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

FAIRWAY REPORT series

Review of measures to decrease pesticide pollution of drinking water

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SUMMARY

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

The overall objective of the EU-project FAIRWAY is

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

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

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

As input for the review a data search was done to find literature and sources for the review. This data is found by a systematic search through online databases and via local searches by partners of the FAIRWAY project throughout Europe, yielding both journal articles and reports of institutes and universities. In addition a survey was done among the partners and case studies to investigate existing measures and their performance. All these measures were uniformly and concisely described and are presented in Annex 1 of this report.

Pesticides are used at different rates in Europe and around the world, with as general rule that more intensive agriculture will also use more pesticide per ha. In the EU the average use is around 3.0 kg/ha per year. Groundwater and rivers are monitored in the EU to control the water quality and also pesticide levels are checked.

Measures can be categorized into either source-based or pathway-based measures. Each pathway (leaching to ground water, or overland transport to surface water) has its own specific and effective measures. Besides that spray drift forms a separate pathway to surface

water. Preventing diffuse pollution from agriculture can be done in both ways. Chapter 4 gives an overview of the existing pathways and transport mechanism of pesticides to water resources. The driving factors for pesticide pollution are in the first place water facilitated transport through or over the soil. Secondly also erosion of sediment can cause transport, when sorbed particles are transported. Areal transport occurs with spray drift during application, and is a threat for surface water quality.

The review consists of a qualitative review of described and tested agricultural measures in scientific literature and in the case studies (chapter 5), and a quantitative analysis of the effectiveness of these measures to reduce pollution of ground and surface water resources (chapter 6). The qualitative review gives an overview of the available measures and evaluates them based on expert opinions from the case studies and peer-reviewed papers. Based on the data collected through the online and local search procedure a quantitative analysis was done to calculate the overall effectiveness of the measures. A total of 112 experimental comparisons have been examined. Most measures were on average effective. However tillage methods did not show a positive effect in terms of reducing pesticide pollution.

Conventional well known measures like vegetated buffers, drift reduction technology and Integrated Pest Management (IPM) are shown to be effective measures with a high potential to reduce pesticide pollution. Buffers are the main effective measure to reduce surface water pollution by overland runoff. Physical agronomical measures are less effective to reduce leaching to groundwater, but IPM which includes reduction of the pesticide input is most effective in this case. These results, described in literature are confirmed by the quantitative analysis of multiple studies we performed in this report. In addition, the analysis showed that tillage methods have a very high variation in terms of their effect on pollution, which can even be counter effective, i.e. increasing the risk of pollution to ground or surface water. Therefore, tillage methods are not regarded as an effective approach to reduce pollution, as concluded by Alletto et al. (2010).

For all measures, the local design and pedo-climatic conditions are of major importance to be effective. A quantified relation between pedo-climatic conditions and measure design or effectiveness is still lacking and would improve the applicability of these measures.

Measures implemented in the case studies of the FAIRWAY project included the implementation of biobeds or bio filters for point source pollution and the use of policy and management changes on higher levels. The biobeds/filters did show good results in the case study evaluation and the quantitative analysis, however, further data on their effectiveness is scarce. Policy and community approaches to pesticide use and pollution are not reviewed in this report, but they can affect the amount of pesticide used to a large extent and thus affect the risk of pollution.

Identifying the most promising measures to reduce pollution of drinking water sources, requires increased details on pedo-climatic zones. Moreover costs, applicability and adoptability are of major importance to identify promising measures. This will be object of further research during the FAIRWAY project.

1. INTRODUCTION

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

The use of pesticides in agriculture increased rapidly during the second half of the 20th century. A side effect of this increased use is the dispersion of unwanted substances in the environment, including drinking water sources, and sometimes also in food. Several studies on food safety reported mixtures of pesticide residues in food (Jardim & Caldas, 2012; Szpyrka, 2015) and even in mother milk (Ennaceur, Gandoura, & Driss, 2007; Honeycutt & Rowlands, 2014; Liu, Pan, & Li, 2015). The side effects of intensive pesticide application on water quality are well studied, and international monitoring programs of water quality show that pesticides and antibiotics are present in surface and groundwater bodies with changing concentrations over the years (Folch, Carles-Brangarı, & Carrera, 2016; Hildebrandt, Guillamón, Lacorte, Tauler, & Barceló, 2008; Larson, Capel, & Majewski, 1997; Wang et al., 2016).

Within the EU a precautionary boundary is set at (0.1µg/L) for contamination of water sources with pesticides to prevent any harmful effects on 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 on safety by the EFSA (European Food Safety Agency).

However, there is also a debate about the safety of allowed pesticides, with glyphosate as a recent example (Samsel & Seneff, 2013). Safety not only in terms of possible health effect, but also regarding the potential of pesticides to pollute off-site locations including ground and surface waters. For example glyphosate is regarded relatively safe environmentally, but recent investigations indicate possible leaching and toxicity problems with its use (Mesnage & Antoniou, 2017). Even though the use of glyphosate may be considered environmentally neutral, toxicological problems still persist with the additives (surfactants) that are needed for glyphosate to penetrate plant cuticles.

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, and pollution in general, by pesticides 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 and the Groundwater Directive require Member States to protect drinking water resources against pesticide 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 pesticides (0.1 µg/L) are still exceeded in some areas with vulnerable water resources (Eurostat, 2011). Diffuse pollution of pesticides from agriculture is a main obstacle to meeting the Drinking Water Directive targets.

Soil or field conditions and pesticides characteristics are the main factors defining the potential pollution of drinking water by pesticides. If a pesticides is not transported anywhere after application there is no risk of pollution of drinking water. However, combined with water flow dynamics, infiltration and runoff after rainfall events, transport is often possible. Several reviews on pesticide pathways to ground- and surface water exist (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). Different soils and climatic conditions influence the most occurring pathways on a field (Borggaard & Gimsing, 2008; Reichenberger, Bach, Skitschak, & Frede, 2007). For example flat peat soils will have a much higher leaching risk than a Mediterranean vineyard on a steep slope, where overland transport is the main transport route. Besides the pathways, the characteristics of the applied pesticide also have a major effect on potential pollution. Main identified characteristics are the solubility, sorbtivity and half-life time of the pesticides (Rittenburg et al., 2015; Wauchope, 1978).These influence the availability for transport to water.

To reduce the transport of pesticides from agricultural fields, and thereby pollution of drinking water, various measures and good agricultural practices have been developed and implemented in practice at farm level in the EU. Reviews focussing 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). 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 pesticides 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 the 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.

The overall objective of the FAIRWAY project is to review current approaches and measures for protection of drinking water resources against pollution caused by nitrate and pesticides from
agriculture in the EU, and to identify and further develop innovative measures and governance approaches for a more effective drinking water protection (https://www.fairway-project.eu/). The project started in June 2016 and will last till June 2020. FAIRWAY has 8 work packages and 13 case-study sites in 11 countries across the EU. The objective of work package 4 is to review and assess measures and practices aimed at preventing and decreasing nitrate and pesticides pollution of drinking water.

This report reviews and assess measures and practices to decrease pesticides pollution of drinking water. The work builds on insights and results gathered in EU-wide and global projects and studies. It provides an overview and assessment of the effectiveness and efficiency of measures and practices aimed at decreasing pesticides pollution of drinking water reservoirs. The first chapters provide a qualitative overview of sources and factors that contribute to pesticides pollution of groundwater and surface waters, as a basis for understanding the measures aimed at decreasing pesticides pollution. Chapters 5 and 6 then provide a review and quantitative analyses of the effectiveness of the measures that have been tested in the field experimentally. This report is deliverable D4.2 of FAIRWAY (Review report on effective pesticides pollution mitigation measures and practices). It complements the related deliverable D4.1 (Review report on effective nitrates leaching mitigation measures and practices).

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

2. REVIEW METHODOLOGY

This chapter presents a brief overview of the process and procedures related to the execution of the review. A total of 16 institutions across EU-28 have been involved in the review process.

2.1 LITERATURE REVIEW PROCEDURES

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

The review presented in this report focusses on source-based measures and pathway-based measures, receptor-based measure are not anymore related to agricultural management and practises, so outside the scope of this review. At the start of the review a protocol was written and discussed by all partners involved in the review. The purpose of the protocol was 'to provide guidance for a uniform, effective and efficient literature review and assessment of measures aimed at decreasing pollution of drinking water resources by pesticides'. Two types of reviews were made (i) a qualitative review of measures, practices and factors that affect pesticide pollution of groundwater and surface waters, and (ii) a quantitative review of the effectiveness and efficiency of measures, based on experimental studies in the field.

The qualitative review focussed on the processes and factors that control the pollution of groundwater and surface waters with pesticides from agricultural sources. This review yielded an overview of controlling factors and a qualitative overview of possible measures to reduce pesticide pollution of groundwater and surface waters. The encountered measures were characterized using a common format (Table 1).

Based on the qualitative review, a tentative list of key measures was established, with the objective to collect quantitative data and information about these measures for a quantitative assessment. The subsequent quantitative review provided the basis for a meta-analysis of the effectiveness and efficiency of measures, and for the identification of most promising measures. 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 study should be about an measure to decrease pesticide transport/pollution, (3) the study must be an experiment, with quantitative data presented in the source, so a meta-analysis is possible. For the online systematic search three online databases were used; Scopus, Ovid and Web of Science. The following search formula was used in these databases:

> **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*)

This resulted in 180 unique records. In Web of Science the formula was slightly different, 'IN ABSTRACT' was changed for 'TOPIC' which also includes title and keywords, this is done because 'IN ABSTRACT' is not available.

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 pesticide leaching and surface runoff has been conducted before the 1990s and 2000s when it was still common to publish the results in reports and documents. These reports and documents quite often have not been digitalized and made available to the international scientific audience and as such are not traced by the search machines of Google Scholar and Scopus.

Data and results of reviewed reports and articles were collected in Excel spreadsheets in a uniform manner. The Excell spreadsheets were subsequently transferred to a flat csv database for statistical analyses (see section 2.1).

Table 1: Format for the description of measures of the so-called longlist.

Name of the measure	One sentence
Description	Brief characterization of the measure in maximal three sentences; what is (are) the <u>action(s)</u> of the land manager/farmer/citizen
Mode of action	Brief description of the <u>mechanism(s)</u> of the measure in maximum 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
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, contributes to landscape diversity • No • Unknown • Other: please specify
Disadvantages (other than implementation costs and labour)	Does the measure contribute to negative side-effects: select one or more answers out of four options: • Yes, decreases crop yield • Yes, decreases crop quality • Yes, decreases soil quality and biodiversity • Yes, contributes to (more) pest and diseases • No • Unknown
References	Provide up to three key literature references

The flowchart in Figure 1 shows the general lay-out of the protocol of the review. Each block represents a set of questions, as described here further below:

(i) Contributor: information on person(s) who did the data collection
(ii) Reference: Two option available, 1) peer reviewed articles, and 2) book or report. This last category includes so-called ‘grey literature’.
(iii) Number of measures: the number of measures described in the literature source.
(iv) Pollution type: Nitrate or pesticides or both.
(v) General information: Data about the location, land use, soil type etc. This information is used to categorize and specify the results (and effectiveness of the measure).
(vi) Control treatment: Describe the characteristics of the reference or control situation. This information is essential for estimating the effectiveness and efficiency of the measure(s).
(vii) Measure: Describe briefly the characteristics of the tested measure.

(viii) Effectiveness: Describe the test results, in terms of reduced leaching and/or loading of the pollutant.

(ix) Economic cost: Describe the operational (running) economic cost of the tested measure, in euro per ha per year, compared to the control (reference) treatment.

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

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

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

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

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

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

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

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

2.1. Analysis of the effect size of measures

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

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

$$RR = Y_T/Y_R$$

where *RR* is the response ratio (dimensionless; or percentage), Y_T is the measured result of the treatment measure, and Y_R is the measured result of the reference treatment. The latter is usually current practice or conventional practice. The ratio may vary from 0 to more than 1; a value smaller than 1 indicates that the treatment measure decreases the pesticide transport relative to the reference treatment. A ratio of 1 means no effect. Instead of a relative comparison of pesticide losses, the response ratio was sometimes derived from a comparison of pesticide concentration in waterbodies or from the content of pesticides in the soil between treatments, depending on the availability of the data in the reviewed publications.

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

$$ES = \frac{Y_\mathrm{T} - Y_\mathrm{C}}{Y_\mathrm{C}} = \frac{Y_\mathrm{T}}{Y_\mathrm{C}} - 1$$

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

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

$$L = \ln\left[\frac{Y_\mathrm{T}}{Y_\mathrm{C}}\right]$$

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

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

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

In this report, we estimated and used RR (see chapter 6).

The data as collected through the structured data review from the excel sheets was processed in R and also manually to obtain a good quality uniform database. The main focus during the processing was on homogenizing units of measurement and setting the right reference treatment. This was done to optimize the calculation of the response ratio for each treatment in each study.

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

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

It was intended to analyse the efficiency of the measures as a combination of effectiveness and costs. However the amount of data included in the database about costs of application and maintenance were too scarce to make any general calculations. This will be taken into account during further research analysis.

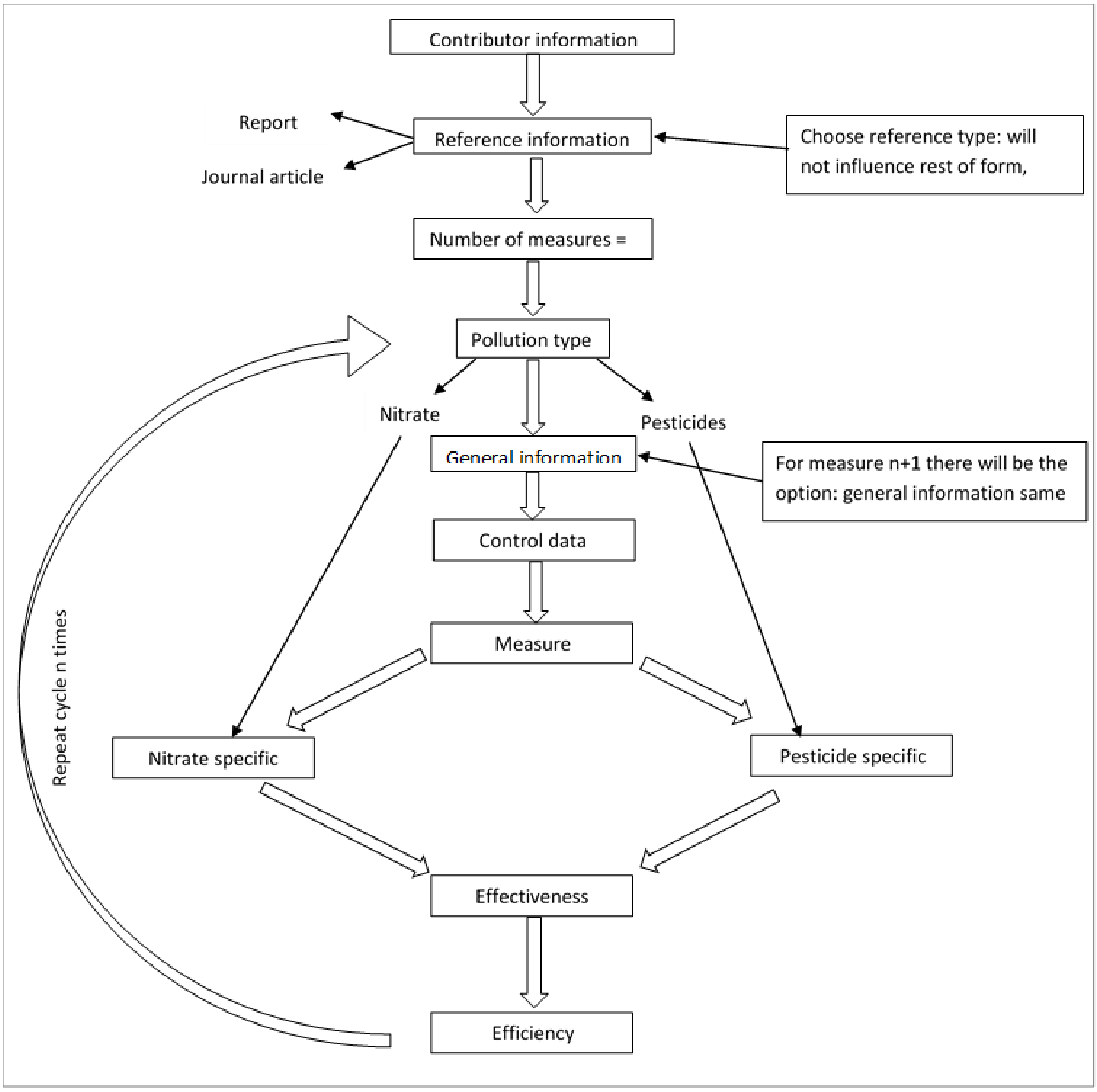


Figure 1: Flowchart of the quantitative literature review in FAIRWAY WP 4 (results for nitrate measures are presented in a separate report).

