agricultural payments database.
Netherlands	Timing	(climate adaptive) timing manure application	Optimizing the timing of manure application (not in autumn)	Manure N is applied early in the growing seasons to synchronize uptake of N by crops and release in soil	GW	++	++	+++	++	higher NUE, higher crop yields, less purchase of concentrates	big manure storage required to keep manure in winter	
Denmark	Timing	IPM, precision farming and timing	Spatial and temporal targeted nitrate and pesticides application	Reduction and application of the most effective legal pesticides in minimal amounts	GW	+++	+	?	++	Decreases GHG emissions	Labour consuming	
Denmark	Timing	Legal measures.	Manure is not allowed to be used in the autumn. Combined with quotes on nitrogen application and high utilisation	Reduction of nitrate leaching	GW	+++	+	+++	+++	Decreases GHG emissions; lower energy consumption	Increased management requirements	

			of organic manure.									
Greece	Timing	Application time	fertilizer application time and quantity	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, fertilzation avoidance on frozen or snow-covered soils, application of legume cover crops on sloping land, fertilization over small distances using spreader machine, avoidance of fertlization during strong winds, use of fertilizers in precise quantities and avoid of spreading in uncultivated land	GW/SW	?	?	?	?	Unknown	Unknown	

Greece	Timing	wheat split fertilization	nitrogen management for Wheat cultivation	split fertilization to a number of doses for each field and rational management of irrigation water for each field	GW	++	+	++	++	Increased NUE	Unknown	Discouragement of crop production is also suggested in the regions where pollution risk is extremely high
Romania	Timing	manure application at proper time	Animal manure is applied and incorported 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	Manure is properly managed in terms of storage and soil application as fertilizer.	GW/SW	++	+++	++	+++	Decreasees GHG emissions; increases NUE, SOM	Cost with manure management (storage, transport, application and incorporation	The animal manure applied in autumn usually is partially decomposed, while in spring, usually, totally decomposed animal manure is applied.
Slovenia	Timing	Timinig manure application	Sets time limits for the application of organic and mineral fertlisers.	a) Reduction / substitution of contaminant input	GW/SW	?	?	+++	+++	Decreaes NH3 emissions	No	
Norway	Waterways	Grass covered waterways	Grass covered waterways Relatively small areas on a field can account for a very large part of the soil erosion (and associated nutrient losses),	The measure of grass covered waterways, which involves sowing grass in water-bearing and erosion-induced drops, is a very im-	SW	+++	++++	+	+	Landscape diversity, lowers soil erosion	None	Reduces the amount of cropland.

			especially when a large amount of surface water seeks it way to lower and narrower parts of the fields .	portant measure that is given high priority. Grass covered waterways are established in droughts where the water digs.								
Germany	Whole-farm	Farm-holistic fertilization planning with generic software	Farm-holistic planing (including economic scenarios) to better estimate the amount of fertilizer needed	• 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)		*	+	+++	+++	yes, potentially various	No	
Germany	Whole-farm	Calculation of nutrient balances (different scenarios)	Calculation of nutrient balances both field-based and farm-based	• decrease of total nitrate/phosphate of nutrients applied • identification of critical factors (such as crops, techniques, ..)		*	+	+++	+++	Unknown	No	comment concerning adoptability: farmers are legally obliged to do so