3. Agriculture and pesticides use in the EU-28 and worldwide

Agriculture is a main source of pesticides pollution of the aquatic system, both groundwater and surface water. This is related to the facts that (i) agricultural land covers roughly 40% of the total land area of EU-28, equivalent to 174 million ha in 2013, (ii) agriculture is a large user of pesticides for producing food and feed. The applied pesticides can be transported to water bodies via leaching and surface runoff. The loss of pesticides from agriculture to groundwater and surface waters depends on farming system, management, soil type, geomorphology, and climate. These factors define both (i) the sources of pesticide pollution and (ii) the transport pathways (e.g., downward leaching to groundwater or overland flow (surface run-off), erosion, and subsoil lateral leaching to surface waters).

This chapter provides a brief overview of the sources of pesticide pollution in agriculture. A summary of farming systems and of management in EU-28 is presented, as these define the use of pesticides in agriculture.

3.1 Farming systems and management in the EU

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

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

Table 2: Agricultural holdings by farm type in EU-28 in 2013 (Eurostat, 2015a)

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

[1]) Granivorous literally means 'feeding on grains and seeds'. In practices it means farms with monogastric animals, mainly pigs and poultry, where often a significant fraction of the feed is imported.

[2]) *Mixed crop-livestock holding have neither livestock nor crop production as dominant activity; an activity is called dominant if it provides at least two-thirds of the production of an agricultural holding.*

The type of farm and the management on the farm both influence the potential transport of pesticides to drinking water resources. Pesticides are predominantly used in specialist crop production systems, which will therefore get most attention in the further review.

Management is often considered to be the fourth production factor, next to land, labour and capital. It is considered an important factor for the pollution pressure of pesticides on drinking water resources. Management is usually defined as 'a set of activities to achieve objectives'. It includes a sequence (cycle) of (i) analysis of the current situation and of possible options, (ii) decision making, (iii) planning of the activities, (iv) execution, (v) monitoring, and (vi) verification and control of achievements. These management activities relate to different components of the farm.

The management affects inputs, transport and output of pesticides. Following the division into crop farms and animal farms, a distinction is made between crop management and livestock management, where in the case of pesticides the main focus will be on the crop management, because pesticides are used most for crops and crop protection.

Crop management includes:

- (i) crop rotation aspects, e.g. crop sequence, use of cover crops and under growth, use of legumes, use of buffer zones.
- (ii) soil cultivation aspects, e.g., conventional (mouldboard) ploughing or minimum tillage or zero tillage.
- (iii) nutrient management, e.g., use of soil fertility analyses, organic farming approaches, use of animal manures without low emission techniques, use of animal manures with low-emission techniques, use of fertilizers, use of GPS controlled fertilizer application.
- (iv) pest management, e.g., use of chemical control and/or biological control measures.
- (v) water management (irrigation and drainage aspects), i.e., no irrigation, sprinkler irrigation, flood irrigation, drip irrigation and/or fertigation.

Crop rotations are important for the sustainability of agricultural system (Mudgal et al., 2010). However, empirical data are scarce about crop rotations, because there is little or no monitoring of crop rotations in EU countries (Lorenz, Fürst, & Thiel, 2013; Schönhart, Schmid, & Schneider, 2011). Crop rotations can vary from no rotation monoculture, (one crop only) up to six and even beyond. Typical four year crop rotations in Western Europe may consist of "winter wheat-sugar beet-winter wheat-potato", or "winter wheat-silage maize-winter wheat-sugar beet". A typical three year rotation may consist of "winter wheat-winter barley-sugar beet/silage maize" or "winter wheat-winter wheat-sugar beet". A typical two year rotation may consist of "winter wheat-silage maize/sugar beet" (Leteinturier, Herman, Longueville, Quintin, & Oger, 2006).

The crop statistics from Eurostat distinguish 17 categories for cereals and 29 for other main crops, 40 categories for vegetables, 41 for permanent crops (Eurostat 2015). Within each crop large differences can exist. Cereals can be managed intensively, such as in northern France, Germany and the United Kingdom, but can also be important for nature conservation such as in parts of Spain. The pesticide usage differ greatly between these crops and cultivation intensities.

3.2 USE OF PESTICIDES IN THE EU

The use of pesticides within the EU is not measured on the field or at farm level. So a estimation can be made based on the sales values for each country. ‘Fungicides and Bactericides’ and ‘Herbicides, haulm destructors and moss killer’ are the two groups of pesticides that are sold most throughout the EU (figure 2). France, Germany, Italy and Spain are the largest agricultural producers in the EU and also use the most pesticides in total volumes. These countries use 3 up to 7 kg/ha pesticides averaged for all the agricultural land. The average pesticide use in the EU was 2.9 kg/ha in 2015, with the Netherlands, Belgium[2] and Italy the most intensive users. They applied 9.3, 7.7[2] and 7.0 kg/ha respectively (FAOSTAT, 2018). Figure 2 shows data for 16 EU countries, data for other countries is not public available.

Compared with 2011 a slight increase (1.6%) in total amount of pesticides used is seen in 2016. However, large differences between countries exist. For example, Denmark reduced the pesticide sales by 50% between 2011 and 2016. This can be related to the pesticides tax increase that was introduced in 2013 (Ørum et al., 2018) A large part of the revenue from the pesticide tax is used for pesticide research programs in Denmark (Nielsen et al., 2011).

Sales of pesticides in 16 EU Member States, 2011 and 2016
(tonnes)

	Fungicides and bactericides		Herbicides. haulm destructors and moss killers		Insecticides and acaricides		Molluscicides		Plant growth regulators		Other plant protection products	
	2011	2016	2011	2016	2011	2016	2011	2016	2011	2016	2011	2016
Belgium	2 354	2 848	2 483	2 261	659	553	14	20	245	336	399	808
Denmark	639	407	4 420	1 910	46	42	4	34	173	188	3	8
Germany	10 525	12 141	17 955	15 038	875	15 463	255	232	3 123	3 871	11 123	144
Ireland	618	597	2 831	2 243	48	33	9	14	189	216	20	31
Greece	2 256	1 804	1 455	1 744	109	921	0	2	21	99	733	138
Spain	31 343	38 905	13 835	15 224	8 062	7 501	229	108	223	152	19 421	15 050
France	24 524	31 910	29 209	30 043	2 150	3 637	330	814	2 498	3 149	2 626	2 484
Italy	43 293	37 047	8 327	7 486	7 928	2 022	97	63	467	181	10 138	13 420
Hungary	2 997	3 835	3 668	4 580	522	842	2	6	224	192	1 135	309
Malta	95	84	6	6	3	3	1	0	0	0	24	23
Austria	1 550	2 007	1 505	1 281	242	936	33	11	59	78	58	48
Poland	6 081	7 534	12 408	12 693	991	1 481	12	0	1 593	2 180	689	562
Portugal	9 975	5 474	1 996	1 905	878	766	13	41	4	1	1 158	1 588
Romania	3 482	4 526	6 771	5 066	808	744	1	5	335	443	30	29
Slovenia	797	860	264	247	38	40	1	3	1	3	20	4
Slovakia	541	640	1 080	1 080	64	110	0	2	113	183	9	78

Source: Eurostat (online data code: aei_fm_salpest09)

eurostat

Figure 2: Sales of pesticides in 16 EU Member States, 2011 and 2016

The total pesticide sales provide a general insight for pesticides usage and potential pollution, because it does not take into account pesticide fate and specific pesticide properties. This is important to add because such factors are needed to make good long-term impact indications, also for potential pollution of drinking water sources.

3.3 MONITORING PESTICIDE RESIDUES IN DRINKING WATER IN THE EU

Both ground and surface water resources are monitored in the EU to ensure their quality and control pollution events. Because of the large number of different pesticides the monitoring data is still scarce and a higher density of monitoring points and tested substances is recommended.

[2] FAOSTAT does not contain data for 2015 for Belgium, so 2014 data is used.

Figure 3 shows the groundwater monitoring stations for 2010 and 2011. Several EU countries are not filled because of data restrictions. However when data is available groundwater monitoring showed that 7% of the groundwater monitoring stations measured an exceedance of the allowed levels for at least one pesticide. Atrazine and its metabolite are most frequently detected at too high levels (Eurostat, 2011). Pesticide concentrations in river water do exceed the accepted level often, but it depends a lot on the type of pesticide taken into account (see figure 4).

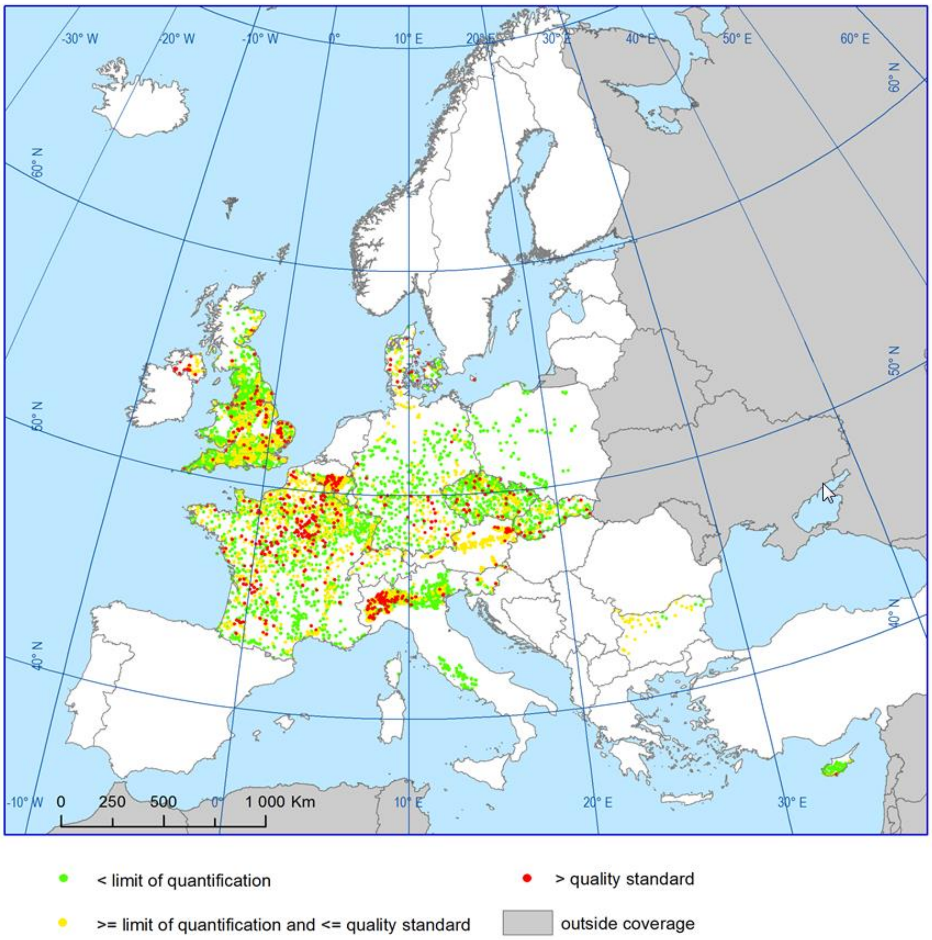


Figure 3: Groundwater monitoring points within the EU, with given quality of the measured groundwater, 2010 – 2011(European Environment Agency, WISE-SoE Groundwater).

It should be noted that higher concentrations are mainly measured in areas with intensive agricultural activities.

Beside groundwater also rivers are monitored for pollution. There are exceedances of the acceptable level, with as main group cyclodiene pesticides (figure 4). Commonly used herbicides like atrazine and alachlor did not exceed the maximum level in any case. Not al pesticides monitored and detected in rivers and groundwater are still applied, for example atrazine is banned in the EU in 2004. This also indicates that there can be a time gap between pesticide usage and actual water source pollution.

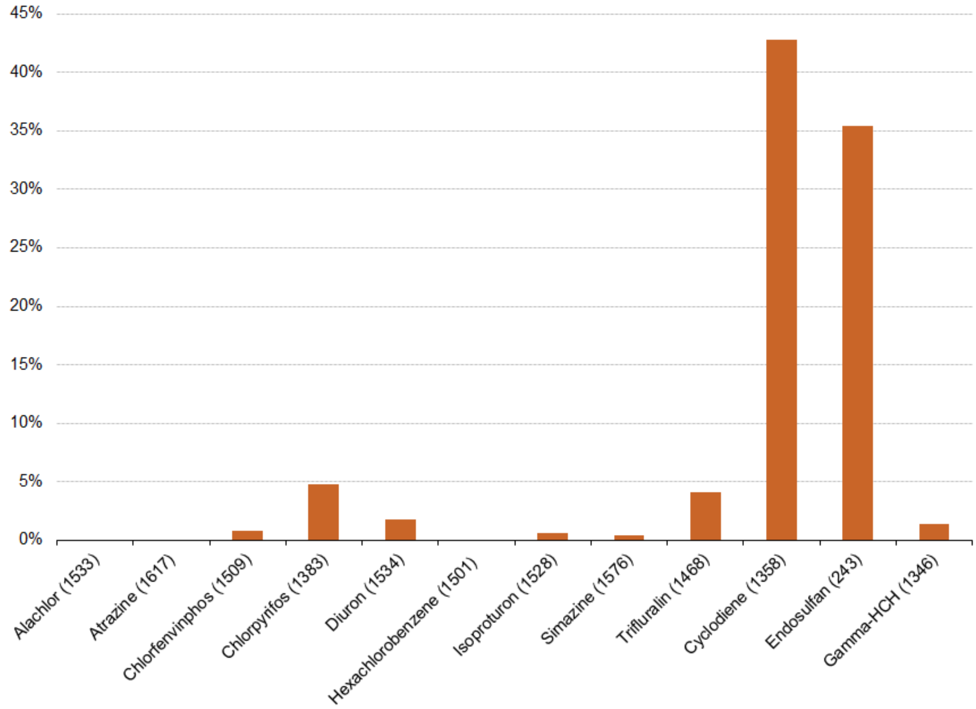


Figure 4: Percentage of river monitoring stations where the Environmental Quality Standard (EQS) (as annual average) for various pesticides is exceeded (%), 2009. Values between (..) are amount of included monitoring stations. Source: European Environment Agency, WISE-SoE Rivers.

3.4 PESTICIDE USE IN THE WORLD

This report, in line with the FAIRWAY project, focusses on the EU. However, pesticides are used worldwide. The amount and types used vary a lot between countries (figure 5), but published global pesticide use data are sparse (Benbrook, 2016). Countries with pesticide intensive cultivation use a much higher amount per hectare than countries with more arable crop production. Beside that improved technologies (precision farming) lower the amount of used pesticides.

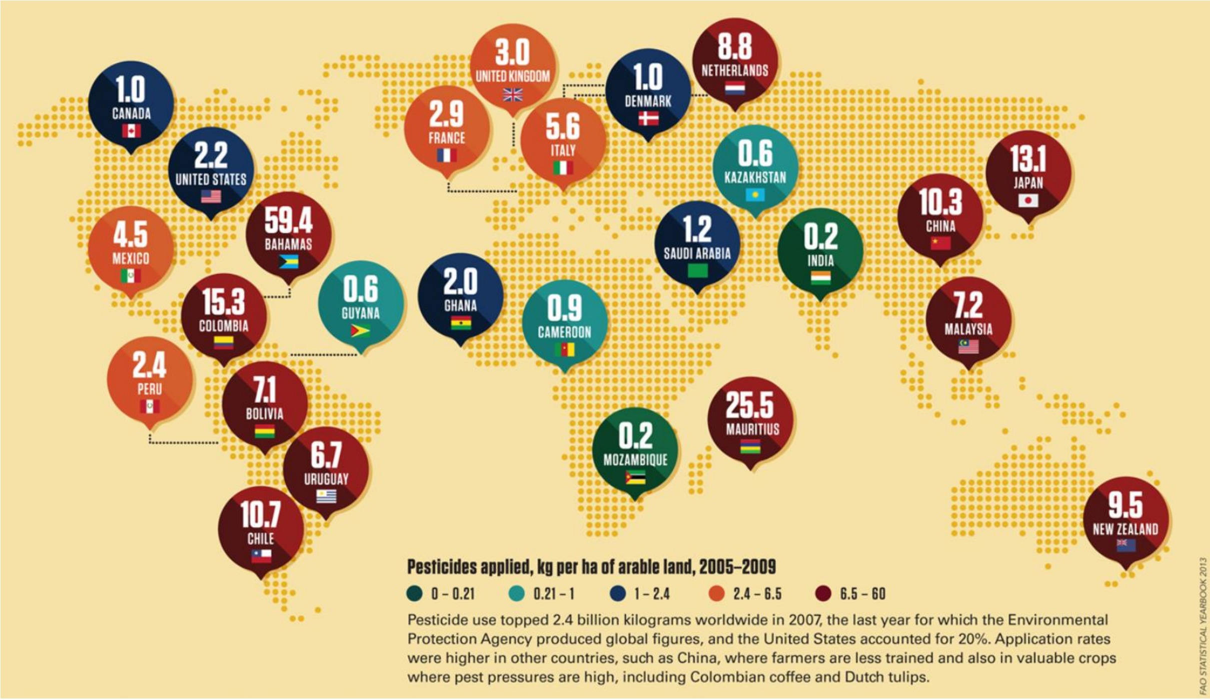


Figure 5: Application rates in kg/ha/y for agricultural countries all over the world (Science, 2013).

High usage rates are found in Latin America and East Asia, where besides the type of agriculture also the training level of farmers causes the higher average amount of pesticides applied.

As mentioned, global pesticide use data are scarce. Benbrook (2016) analyzed the trends in glyphosate use in the United States and globally. He showed that globally, the use of glyphosate has increased 15-fold since so-called ‘Roundup Ready’ genetically engineered glyphosate-tolerant crops were introduced in 1996. Benbrook (2016) concludes that no pesticide has come even remotely close to the intensive and widespread use of glyphosate in the US and likely in the world. Figure 6 shows the glyphosate use in the world between 1994 and 2014 and in the US between 1974 and 2014.

Table 4 Global agricultural and non-agricultural use of glyphosate: 1994 through 2014

	1994	1995	2000	2005	2010	2012	2014
Glyphosate use (1000 kg)	56,296	67,078	193,485	402,350	652,486	718,600	825,804
Agricultural	42,868	51,078	155,367	339,790	578,124	648,638	746,580
Non-agricultural	13,428	16,000	38,118	62,560	74,362	69,962	79,224
Glyphosate use (1000 lb)	124,112	147,882	426,561	887,030	1,438,485	1,584,242	1,820,585
Agricultural	94,508	112,608	342,525	749,108	1,274,546	1,430,002	1,645,927
Non-agricultural	29,604	35,274	84,036	137,922	163,940	154,240	174,658
Share agricultural (%)	76	76	80	84	89	90	90
Share non-agricultural (%)	24	24	20	16	11	10	10

Data in thousands of kilograms or pound of glyphosate active ingredient. See Additional file 1: Table S24 Table for details

Table 1 Glyphosate active ingredient use in the United States: 1974–2014

	1974	1982	1990	1995	2000	2005	2010	2012	2014
Glyphosate Use (1000 kg)	635	3538	5761	18,144	44,679	81,506	118,298	118,753	125,384
Agricultural	363	2268	3357	12,474	35,720	71,441	106,963	107,192	113,356
Non-agricultural	272	1270	2404	5670	8958	10,065	11,335	11,562	12,029
Glyphosate use (1000 lb)	1400	7800	12,700	40,000	98,500	179,690	260,804	261,807	276,425
Agricultural	800	5000	7400	27,500	78,750	157,500	235,814	236,318	249,906
Non-agricultural	600	2800	5300	12,500	19,750	22,190	24,989	25,489	26,519
Share agricultural (%)	57.1	64.1	58.3	68.8	79.9	87.7	90.4	90.3	90.4
Share non-agricultural (%)	42.9	35.9	41.7	31.3	20.1	12.3	9.6	9.7	9.6

Data in thousands of kilograms or pounds of glyphosate active ingredient. From the National Agriculture Statistical Service pesticide use data and the Environmental Protection Agency pesticide industry and use reports (1995, 1997, 1999, 2001, 2007). See Additional file 1: Table S18 for details

Figure 6: Global agricultural and non-agricultural use of glyphosate between 1994 and 2014 (upper table) and glyphosate active ingredient use in the United States from 1974-2014 (lower table). Source: Benbrook, 2016.

Worldwide, glyphosate use was modest in the 1970s, compared to the most heavily applied herbicides then on the market (e.g. atrazine, metolachlor) (Benbrook, 2016). Both worldwide as well as in the United States, the amount increased steadily until 1995, but when genetically engineered crops gained market share, the agricultural application of glyphosate rose rapidly; it increased 14.6-fold between 1995 and 2014 worldwide and 9.1-fold in the same period in the US. Overall, glyphosate use in the agricultural sector rose 300-fold between 1974 and 2014 in the US. The growth of use is also illustrated in Figure 7, showing the importance of use in soybean and corn cultivation in the US.

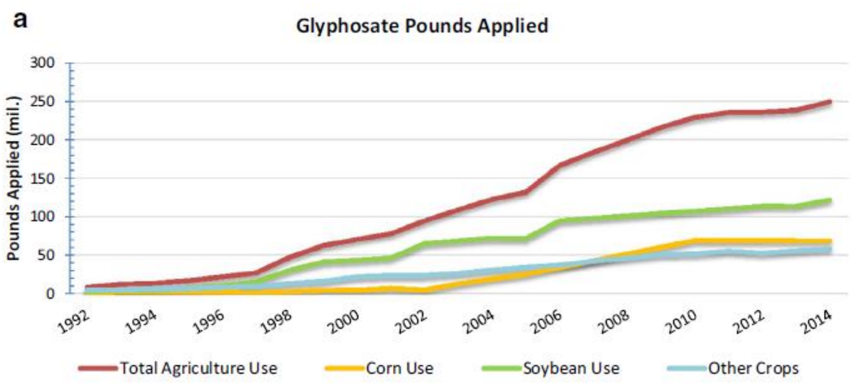


Figure 7: Application amounts of glyphosate in the United States over time (Source: Benbrook, 2016).

4. PROCESSES AND FACTORS THAT TRANSFER PESTICIDES TO DRINKING WATER RESOURCES

Most of the drinking water used in the EU originates from groundwater (66%) followed by surface waters (30%) (Figure 8). The use of groundwater is dominant in Germany, France, Spain, Italy, Denmark, Belgium, and The Netherlands. The use of surface water is dominant in the United Kingdom, Portugal, Czech Republic, Finland, Estonia, and Ireland. The use of groundwater and surface waters greatly depends on the availability of fresh and clean groundwater and surface waters.

The pollution of groundwater and surface waters with pesticides from agriculture depends on the use of pesticides, the hydrological pathways and the pesticides removal/retention processes during transport. This chapter briefly discusses the hydrologic cycle, hydrological pathways and the factors that contribute to groundwater recharge and pesticides removal/retention processes during transport.

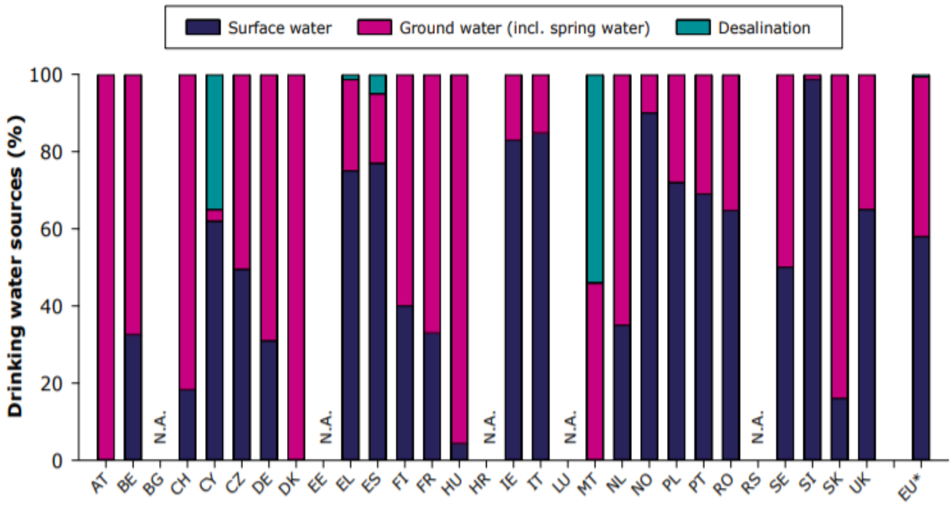


Figure 8: Relative contributions of surface water, groundwater and desalinization to the production of drinking water in EU Member States. The production of drinking water is expressed in terms of number of people served with drinking water per country (http://www.eureau.org/resources/publications/1460-eureau-data-report-2017-1/file).

4.1 THE HYDROLOGICAL CYCLE

Solar radiation is the basic driver of the hydrological cycle (Figure 9). It ‘fuels’ evapotranspiration from plants, soil and water surfaces. The moist air moves up but once in cold air layers it condenses to form clouds, and thereafter returns to the surface as precipitation. Some of the rain evaporates back into the atmosphere, some enters surface waters through surface runoff, and some infiltrates the soil and percolates into groundwater and may ultimately seeps its way to rivers, lakes and oceans, and then is released back into the atmosphere through evaporation (Figure 9).

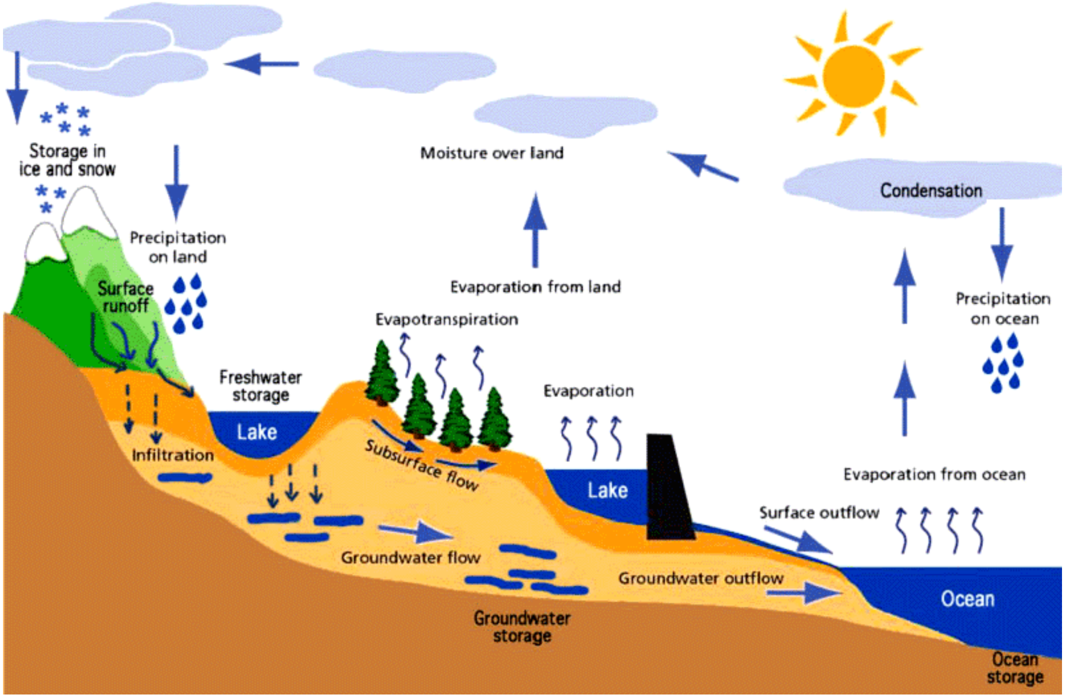


Figure 9: The hydrologic cycle (Source: http://geofreekz.wordpress.com/the-hydrosphere).

Groundwater is often divided in two subsystems (i) the shallow groundwater with the (partly) unsaturated zone with rapid transport of solutes through shallow groundwater to local water courses (subsurface runoff) and (ii) the deep groundwater saturated zone with slow transport towards larger streams and rivers.

The infiltration capacity of the soil depends on its porosity, which depends on its texture and structure. When the rate of rainfall (intensity) exceeds the infiltration capacity of the soil, runoff will be generated and causes potential transport of applied pesticides. The vegetation exerts influence on the infiltration capacity of the soil; a dense vegetation cover often increases the infiltration capacity. Human activities that may affect runoff are the removal of vegetation and soil, grading the land surface, including terracing, and constructing drainage networks. These activities change runoff volumes and travel times to streams or other water bodies. Also, soil sealing in urban and infrastructural areas, and soil compaction by heavy machinery decreases the infiltration of water into the soil.

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

4.2 Pathways of pesticide movement through the environment

Pesticide transport processes from sloping farmland to surface waters have been generally poorly documented (Tang et al., 2012). Depending on their chemical characteristics, pesticides can be either adsorbed to solid (soil) particles or dissolved in water. Thus, they can be transported in particulate (adsorbed) or dissolved form. The pathways of pesticide movement through the environment are mainly through the air (drift) and with water, i.e. following the pathways of water (figure 10). Both include transport with sediment, i.e. in particulate form attached to soil particles, that can be moved by wind erosion and by water erosion over and through the soil.

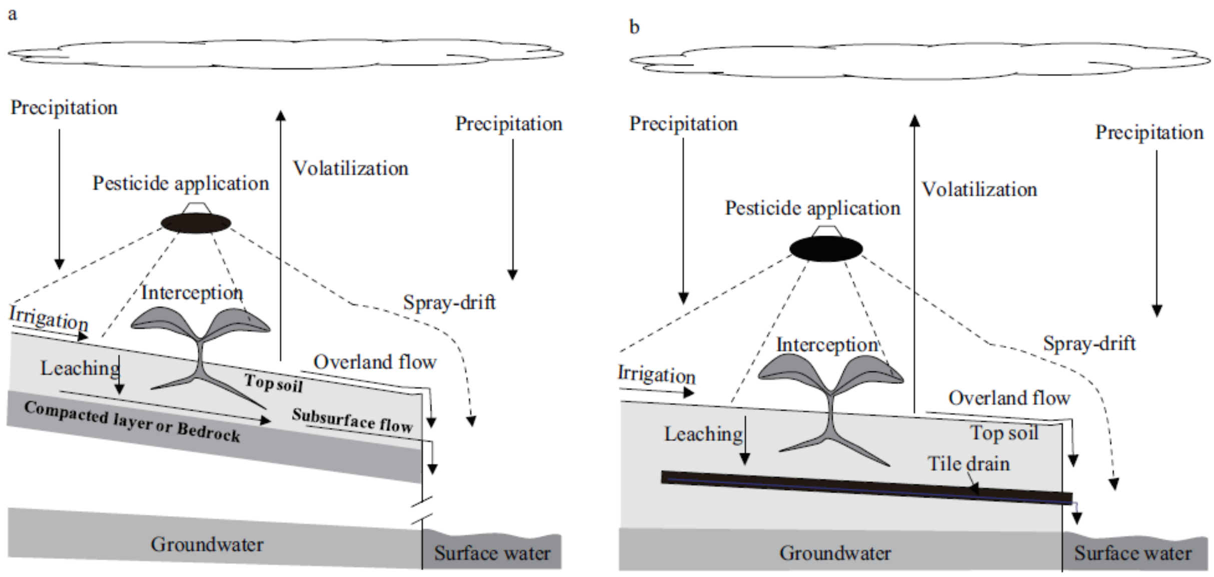
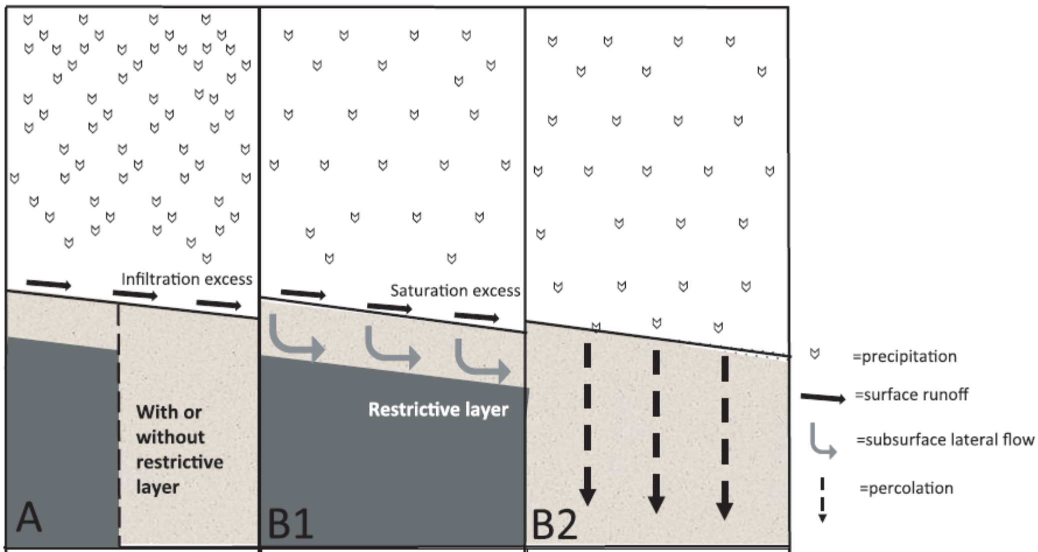


Figure 10: Schematic representation of pathways of pesticide transport with (a) an impermeable layer and (b) tile drains. Source: Tang et al., 2012

Drift occurs during the application of the pesticides when they are sprayed on the field. Spray drift can pollute surface water and off-site locations. This depends mainly on application conditions as wind and humidity, and the used material (Reichenberger et al., 2007; Röpke, Bach, & Frede, 2004). Spray drift is an important route for pesticides into surface waters and should be taken seriously in view of the directness of the input and the high pesticide bioavailability (Tang et al., 2012). Its contribution to surface water pollution in European countries is however thought to be rather small (Neumann & Moritz, 2002; Tang et al., 2012)

Rittenberg et al., (2015) describe the movement of pollutants with the hydrological pathway. Depending on the so-called ‘hydrological land type’ (Figure 11) and the climate characteristics, pollutants either move over the soil surface (type A), partly infiltrate and move in a sub-surface layer (type B1), or vertically leach to the groundwater table (type B2).



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

Figure 11: Framework of hydrological land types with pathways of pesticide movement (Source: Rittenberg et al., 2015). BMP = Best Management Practice, NMP = Nutrient Management Plan, IMP = Integrated Pest Management Plan.

When the precipitation intensity exceeds the infiltration capacity of the soil (case A in Figure 11), infiltration excess overland flow, or Hortonian overland flow, will occur and pesticides may be moved either with the runoff water (in dissolved form) or with the soil particles as soil erosion (in particulate form) downslope. For pesticides showing a high sorption on organo-mineral soil particles, such as e.g. glyphosate, trifluralin, paraquat or organochlorine pesticides, transport by surface runoff is principally associated with the suspended soil particles generated by water erosion (Tang et al., 2012).

If precipitation intensity is smaller than the infiltration capacity of the soil (case B1 in Figure 11), water and pollutants will infiltrate into the soil until a restrictive layer is encountered. Water and solutes will flow laterally over the restrictive layer. When the lateral transport capacity becomes less than the incoming lateral or vertical flux, layers become saturated. In these locations, exfiltration of water and solutes occurs as saturation excess overland flow.

When the restrictive layer is deep or absent, water will predominantly flow vertically downwards (case B2 in Figure 11) via matrix and preferential flow until it reaches the water table. Preferential flow through macro pores is of particular interest in relation to the rapid transport of pesticides from farmland (Tang et al., 2012).

A final pathway of pesticide pollution is direct point loss, which includes spray drift, but also spillage, the clean-up of pesticide application equipment and other operations. The importance of rapid direct point losses, like tank filling, spillages, faulty equipment, washing, waste disposal and overspray of surface waters has been confirmed by monitoring campaigns (Holvoet, Seuntjens, & Vanrolleghem, 2007)

Even though the general pathways of pesticide transport through the environment are known, as shown above, Borggaard and Gimsing (2008) noted that knowledge about subsurface leaching and surface runoff of glyphosate as well as the importance of this transport as related to ground and surface water quality is scarce, emphasising the very scarce direct knowledge of glyphosate transport by overland flow (Tang et al., 2012).

Pesticides are also degraded in the soil into other organic compounds. For glyphosate, this is mainly a microbial process, as practically no degradation has been observed in sterile soil (Borggaard & Gimsing, 2008). Pathways of microbial degradation of glyphosate are twofold, with one leading to the intermediate formation of sarcosine and glycine and the other leading to the formation of AMPA (Borggaard & Gimsing, 2008). Great variability is observed in the ability of soils to degrade glyphosate. It has been correlated with general microbial activity and thus with respiration rate (Borggaard & Gimsing, 2008), but also correlations with other factors have been found.

4.3 FACTORS CONTROLLING PESTICIDE MOVEMENT

As can be deduced from the various pathways in which pesticides can reach ground- or surface waters, there are many factors that affect pesticide movement and these factors vary among locations and soil types. In this section, a brief overview is given of the most important factors controlling pesticide movement in and over the soil to ground- and surface waters.

Sorption to soil is one of the most important processes affecting the fate of pesticides in the environment. Strong sorption to soil solids results almost in immobilisation, while a weakly sorbed compound can be readily leached (Rittenburg et al., 2015). The tendency of pesticides towards sorption is expressed in terms of the sorption coefficient K_d defined as the ratio of the pesticide concentration in the sorbed phase to that in the aqueous solution phase (Tang et al., 2012). Sorption retards the transport of dissolved pesticides, but it can enhance the transport of particulate or colloid-associated forms if rainfall or irrigation triggers soil erosion (Tang et al., 2012). Pesticide physicochemical properties (e.g. solubility, polarity, polarizability, charge characteristics) in combination with soil chemical properties (clay content, pH, organic matter content) govern pesticide sorption in soils (Borggaard & Gimsing, 2008). For example, soil pH determines the electrical charge of glyphosate and therefore its adsorption on the mineral phase (Vereecken, 2005). Almost all pesticides are moderately to weakly sorbed in soils, mainly by soil organic matter (SOM), because most of the pesticide molecules are dominated by apolar groups(Borggaard & Gimsing, 2008). Glyphosate is an exception, as it is strongly sorbed by soil minerals due to its three polar functional groups (carboxyl, amino and phosphonate groups) that have a high affinity for aluminium and iron oxides(Borggaard & Gimsing, 2008). Therefore, the risk of ground and surface water pollution by glyphosate seems limited because of sorption onto variable-charge soil minerals, e.g. aluminium and iron-oxides, and because of microbial degradation(Borggaard & Gimsing, 2008). Glyphosate competes for sorption sites with phosphate, which may have a severe impact on glyphosate bonding, and hence leachability, especially on many agricultural soils in Europe, the USA and elsewhere that are saturated or nearly saturated with phosphate because of surplus fertilisation over many years(Borggaard & Gimsing, 2008).

As becomes clear from sorption, also physical and chemical soil characteristics play a role in determining the movement of pesticides through and over the soil. As Borggaard and Gimsing (2008) state: 'Soil sorption and degradation of glyphosate exhibit great variation depending on soil composition and properties.' As indicated above, soil pH and organic matter content affect sorption of pesticides to the soil solids. Soil structure and texture are important factors determining whether water with solutes move through the soil as matrix (or piston) flow or whether preferential flow occurs. In unstructured, uniform soils (e.g. sandy soils), mainly matrix flow occurs. As this is slower than preferential flow, pesticides have more change to sorb to the soil solids. In structured soils, preferential flow paths exist through which rapid flow to lower layers and the groundwater can occur. In clayey soils, preferential flow bypassing the soil matrix more or less, is common. Preferential flowpaths include macropores, including biopores and fissures / cracks between aggregates, but also bands of higher hydraulic conductivity such as sandy bands in between a clay matrix may occur (Borggaard & Gimsing, 2008). Figure 11 indicates that the presence in the soil of restrictive layers plays an important role, as this prevents vertically downwards flux and leads to more rapid subsurface flow. Similarly, the depth of the soil to either the bedrock or the groundwater affect pesticide transport.

Climate plays a role mainly in terms of rainfall occurrence and intensity. Several authors indicate the role of rainfall in high intensity storms that occur shortly after pesticide application. This increases the risk of both leaching of pesticides through subsurface flow and vertical flow to the groundwater, as well as the risk of loss of pesticides through overland flow (Borggaard & Gimsing, 2008; Tang et al., 2012; Vereecken, 2005). Figure 12 shows a map of Europe with the distribution of excess rainwater. For example, Tang et al. (2012) state that the first overland flow event usually causes the highest pesticide loss, especially after a long dry period during which numerous pesticide applications have been made. Another climatic factor is wind speed and direction, which plays a role in drift pollution.

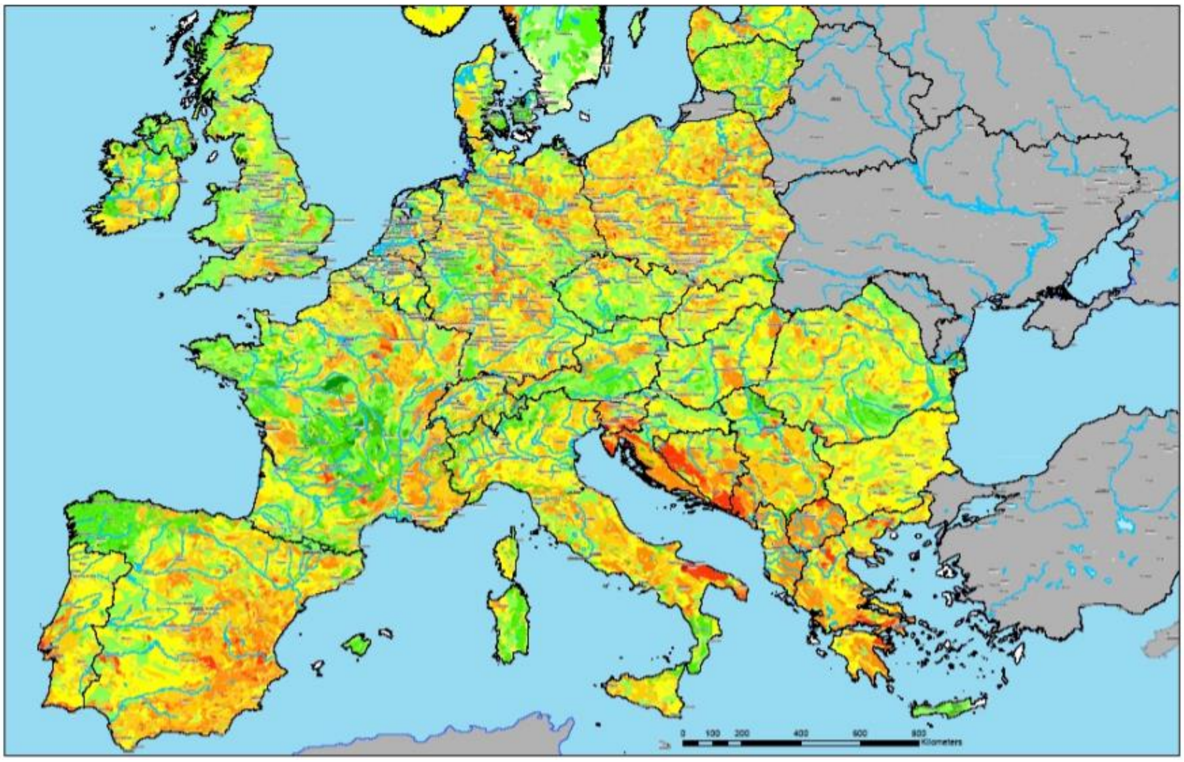


Figure 12: Map of Europe showing the distribution of excess rainwater; dark green colour indicates where transport of excess water to surface waters is maximal; dark red colour

indicates where groundwater recharge is maximal; intermediate colours indicate that both pathways are important (Source: Reichenberger et al., 2007).

For pesticide loss via overland flow (both dissolved as in particulate form), the factors that determine water erosion play a role. These include climatic factors (mainly rainfall intensity, but also amount and length of storms), soil properties, such as texture, structure, crust formation, soil moisture content and erodibility of the soil. These factors determine whether infiltration capacity of the soil is exceeded, leading to Hortonian overland flow, and how susceptible the soil is to erosion. For example, silt textured soils are more susceptible to erosion than sand or clay soils. The topography and geomorphology of the landscape plays a role, in determining the accumulation and redistribution of overland flow and thereby soil particles. Slope steepness is one of the most important factors determining the amount of soil erosion. Vegetation type and density are other major factors for soil erosion and deposition of (polluted) sediment, as well as for infiltration characteristics of the soil.

Topography and landscape position is a factor for subsurface transport of (dissolved) pesticides, because exfiltration may occur. Footslopes are more vulnerable to pesticide loss via overland flow than other parts of a catchment, as the soils in footslope positions receive subsurface flow from higher contributing areas.

Finally, there are technical and management factor that play a role in the risk of pesticide loss. These include the equipment design, pressure, droplet size and spray type (Gil, Sinfort, & Bonicelli, 2005; Tang et al., 2012). Clearly, the timing of application of pesticides relative to (expected) rainfall events is important, as well as the number of applications.

The very wide variation in pesticide movement through the environment is because very often, multiple factors play a role and these factors are different for different types of pesticides. For example, transport of glyphosate may be caused by an interaction of high rainfall events shortly after application on wet soils showing the presence of preferential flows (Vereecken, 2005).

5. REVIEW RESULTS – PART 1: QUALITATIVE REVIEW OF MEASURES AND PRACTISES THAT DECREASE PESTICIDES POLLUTION

This chapter provides a qualitative overview of the measures and practices that decrease pesticides losses to groundwater and surface waters. It discusses the mechanisms and rationales of these measures and practices to decrease these losses.

The actual vulnerability of a site to pesticide pollution via surface runoff and leaching depends on the pedo-climatic conditions and farming practices (Chapters 3 and 4). As pedo-climatic conditions are largely defined by Mother Nature and are not easy to manipulate, they govern the available options for farming practices to ensure environmental protection. Farming practices will hence have to be adjusted to the pedo-climatic conditions, when the objective is to decrease the risk of water pollution with pesticides. Recommendations and regulations directed at the reduction of pollution risks should therefore ideally be tuned to these different situations. Farming practices refer to farm land management (type and nature of pesticide application, rate, timing and method of application) in close connection with the complementary farm management (e.g. crop type choice, dates of sowing and harvest, drainage and irrigation, crop rotation, livestock feeding and housing).

Measures to prevent and reduce the risk of surface runoff and leaching can be categorized according to the *source-pathway-receptor* concept, i.e., there are (i) source-based measures, (ii) pathway-based measures, and (iii) receptor or effects-based measures. Most agricultural measures are aiming at the pathway which is described in more detail in chapter 4. However within the Fairway case studies also source-based measures are implemented (see table 3). Examples of source-based measures are appropriate storage of pesticides, pesticide application according to the rules of integrated farming, organic farming, and prohibition and restrictions on the application (types of) pesticides. Examples of pathway-based measures are buffer strips, tillage management and drift reducing technologies.

The effectiveness of measures to reduce pesticide pollution of surface waters and groundwater depends on the site-specific adjustments of these measures to the pedo-climatic conditions and farming systems. It is well-known that ‘blanket recommendations’ are not effective, because they are not specific. However, detailed top-down prescriptions of when, how and where to do what in all pedo-climatic (sub) zones are not effective either. The recommendations need to be made farm and site specific to become really effective. This may require the involvement of both local farmers and advisors.

5.1 FAIRWAY CASE STUDIES

Within the FAIRWAY project 13 case studies are used, of which 9 study pesticide pollution, to investigate the relation between pollution of drinking water and nitrate and pesticide use. In these case studies several agricultural measures are already applied or tested to minimize pollution by pesticides. The case studies are located all over Europe reflecting different pedo-climatic zones (figure 13).

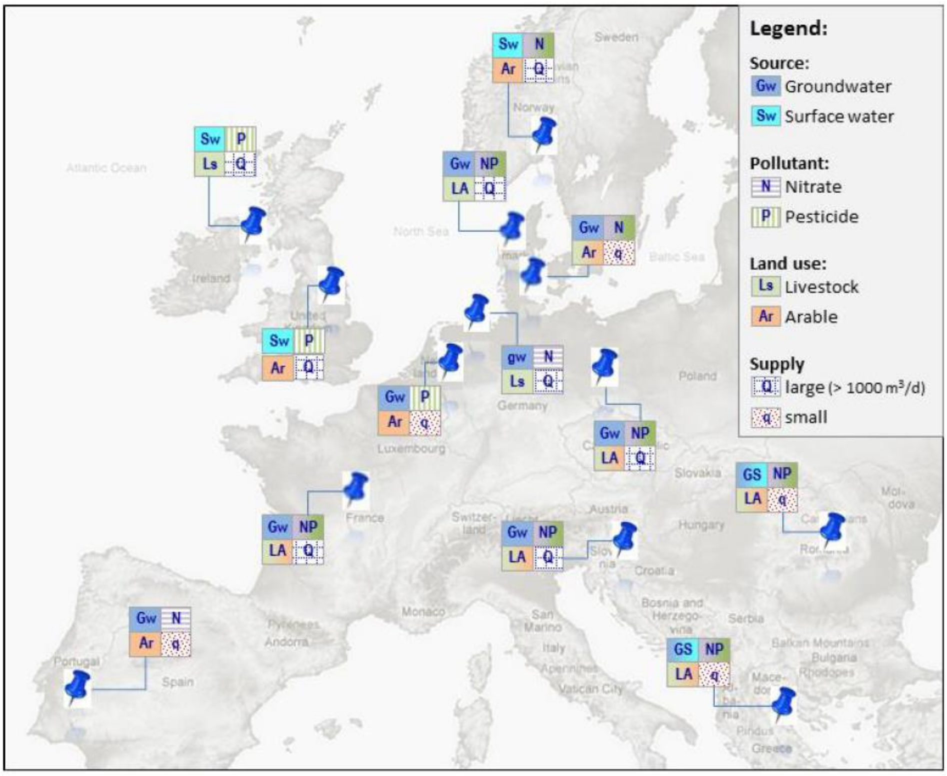


Figure 13: FAIRWAY case study locations; https://www.fairway-project.eu/index.php/case-studies

Table 13 shows the implemented measures in the case studies including evaluation factors as local experts grade them. Source based measures aiming at safe storage are mainly effective for surface water safety, which is point source pollution and will reach surface waters by drainage from the storage/cleaning areas. However not much is known about the costs and possibility of implementation. In one case study biobeds are tested as measure against point source pollution. Other source based measures are aiming at the amount of pesticides used by farmers, these are implemented in several case study locations via laws (restrictions or prohibitions) or financial enforcements (increased taxes). As statistics show in figure 2 (chapter 3.2) these measure can be very effective in reducing the amount of used pesticides. In addition, this type of measure will reach many land managers because they are enforced on a higher level.

The other measures implemented in the case studies are aimed at reducing transport of pesticides. The possible pathways of transport are presented in chapter 4. Within the case studies the applied measure are ‘edge of field’ measures including buffer strips. These measures are evaluated as effective by experts, which is underpinned in literature (Arora, Mickelson, & Baker, 2003; Lerch, Lin, Goyne, Kremer, & Anderson, 2017; Reichenberger et al., 2007). Also crop rotation changes and Intergrated Pest Management are implemented as a measure. Integrated Pest Management (IPM) is a farm management measure and can be applied in almost any situation, if designed well it is a very effective measure, because it often includes measure described above in an optimal combination. The effectiveness of crop rotation changes depends a lot on the design of the rotation and on the 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, Di Guardo, Vischetti, & Trevisan, 2008).

Table 3: Applied measures within the FAIRWAY case studies, with indicated properties based on expert judgement by experts working in the case study.

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

NOTE: Symbols in the table indicate a scale from negative to positive with – is negative, +/- is neutral and +++ is very positive. For the cost three categories are made low (€), moderate (€€) and high (€€€). When there is no data a ? is shown.
[1]Network engagement: embedding information and communication at all levels from supply chain to agronomist to farmers to stimulate change of practice.
[2]Intergrated Pest management, is a holistic farm management 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, which is intented as an extra incentive to look for alternative crop management methods.

5.2 QUALITATIVE LITERATURE REVIEW OF MEASURES AND PRACTISES

Beside the results gathered in the case studies, literature sources were reviewed to gather qualitative data about the performance (effectiveness, costs, applicability and adoptability) of a range of measures. As starting point, major reviews from 2000 until present were used (Reichenberger et al., 2007; Rittenburg et al., 2015; Tang et al., 2012). Beside that there were some excellent reviews about specific measures in relation to pesticide pollution (Alletto, Coquet, Benoit, Heddadj, & Barriuso, 2010; Krutz, Senseman, Zablotowicz, & Matocha, 2005). From these reviews and extra literature that was collected for the quantitative analysis, a qualitative overview is made of the most used and studied measures to reduce pollution of ground and surface water (table 4). The evaluation is based on results of these studies, which contain in general clear data to assess the effectiveness of the measures. However costs, applicability and adoptability were often not well documented. Costs vary per location and time, but are often reflected in the amount of adjustments needed and how complicated the measure is. Estimates presented are gathered from literature but indicate low, moderate or high costs without clear quantitative boundaries. Applicability and adoptability are defined in chapter two, however in the reviewed literature there is not sufficient data available to give reliable results. A more general practicability was more often found, indicating the ease of use and possibility to apply the measure in practise.

The reviewed measures are divided into three groups, based on the management level; pathway modifications, input control and redesigning of the farming system. Pathway modifications are often physical measures that are most studied (and implemented) on field scale. Input control and redesigning farming systems are farm level measures. In the reviewed literature the main focus was on diffuse pollution, or pollution from the field. Although point source pollution also occurs it is identified as less complex to control and as a less important pollution source (Bach, Huber, & Frede, 2001).

Pathway modifications are physical interventions in the transport route from the source of the pesticide towards ground or surface waters. The effectiveness of the measure is therefore greatly influenced by the local situation like field characteristics (slope, soil type) and climate. This was explained in more detail in chapter 4.

On locations where overland flow dominates (case A in Figure 11), effective measures can be grouped into two general categories: (1) measures that increase the soil's ability to infiltrate and store water, thus reducing overland flow, and (2) measures that reduce the overland flow velocity when it is generated and prevent offsite transport (Rittenburg et al., 2015).

Vegetated buffers or filter strips have been shown to be effective in reducing overland flow and soil erosion (Krutz et al., 2005; Lerch et al., 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 (Tang et al., 2012). Vegetated buffer strips have been shown to have high removal efficiencies for pesticides and sediment (Arora et al., 2003; S. Otto, Vianello, Infantino, Zanin, & Di Guardo, 2008). 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). However, the environmental fate of the pesticides and their metabolites retained in the filter strips has rarely been evaluated, and the increased infiltration of pesticides in a buffer strip can enhance leaching to groundwater (Krutz et al., 2005).

If well designed and adjusted to local conditions, vegetated buffers are very effective measures. 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. The practicability is low because the buffers need specific design to be effective (Rittenburg et al., 2015) and the application is limited to fields where slopes are steep enough to give regular overland flow events.

Constructed wetlands are less studied than buffer strips but if well designed, maintained and implemented they can have be very effective with rates of pesticide reduction up to 100% (Tournebize, Chaumont, & Mander, 2017; Vymazal & Březinová, 2015). However the cost are high, and they the take a relative large surface of productive land to be installed.

Tillage is strongly related to runoff and infiltration processes on the field, and thus will influence the transport pathways of pesticides. In an extensive review Alletto (2010) reviewed the effectiveness of tillage methods on both overland and leaching transport of pesticides. In both cases changes in tillage methods can be effective, but local design and application are very important for success (Tang et al., 2012). 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. The costs of changing tillage methods are generally low and practicability is good. However there is a risk that tillage methods will not remediate total pollution but only will change the transport route, because infiltration (leaching) and overland transport are often mutually exclusive (Flury, 1996). Tillage alters the soil hydraulic properties and thereby the transport pathways of water and related solutes such as pesticides (Alletto et al., 2010). If preferential flow is significant, tillage can reduce pesticide leaching by disrupting continuous macropore flowpaths. On the other hand, in soils where matrix flow is predominant, conventional tillage may enhance pesticide leaching as compared to reduced tillage or no-tillage (Tang et al., 2012). Conservation tillage (i.e. zero-tillage or reduced tillage) increases retention/sorption of pesticides in topsoil, particularly because of retarded degration of soil organic matter compared to tillage, while increasing the availability of pesticides for biological degradation, leading to enhanced persistence in soils. However, reduced tillage also reduces erosion and thereby the particulate transport with sediment (Alletto et al., 2010).

For situations/locations with mainly subsurface flow (case B1 in Figure 11), reduction of pesticide loss to surface and groundwater is challenging. Source input management (i.e.Intergrated Pest Management) is of course possible, but altering the pathway of water flow is difficult. Tile drainage may decrease the overland flow volume, but it may create subsurface flow paths which does not necessarily reduce overall pollutant transport (Rittenburg et al., 2015). Optimizing drainage is shown to be possibly effective but not regarded as the best approach to reduce pollution (Flury, 1996), however combined with other measures it can be used to be overall more effective.

Locations with deeply drained soils and thus posing a risk of leaching to groundwater (case B2 in Figure 11) 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 (Rittenburg et al., 2015). This second option can be obtained by mulching or crop rotation adjustments. Increased organic matter in the soil will give more sorbtion options for the pesticide, reducing the risk of transport by water (Alletto et al., 2010).

Drift is a transport route and pollution pathway that is isolated from the other pathways. Preventing drift is mainly studied by reducing the transport route from the spraying device to offsite areas including open water bodies. Input control is a very effective measure to reduce drift pollution, because if less or no pesticide is sprayed this relates directly to the potential pollution. This is mentioned in literature, but not tested because of the clear relation. The practicability of reduced input for drift pollution depends a lot on the local situation and solutions to combat the pests (Felsot et al., 2010). If the solutions are expensive or not available the practicability will be low.

Table 4: Measures reviewed in literature with evaluated performance

Measure	Effectiveness		Costs	Adoptability/Applicability	Notes	Sources
	Groundwater	**Surface water**				
Modify Pathway						
1. Buffer strips	+	+++	€€	?	Effectiveness depends on design, added ecological value	(Arora et al., 2003; Krutz et al., 2005; Lerch et al., 2017; Reichenberger et al., 2007)
2. Constructed wetlands	+	+++	€€€	-	Effectiveness depends on local design, drain systems, sufficient hydraulic capacity	(Moore, Schulz, Cooper, Smith, & Rodgers, 2002; Tournebize et al., 2017; Vymazal & Březinová, 2015)
3. Erosion reduction	-	++	?	+		(Fawcett, Christensen, & ... 1994; Sadeghi & Isensee, 2001)
4. Tillage methods	+	+	€	?	Effectiveness depends on local design	(Alletto et al., 2010; Ghidey et al., 2005; Tang et al., 2012)
5. Drainage optimization	?	+	€	-/+		(Dinnes et al., 2002; Flury, 1996)

6. Residue management/ Mulching	?	++	€	+		(Alletto et al., 2010)
7. Drift reduction; no spray zones	Na	++	€€	+	High ecological value	(de Snoo & de Wit, 1998; Felsot et al., 2010)
8. Drift reduction; wind breaks	Na	++	€	+	High ecological value	(S Otto et al., 2015)
9. Drift reduction: mechanical spraying optimization	na	+	€€	+		(S Otto et al., 2015; Zande et al., 2008)
10. Crop rotations	++	++	€€	?		(Brown & Van Beinum, 2009; Rittenburg et al., 2015)
Input control						
11. Application rate reduction	+	+	€	+/-		(Reichenberger et al., 2007)
12. Alternative pesticide	?	?	?	++/--	Depends on choice	(Reichenberger et al., 2007)
Redesign system						
15. 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. For the cost three categories are made low (€), moderate (€€) and high (€€€). An ? indicates that no clear data is available and the evaluation of the measure is still unknown.						

Besides input reduction three main measures that are used to reduce drift pollution are no spray zones, windbreaks and mechanical drift reduction technology (Felsot et al., 2010; S Otto, Loddo, Baldoin, & Zanin, 2015). All three measures are effective. Beside that, no spray zones and windbreaks often have a high ecological value which within the EU is also rewarded within the Common Agriculture Policy (Reichenberger et al., 2007). This results in a good practicability for these measures. The mechanical drift reduction consists of a broad spectrum of technologies to reduce drift by changing spraying nozzles (vd Zande 2005) or ventilator design (Otto et al., 2015). Beside these agronomic measures also regulations are made to reduce drift, like restrictions based on weather conditions.

Reduced input and redesigning the system is sometimes referred to as 'Good Agricultural Practices' (GAPs) or 'Best Management Practices', 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 (Gentz et al., 2010). Integrated Pest Management (IPM) is a farm management measure and can be applied in almost any situation, if designed well it is a very effective measure, because it often includes measure described above in an optimal combination. However, the costs are high of IPM because the number of required changes on the farm. Moreover, reducing pesticides input often implies a (temporal) reduction in yields (Reichenberger et al., 2007).

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). A few factors, beside applied measure, seem to be of major importance in pesticide application management: applications should not coincide with large precipitation events and should be applied when crops can uptake the chemicals or when there is enough organic matter and residue in the soil to either immobilize or bind them allowing for biodegradation (Rittenburg et al., 2015).

6. Review results – part 2: Quantitative analyses of measures and practises

This chapter presents the results of the systematic literature search and data analyses. In total 37 sources about pesticide measures were reviewed, 4 studies were excluded because of study design of data incompleteness. The 33 studies that were analysed contain 104 experimental comparisons on the effectiveness of pesticide measures. Of these 8 cover groundwater pollution, 88 contain data about surface water pollution (of which 36 are specific about drift reduction) and 9 experiments cover both ground and surface water pollution. Table 5 shows the topics covered by the collected sources, groundwater and surface water pollution have been separated, because transport mechanisms in this two cases differ a lot.

Table 5: Summary of database content for pesticide mitigation aimed at decreasing pesticide pollution of groundwater and surface waters (Status 1 October 2018)

Pathway	Pesticide category	# experiments	Type of measures
Groundwater (11)	Herbicides, haulm destructors and moss killers	9	-Tillage methods (6) -Input control(2) -IPM(1) -Crop changes(1)
	General	2	-IPM(2)
Surface water (61)	Herbicides, haulm destructors and moss killers	51	-Tillage methods(18) -Buffers(22) -Input control(7) -Erosion reduction (3) -Crop types (3) -Drainage(3) -IPM(1)
	Insecticides and acaricides	2	-Input control(1) -Constructed wetlands(1)
	Fungicides and bactericides	2	-Erosion reduction(2)
Drift (36)	General	32	-Drift reduction – mechanical (28) -No spray zones (9)
	Herbicides	4	

The analysis of the effect of the measures is done for each of the three pathways separately. The pesticide categories have been combined during this analysis.

The literature search and data screening took more time than initially expected and the number of studies included in the database is less than initially expected. The 37 studies included in the database have been conducted mostly in the EU-28, but some studies originate from other continents. Most of the studies from EU originated from western Europe. Most studies dealt with pesticide overland transport reduction with buffers and tillage methods (Table 5). As such, the database is not well balanced with a proper distribution of studies across measures. Our preliminary conclusion is that more literature sources need to be added to the database to allow a more balanced and complete meta-analysis.

Based on the aforementioned conclusion, the decision was to apply the method of meta-analysis on the available data and present in this chapter a first quantitative analyses of the measures in the database. A full meta-analysis of an updated database will be reported in the report on ‘most promising measures to decrease nitrate pollution of groundwater and surface waters’, which will be released by the end of 2019.

6.1 SUMMARY OVERVIEW OF THE EFFECTIVENESS OF MEASURES

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

Table 6 provides an overview of the response ratio RR of some key treatment measures. The overall mean RR ranged from 0.2 to 5.6, indicating a wide range of effectiveness of the measures. Most measures had an RR in the range of 0.2-0.5. Treatments related to tillage methods did not result in effective decrease of pollution, in fact for both ground and surface water the mean response ratio was above 1, which means the loss of pesticides increases. This overview suggests that vegetative buffers, reducing overland transport, and mechanical drift reduction are the most effective measures.

Table 6: Summary of response ratios for each measure.

Pathway	Measure	Response ratio	n*
Drift	Mechanical drift reduction	0.26	27
	No spray zones	0.30	9
Groundwater	Tillage methods	5.6	6
	IPM/ input control	0.22	4
Surface water	IPM/ input control	0.41	9
	Vegetative buffers	0.28	22
	Tillage methods	2.5	18
	Erosion reduction	0.52	5

*number of experiments

This first analysis shows that treatment measures greatly differ in their effectiveness and that there is a large variability in effectiveness within a set of treatment measures. A few additional comments have to be made here. Firstly, the number of studies/comparisons differed greatly between treatment measures; some of the treatment measures (e.g. tillage methods and vegetative buffers for surface water) have a much greater experimental basis than others (e.g., IPM and input control). Secondly, the mean response ratios have as yet not been corrected for the number of measurements and variance within studies. Third, the effectiveness of the treatment measures has not been analysed taking into account different environmental and socio-economic conditions. These aspects need to be taken into account while further analysing a (larger) database.

6.2 DRIFT REDUCTION MEASURES

Drift pollution is a specific pathway of pesticides to surface water, or offsite areas. When pesticides are applied by spray application, a part of the spray liquid can be transported through the air to other locations. Two main approaches to reduce this transport are; 1, technical modifications in the spraying technique to reduce the potential of drift transport and 2, no spray zones between an application field and open water sources. These two approaches are both analysed in more detail.

Mechanical drift reduction

Mechanical measures to reduce spray drift are often related to the nozzle type of the sprayer, the height of the spraying boom above the surface and the driving speed. Adjustments always have to optimize both the reduction of spray drift as well as a uniform and efficient application of the pesticide to the field/crop. Figure 14 shows the effect ratios for the gathered experiments, it is clear that all tests show a decrease in pollution; all effect ratios are below 1.

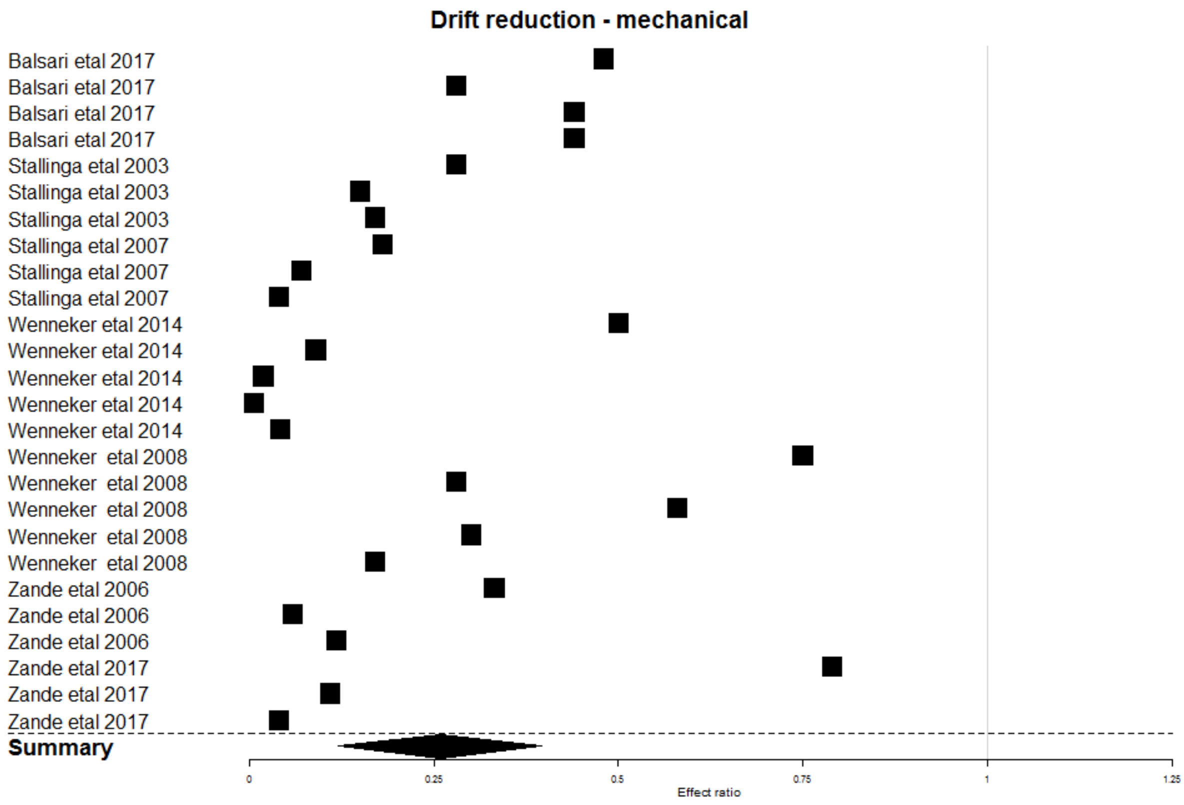


Figure 14: Effectiveness of mechanical drift reduction measures. n = 27 with 7 studies. Summary is mean ± se

The mean effect ratio of drift reduction measures is 0.26 with the 95% Confidence Interval (CI) ranging from 0.0 to 0.53, showing a strong significant effect with the control treatment. This shows that technical drift reduction technologies are very effective to reduce pollution of off-site locations. In the reviewed experiments these were often streams and open water bodies bordering the agricultural fields.

No spray zones

Another option to reduce pollution by spray drift is to create no spray zones between the open water sources and agricultural fields. These areas will function as a buffer for the occurring spray drift and prevent the pollution of the open water.

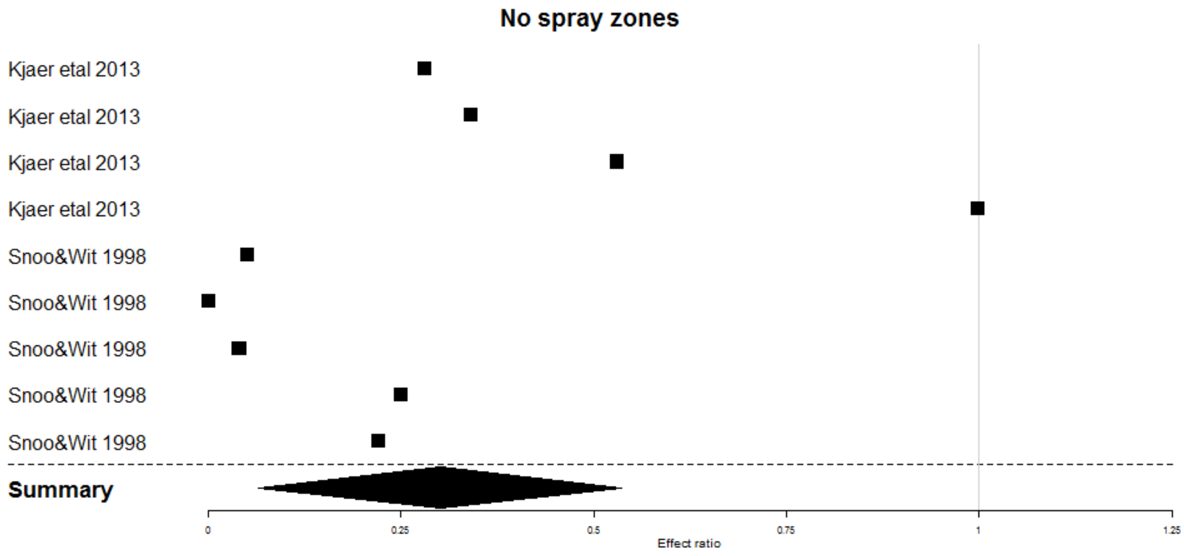


Figure 15: Effectiveness of no spray zones in reducing open water pollution. n = 9 with 2 studies. Summary is mean ± se

Based on the results in figure 15, no spray zones seem effective to reduce pesticide pollution. The 95% CI ranges from 0.0 to 0.76 with a mean effect ratio of 0.30. In this analysis the width of the buffer zone is not taken into account, because of the low number of study results. However it is likely that the width of the no spray zone is a co-variable to explain effectiveness, where broader zones will be more effective.

6.3 Measures to reduce groundwater pollution

Pollution of groundwater occurs mainly through transport of pesticides with leaching of water deeper into the soil. To reduce this, the amount of input in the system can be changed by for example integrated management or reduction of applied pesticides. Besides that the soil management has a large influence on infiltration and leaching of pesticides, optimizing the tillage method can be a measure to reduce pollution of groundwater by pesticides.

In the data base 1 experiment studied the effect of increased vegetative cover on leaching to groundwater, this study showed a positive effect with a response ratio of 0.68. However no further analysis can be done with only 1 data point.

Tillage methods

The mean response ratio of tillage methods to reduce leaching towards groundwater is very high. As figure 16 shows it is far above 1 indicating an increase in pollution by changing the tillage method.

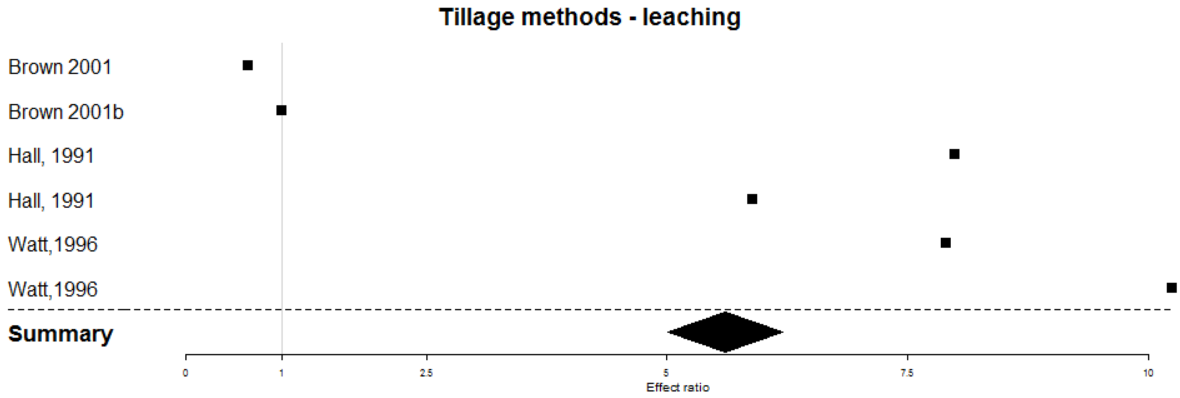


Figure 16: Effect distribution for tillage methods to reduce pesticide leaching. n = 6 with 3 studies. Summary is mean ± se

The mean effect ratio of these 6 experiments is 5.6, and the distribution of the results is very large. To get a better insight in the actual effect more studies should be added to this analysis. Besides that, the effectiveness is influenced by the chosen reference point. For tillage methods, conventional tillage in used as a reference, in the studies by Hall et al., (1991) and Watt et al., (1996) the treatments are either mulch tillage or no tillage, these land management methods are well known for their erosion reducing effect and an increase in infiltration. The reviewed data agrees with that because an increase in infiltration may also lead to higher leaching of pesticides to groundwater. However, this also means that when the reference is changed e.g. there is a switch from a no tillage system to conventional tillage, this data suggest a decrease in pesticide leaching.

IPM and input control

Managing the amount of pesticides that are applied to the system is an effective way of reducing pollution. When the input is reduced this will very likely also show in a reduction in pollution. However, when reducing the input of pesticides the productivity of the system should be kept at a good level, otherwise the efficiency of these measures is still low.

Because there are only a few experiments in this database, input reduction and IPM are combined. The difference between both is that IPM is a more holistic approach taking into account the needed adjustments of the whole agricultural system, where input control experiments often only test the effect of a reduced pesticide application. Figure 17 shows the effectiveness of experiments with input control to reduce leaching of pesticides.

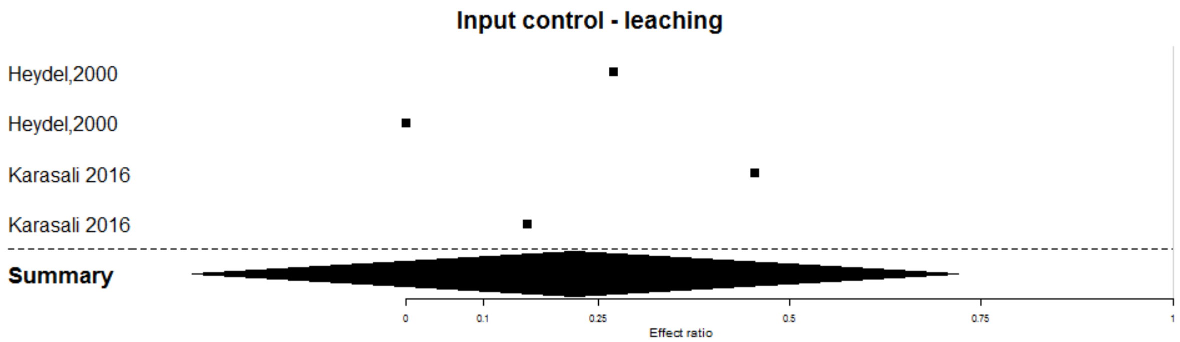


Figure 17: Effect ratio for input control measures. n = 4 with 2 studies. Summary is mean ± se

The mean effect ratio is 0.22 which indicates a strong effect of input control on pesticide leaching to groundwater, however there is a very low number of reviewed experiments (n=4), which should increase to obtain a better insight in the effectiveness of input reduction. For input control the amount of reduction will very likely be related to the effectiveness so this should be taken into account as a co-variable.

6.4 SURFACE WATER

Most studies within the collected database focus on transport of pesticides to surface water. The main pathway for this pollution is via overland transport during and after intense rainfall events. Many measures aim at reducing the runoff potential by delaying runoff time or increasing infiltration. Besides that also measures for input control are used. Some studies differentiate between transport by water and adsorbed transport with eroded sediment. However in this analysis both processes are combined and total overland transport is used.

Input control and IPM

As for pollution to groundwater also surface water pollution can be reduced by decreasing the input of pesticides into the system. Figure 18 shows the distribution of response ratios for input control measures to reduce surface water pollution.

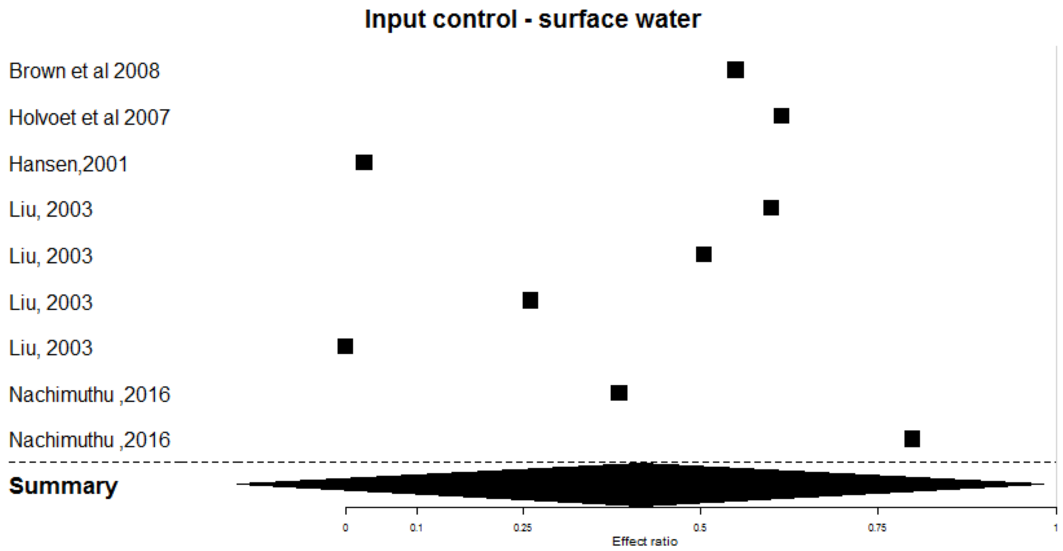


Figure 18: Effect ratio of input control to reduce surface water pollution. n = 9 with 5 studies. Summary is mean ± se

The mean response ratio 0.41 which tends towards an effective measure, however the variation in the results is large and there is no significant difference with the reference studies. As described for grondwater, a strong relation is expected between the input of pesticides and the pollution on agricultural fields. The mean response ratio for surface water is a bit higher than for groundwater which indicates less effect. To improve the analysis the number of experiments will be increased and the amount of input reduction will be used as a co-variable to explain the effectiveness of the measure.

Overland transport reduction

If the pesticide is applied to the crop/field, it should remain on the field without being transported to other locations. For many herbicides overland transport is a main pathway towards open water bodies. Several measures are reviewed to minimize the transport along this pathway.

Vegetated buffer strips are used to decrease the flow velocity of the runoff water, in this way the potential infiltration is increased, moreover this vegetative buffers also function as erosion reducing measures. In figure 19 the effectiveness of buffer strip experiments is shown. All experiments show a decreasing effect on the transport of pesticides to groundwater.

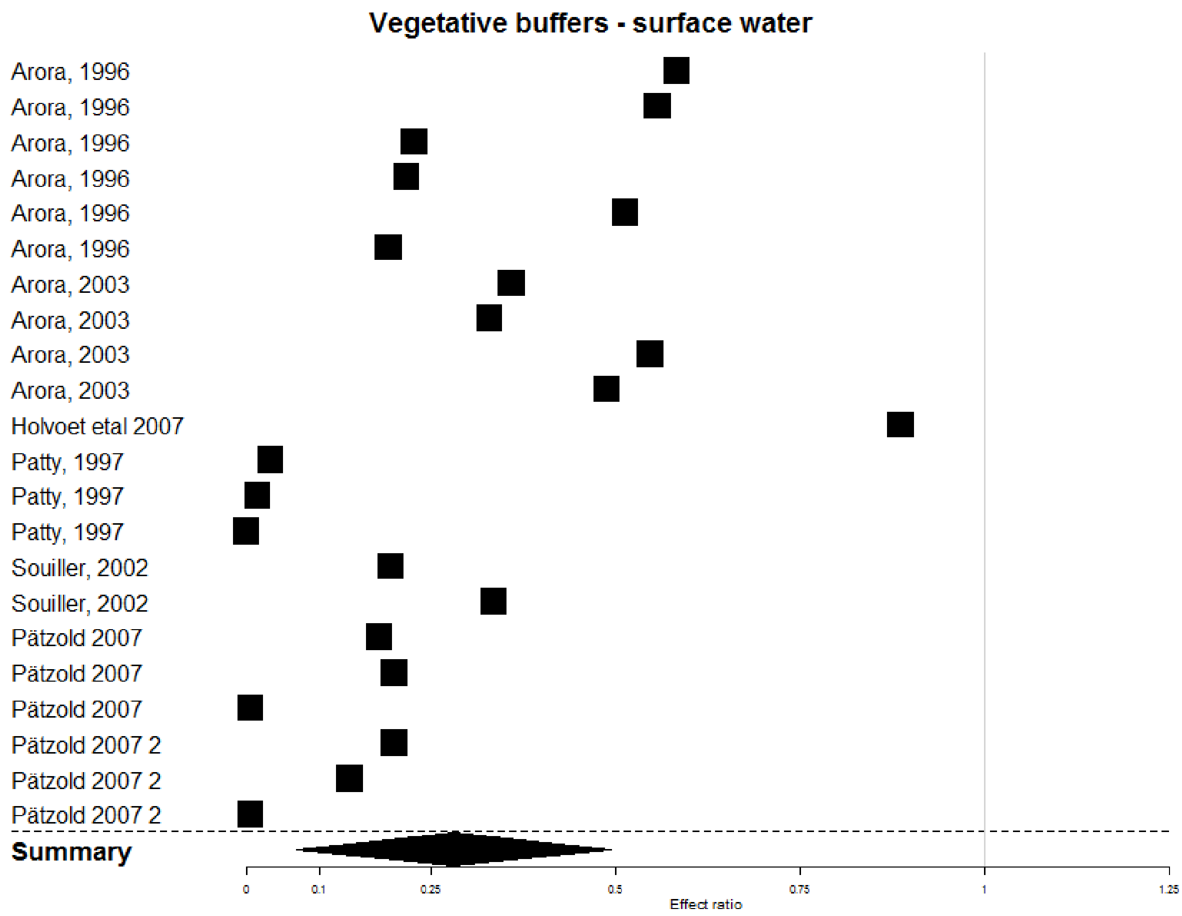


Figure 19: Effect of vegetative buffers in reducing pesticide transport to open water. n = 22 with 6 studies. Summary is mean ± se

The mean effect ratio of applying buffers at the edge of a field is 0.28 with a 95% CI ranging from 0 to 0.70, which means there is a significant effect. To understand the influence of buffers better, the buffer width or the buffer to source area ratio are good co-variables to explain effectiveness. However the gathered studies do not consistently include the required data for the meta analysis. Reichenberger et al. (2007) also attempted to review the effect of buffers quantitatively, however they did not come to a final effectiveness, due to the high heterogeneity within the data.

Changing the tillage method influences the infiltration characteristics of the soil and by altering the surface roughness also the potential runoff of water. The reference treatment for tillage methods is fixed at conventional ploughing, as in the analysis for groundwater pollution. The results of the tillage studies is mainly spread around 1 with a group of outliers to the negative effect side (figure 20). This result was also found for tillage methods and groundwater pollution. However more data is needed to apply a co-variable analysis to understand the wide spread of results. Often the results depend on the agricultural system in which the tillage measure is applied. The mean effect ratio is 2.5 but this is strongly affected by the outliers.

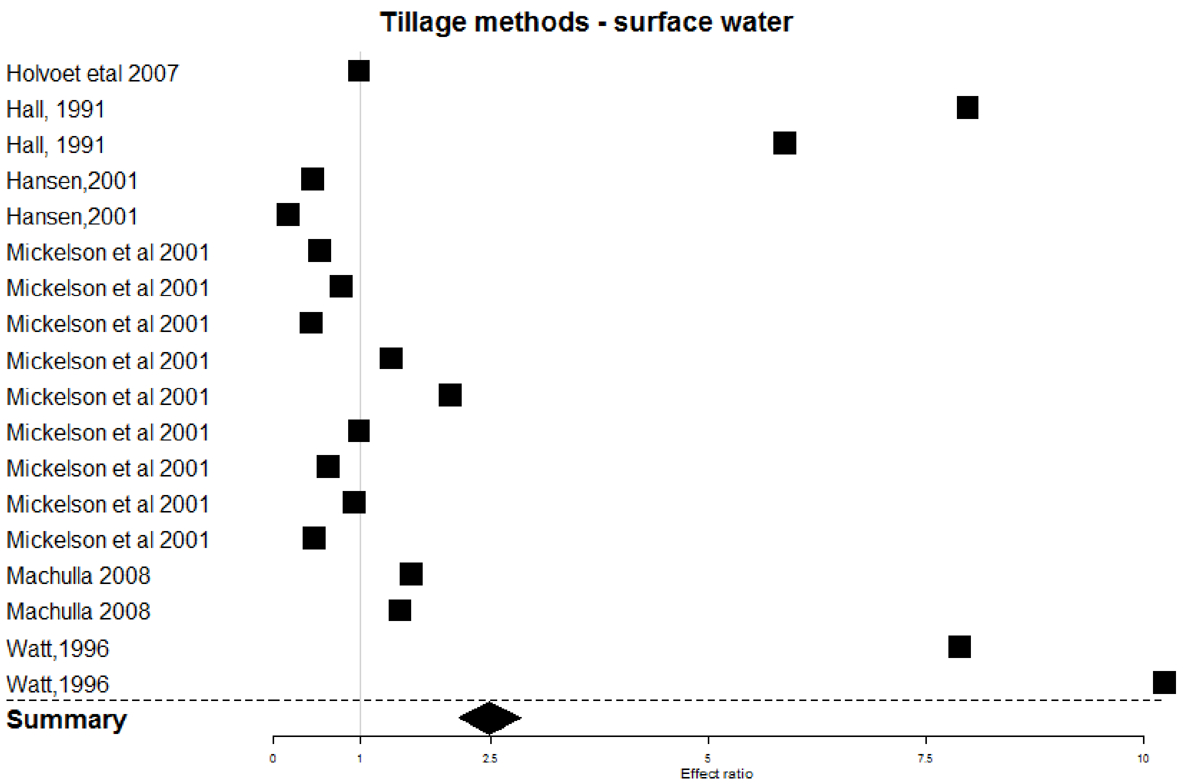


Figure 20: Effect size distribution for tillage method measures. n = 18 with 6 studies

Within the reviewed database also a group of measure was collected which aimed to reduce the amount of erosion on the field, and through that indirectly the transport of pesticides. These measure will be mainly effective when erosion and runoff occur a lot.

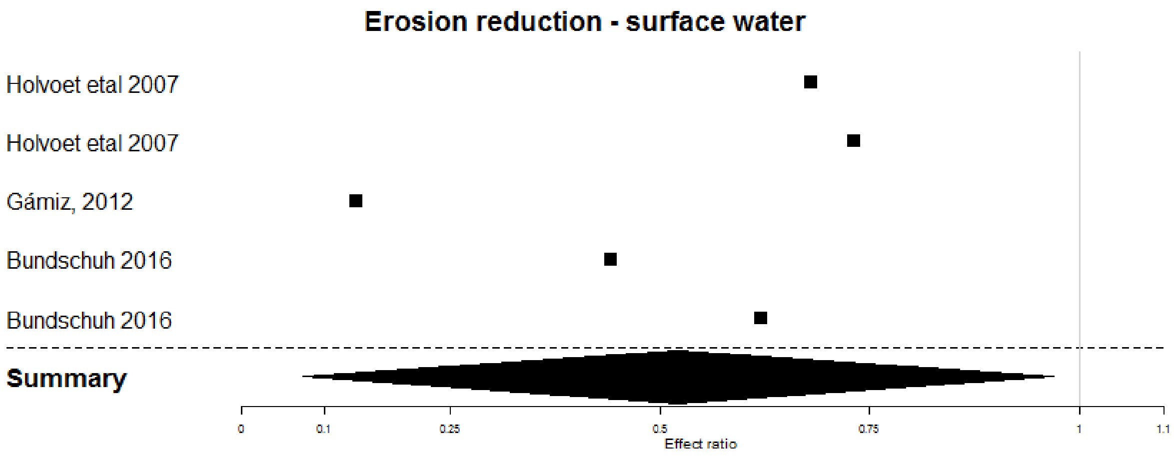


Figure 21: Effect of general erosion reduction measures. n = 5 with 3 studies

The mean effect ratio of erosion reducing measure is 0.52 (Figure 21), however this does not give a significant difference with the reference. This is mainly because of the low number of experiments included in the analysis.

Within the dataset also experiments with drainage and crop type changes were included. These were too few for a statistical analysis and to show quantitative results. For drainage there is a trend that shows that with less drainage, or a wider spacing of the drainage pipes there is less transport through the drainage system. Changing land use influences the dynamics within a system, often the type and amount of applied pesticides will change and the hydrologic conditions will be altered. To unravel and understand the effect of landuse changes, more data with well-defined co-variables is needed. For example the change from arable land to forest is not comparable with the change from a monocrop orchard to an intercropping system.

7. DISCUSSION

The two review parts (qualitative and quantitative) show that there a large number of measures are available to reduce pollution of drinking water sources by pesticides from agriculture. In the literature the main focus is on diffuse source pollution, where it is important to reduce transport from agricultural fields to water sources. The reviewed measures can be grouped into two main approaches; pathways based measures and source based measures. In the first group the aim is to reduce the transport, either overland or by leaching, of the applied pesticides. The source based measures focus on reducing the total input of pesticides in the system and by that reducing potential pollution.

7.1 EFFECTIVENESS OF MEASURES

When comparing the results of the literature review with the quantitative analysis many similarities emerge. Literature is clear about the potential effectiveness of buffer strips and drift reduction measures, although they have to be designed to match local conditions. The calculated effect ratios of these measure are both low, 0.26 and 0.28 for drift reduction and buffer strips respectively, indicating that athese are very effective measures to decrease pesticide pollution. This is also shown in literature for drift reduction (Zande et al., 2008) and buffer strips (Krutz et al., 2005; Reichenberger et al., 2007).

Tillage methods are clearly related to transport pathways of pesticides and are therefore extensively studied (Alletto et al., 2010). However, the effectiveness of tillage adjustments to reduce either overland transport or leaching of pesticides is reviewed as unclear and often small. In addition, Flury (1996) indicates that for tillage methods the transport pathways are often mutually exclusive. So if overland flow is reduced, infiltration will most likely increase and, as a consequence the leaching risk for pesticides increases as well. The performed quantitative analysis also shows this uncertainty for tillage methods, given a very wide variation in experimental results for both groundwater and surface water pollution, with average effectiveness in both cases above 1, indicating a negative effect on pollution. However, many studies focussing on the effect of tillage on the overland pathway show a slightly positive effect on surface water pollution. So, as stressed by Alletto (2010), tillage method changes can be used to reduce pollution of mainly surface water, but never as main measure. It can be applied in combination with other measures. To understand the effectiveness of tillage method changes a more detailed quantitative analysis could provide useful insight, in this case co variates like climatic zone, soil type and vegetation type should be included.

As expected, input control measures are shown to be effective in the quantitative analysis, all reported experiments show a decrease of pesticide transport to both ground and surface water sources. However, input control measure often are less easily applied and adopted due to the effect of the reduced pesticide uses on yields and weed pressure. A good alternative approach has to be present otherwise this measure will not be profitable for farmers to apply (Gentz et al., 2010). A combined approach, with Integrated Pest Management (IPM) is regarded as an effective measure (Reichenberger et al., 2007). However, investigation on the effectiveness of IPM is scarce because of the larger (farm) scale on which this is often applied, which makes quantitative analysis of effectiveness complex.

Within the case studies also examples are given of national laws or regulations which restrict or prohibit the use of pesticides. Such measures are effective on a higher policy levels and not reviewed or studied in detail for this report, however this might be a promising approach to reduce pesticide pollution of drinking water sources.

In some case studies approaches of social change are used, where not the direct physical measure on the field is the object of study or the reduction of used pesticides, but more the management choices that farmers make. This also relates to other work packages within the FAIRWAY project. We did not elaborate on this approach since this is outside the scope of this review report.

7.2 NEXT STEPS

The overall objective of the FAIRWAY project is:

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

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

The review presents a quantitative analysis of experimental measures as derived from 38 publications. As indicated in literature and in the discussion of the report, identifying the most promising measures to reduce pollution of drinking water sources must include increased detailed on climatic zones and soil types. This will be object of further research during the FAIRWAY project. Besides that, costs, applicability and adoptability are often not included in studies about measure effectiveness, but are of major importance to identify promising measures. The starting point for measure quality will remain its effectiveness, since this is what will actually reduce pollution. However separate investigation of cost, applicability and adoptability will have to be done, either through literature studies or further investigation of expert and user knowledge in the available case studies. Moreover cooperation is started with the related EU project WaterProtect. Cooperation with WaterProtect will create synergy; both projects have similar objectives but different approaches. While the FAIRWAY review focusses more on the scientific basis and robustness of measures (in terms of effectiveness and efficiency), the WaterProtect review focusses more on collecting empirical information related to the feasibility and adoptability of measures.

8. CONCLUSIONS

This report reviewed studies and literature sources on the effectiveness of agricultural management practises to reduce pollution of ground and surface water sources by pesticides. The report contains both an qualitative overview of available literature and the evaluation of measures based on that and a quantitative analysis of experimental studies testing the effectiveness of specific measures to reduce pollution.

Conventional well known measures like vegetated buffers, drift reduction technology and Integrated Pest Management (IPM) are shown to be effective measures with a high potential to reduce pesticide pollution. Buffers are the main effective measure to reduce surface water pollution by overland runoff. Physical agronomical measures are less effective to reduce leaching to groundwater, but IPM which includes reduction of the pesticide input is most effective in this case. These results, described in literature are confirmed by the quantitative analysis of multiple studies we performed in this report. In addition, the analysis showed that tillage methods have a very high variation in terms of their effect on pollution, which can even be counter effective, i.e. increasing the risk of pollution to ground or surface water. Therefore, tillage methods are not regarded as an effective approach to reduce pollution, as concluded by Alletto et al. (2010).

The main findings of this review are:

- Measures can be categorized into either source-based or pathway-based measures. Each pathway (leaching to ground water, or overland transport to surface water) has its own specific and effective measures. Besides that spray drift forms a separate pathway to surface water.
- The driving factors for pesticide pollution are in the first place water facilitated transport through or over the soil. Secondly also erosion of sediment can cause transport, when sorbed particles are transported. Areal transport occurs with spray drift during application, and is a threat for surface water quality.
- Buffers, drift reduction measures and IPM are effective measures to reduce pollution.
- Tillage methods are extensively studied in relation to pesticide pollution, but they do not have a clear effect and are thus not effective to be used to reduce pollution of either ground or surface water
- For all measures, the local design and pedo-climatic conditions are of major importance to be effective. A quantified relation between pedo-climatic conditions and measure design or effectiveness is still lacking and would improve the applicability of these measures.

Measures implemented in the case studies of the FAIRWAY project included the implementation of biobeds or bio filters for point source pollution and the use of policy and management changes on higher levels. The biobeds/filters did show good results in the case study evaluation and the quantitative analysis, however, further data on their effectiveness is scarce. Policy and community approaches to pesticide use and pollution are not reviewed in this report, but they can affect the amount of pesticide used to a large extent and thus affect the risk of pollution.

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ANNEX 1. OVERVIEW OF MEASURES TO REDUCE PESTICIDE POLLUTION OF DRINKING WATER RESOURCES.

Measures identified in FAIRWAY case studies:

Location	Netherlands - Noord Brabant
Targeted pollutants	pesticides
Target of the measure	quality surface water resources
Name of measure	Installing a wash basin and processing/purefying contaminated water
Description	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).
Mode of action	End-of pipe
Expected effectiveness	Low: 5-10% decrease in concentration/load
Expected cost	Unknown
Underpinning	Yes (> 5 reports)
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	No (on <25% of the addressees)
Other benefits	No
Disadvantages	No
References	http://edepot.wur.nl/211455
	http://library.wur.nl/WebQuery/wurpubs/fulltext/237692
	http://edepot.wur.nl/213674
Additional comments	

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

Location	France - La Voulzie
Targeted pollutants	Pesticides
Target of the measure	quality groundwater resources
Name of measure	Rotation improvement
Description	Respect for an annual maximal proportion of surfaces

Mode of action	Improvement of the crop rotation to minimize the pesticide use
Expected effectiveness	Moderate: 10-25% decrease in concentration/load
Expected cost	High: 50-100 euro per ha
Underpinning	Partly (1-5 reports)
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	No (on <25% of the addressees)
Other benefits	Yes, contributes to landscape diversity
Disadvantages	
References	1. Reichenberger S et al, 2007
Additional comments	

Location	France - La Voulzie
Targeted pollutants	pesticides
Target of the measure	quality groundwater resources
Name of measure	Pesticide decreace
Description	Respect for an maximal IFT fixed for year
Mode of action	Reduction of the maximun pestidide load by the farmer during the cropping season.
Expected effectiveness	Moderate: 10-25% decrease in concentration/load
Expected cost	High: 50-100 euro per ha
Underpinning	Partly (1-5 reports)
Applicability	Partly (on 25-75% of the agricultural land)
Adoptability	No (on <25% of the addressees)
Other benefits	No
Disadvantages	
References	1. Reichenberger S et al, 2007
Additional comments	

Location	England - Anglian Region (UoL)
Targeted pollutants	Pesticides
Target of the measure	Quality surface water resources
Name of measures	1. Network engagement (information events/discussions/ field days) 2. Alternative product substitution (replace metaldehyde with ferric phosphate) 3. Limited intervention (control for comparison) Metaldehyde best practices – innovative approaches to farmer engagement e.g. MAP.
Description	The Anglian region case study is a social science approach to understanding farmer motivation for uptake of 'best practice' for farm management systems to mitigate on farm pesticide use with a specific reference to the use of metaldehyde (slug control), and its impact on drinking water bodies. The UoL study, in conjunction with Anglian Water(AW) is comparing three approaches to encourage behavioural change in farmers to reduce on-farm pesticide usage, across three different areas in the Anglian region: - i) <u>Knowledge transfer through network engagement</u> with agronomists and farmers by Anglian Water catchment advisors, ii) <u>Product substitution</u> for metaldehyde and subsidies to offset increase product cost to the farmer; the substitute product is easier to remove from drinking water. In these areas, the AW's "Slug It Out" campaign in 2015, secured 100% farmer agreements on over 7,600ha, to switch to an alternative method of slug control using ferric phosphate. Water quality has been monitored.

	Farmers receive a financial 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) iii) In a catchment with minimum intervention by Anglian Water, looking at the development of innovative approaches to farmer engagement based on multiple actor platforms (MAPs) - this area is in the Cringle Brook Catchment. This approach will be monitored and compared to the two other modes of farmer engagement UoL (LIAT) are using surveys and interviews with farmers in the three study areas, to gather data around farmers' current pesticide handling behaviour and practices, business characteristics, factors influencing practices and cost-effectiveness as well as wider effects.
Mode of action	Reduction of input through behaviour change
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	Unknown
Applicability	Unknown
Adoptability	1.Knowledge Transfer – unknown; 2.Product substitution – Yes, more than 75% of the addressees (post SIO will determine the sustainbility and adoption of this method); 3. MAP (Cringle Brook) - Unknown
Other benefits	Unknown
Disadvantages	Unknown
References	J. Mills et al (2017). Engaging farmers in enviromental management through a better understanding of behaviour. Agric Hum Values(2017) 34:83-299 K Prager, Rl Creaney (2017) Achieving on-farm practice change through facilitated group learning:Evaluating the effectiveness of monitor farms and discussion . Journal of Rural Studies 56(2017) 1 -11 M Le Gall, J F. Tooker (2017)Developing ecologically based pest management programs for terrestrial molluscs in field and forage crops. J Pest Sci (2017) 90:825–838 S.P. Pullan et al.(2016). Development and application of a catchment scale pesticide fate and transport model for use in drinking water risk assessment. Science of Total Environment 563-564 (2016) 434- 447 J.W. Bloodworth et al. (2015) Developing a multi-pollutant conceptual framework for the selection and targeting of interventions in water industry catchment management schemes.Journal of Environmental Management 161 (2015) 153e162 M. Reed et al (2017) A theory of participation: what makes stakeholder and public engagement in environmental managementwork? Restoration Ecology J de Vente et al.(2016) How does the context and design of participatory decision making processesaffect their outcomes? Evidence from sustainable land management in global drylands.Ecology and Society 21(2): 24 Herman Brouwer and Jim Woodhill with Minu Hemmati, Karèn Verhoosel and Simone van Vugt The MSP guide 2016 Herman Brouwer& Jan Brouwers MSP Tool Guide

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

Location	Denmark - Island Tunø and Aalborg
Targeted pollutants	pesticides
Target of the measure	quality groundwater resources
Name of measure	Legal measures.
Description	Farmers cannot use pesticides which will exceed the treshold of 0,1 µg / l.
Mode of action	Substitution of contaminant input
Expected effectiveness	High: >25% decrease in concentration/load
Expected cost	Low: < 10 euro per ha
Underpinning	Yes (> 5 reports)
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Yes (more than 75% of the addressees)
Other benefits	No
Disadvantages	No
References	3. Rosenbom, et al. 2016: http://pesticidvarsling.dk/xpdf/vap-results-99-16.pdf
Additional comments	References are written in Danish

Location	Denmark - Island Tunø and Aalborg
Targeted pollutants	pesticides
Target of the measure	quality groundwater resources
Name of measure	Economic measure
Description	Variable tax on different pesticides depending on their impact on the environment
Mode of action	Reducing the application of the worst pesticides
Expected effectiveness	High: >25% decrease in concentration/load
Expected cost	Moderate: 10-50 euro per ha
Underpinning	Partly (1-5 reports)
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Yes (more than 75% of the addressees)
Other benefits	Other environmental effects and human health
Disadvantages	Cost
References	
Additional comments	References are written in Danish

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

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

Targeted pollutants	pesticides
Target of the measure	quality surface water resources
Name of measure	Installation of a pesticide sprayer loading area and wash down area
Description	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
Mode of action	Source Reduction
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	Partly (1-5 reports)
Applicability	Unknown
Adoptability	Unknown
Other benefits	No
Disadvantages	No
References	https://voluntaryinitiative.org.uk/media/1085/design_manual_updated_922015.pdf
Additional comments	

Location	Northern Ireland - Derg Catchment
Targeted pollutants	pesticides
Target of the measure	quality surface water resources
Name of measure	Biobeds
Description	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
Mode of action	Source Reduction
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	Partly (1-5 reports)
Applicability	Unknown
Adoptability	Unknown
Other benefits	No
Disadvantages	No
References	https://voluntaryinitiative.org.uk/media/1085/design_manual_updated_922015.pdf
Additional comments	

Location	Northern Ireland - Derg Catchment
Targeted pollutants	pesticides
Target of the measure	quality surface water resources
Name of measure	Biofilters
Description	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.
Mode of action	Source Reduction
Expected effectiveness	Unknown

Expected cost	Unknown
Underpinning	Partly (1-5 reports)
Applicability	Unknown
Adoptability	Unknown
Other benefits	No
Disadvantages	No
References	https://voluntaryinitiative.org.uk/media/1085/design_manual_updated_922015.pdf
Additional comments	

Location	Northern Ireland - Derg Catchment
Targeted pollutants	pesticides
Target of the measure	quality surface water resources
Name of measure	Pesticide storage unit
Description	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.
Mode of action	Source Reduction
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	Partly (1-5 reports)
Applicability	Unknown
Adoptability	Unknown
Other benefits	No
Disadvantages	No
References	https://voluntaryinitiative.org.uk/media/1085/design_manual_updated_922015.pdf
Additional comments	

Location	Northern Ireland - Derg Catchment
Targeted pollutants	pesticides
Target of the measure	quality surface water resources
Name of measure	Contractor for Weed Wiping to replace MCPA Use
Description	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
Mode of action	Source Reduction
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	No (≤ 1 report)
Applicability	Unknown
Adoptability	Unknown
Other benefits	No
Disadvantages	No
References	
Additional comments	

Location	Slovenia - Dravsko polje

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

Location	Slovenia - Dravsko polje
Targeted pollutants	pesticides
Target of the measure	quality surface and groundwater
Name of measure	Prohibition of problematic PPP
Description	Prohibits the use for the health and environment harmful PPPs. Has to be scientificly confirmed. In use all over the country with stricter list of prohibited PPP on drinking water protection zones.
Mode of action	a) Reduction / substitution of contaminant input
Expected effectiveness	Unknown
Expected cost	Unknown
Underpinning	No (≤ 1 report)
Applicability	Yes (on more than 75% of the agricultural land)
Adoptability	Yes (more than 75% of the addressees)
Other benefits	positive effect on biodiversity
Disadvantages	No
References	Glavan, M., Pintar, M. and Urbanc, J., 2015. Spatial variation of crop rotations and their impacts on provisioning ecosystem services on the river Drava alluvial plain. Sustainability of Water Quality and Ecology, 5(0): 31-48. https://doi.org/10.1016/j.swaqe.2015.01.004

	Glavan M, Jamšek A, Pintar M. 2017. Modelling Impact of Adjusted Agricultural Practices on Nitrogen Leaching to Groundwater. In Water Quality, Tutu H (ed). InTech: Rijeka, Croatia. https://www.intechopen.com/books/water-quality/modelling-impact-of-adjusted-agricultural-practices-on-nitrogen-leaching-to-groundwater
Additional comments	Monitoring results show that concentrations of pesticides and their products from red list (e.g. atrazine) have droped after inplementaion of this measure in all groundwaters.
	Scientific literature in Slovene and English language is quite limited for our Case study - practicaly non-existent.

Measures listed in literature:

Type of measure	Soil management
Measure	Cultivate compacted tillage soils to increase aeration and water infiltration rates; Endeavour to establish a vegetative cover from a drilled crop, through natural regeneration or broadcast (barley) seed.
Targetted pollutant	pesticides
Mode of action	The method reduces surface runoff and soil erosion. Cultivation of the soil surface (during dry conditions) will increase surface roughness, which will enhance water infiltration rates into the soil and reduce surface runoff volumes.
Target of measure	
Expected effectiveness	-
	unknown
Expected implementation costs	50 - 1,600 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	The method is applicable to all tillage land where soils are compacted, and particularly sloping land in high rainfall areas.
quantified (classes):	Unknown
Adoptability of the measure	If compaction is identified as an issue it is likely to be alleviated by farmers
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	There may be a small reduction in direct N2O emissions, as a result of increased soil aeration.
(Phosphorous)	Particulate P and associated sediment loss reductions would typically be in the range 10 and 50%.
(Carbon / CH4)	CO2 emissions would be increased by a small amount from the additional cultivation.
(Other)	
Disadvantages	unknown
References	DEFRA report

Type of measure	Soil management
Measure	Cultivate and drill land along the slope (contour) to reduce the risk of developing surface runoff
Targetted pollutant	pesticides
Mode of action	Cultivate and drill land along the slope (contour) to reduce the risk of developing surface runoff. The ridges created across the slope increase down-slope surface roughness and provide a barrier to surface runoff. As a result, particulate P and associated sediment losses will be reduced
Target of measure	
Expected effectiveness	-
	unknown
Expected implementation costs	20 - 500 £/farm, depending on the farm system
cost class:	Low: <1000 £/farm
Underpinning of the measure	Partly (1-5 reports)

Applicability of the measure: qualitative	applicable to all cultivated soils where fields have simple slope patterns
quantified (classes):	Unknown
Adoptability of the measure	Uptake is most likely on fields with gentle/moderate slopes and simple slope patterns, and that are longer across slope than in the upslope direction
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	-
(Phosphorous)	Limited evidence indicates that cultivating/drilling across the slope can reduce particulate P and associated sediment losses by 40-80%.
(Carbon / CH4)	-
Disadvantages	unknown
References	DEFRA report

Type of measure	Soil management
Measure	Leave autumn seedbeds rough (Avoid creating a fine autumn seedbed that will ‘slump’ and run together)
Targetted pollutant	other pollutants
Mode of action	Avoid creating a fine autumn seedbed that will ‘slump’ and run together; Leaving the autumn seedbed rough encourages surface water infiltration and reduces the risk of surface runoff, thereby reducing particulate P and associated sediment loss risks
Target of measure	
Expected effectiveness	-
	unknown
Expected implementation costs	100 - 2,500 £/farm, depending on the farm system
cost class:	Moderate: 1000 - 5000 £/farm
Underpinning of the measure	No (≤ 1 report)
Applicability of the measure: qualitative	applicable to the establishment of ‘large’ seeded crops on tillage land (particularly on light soils). It is most applicable to winter cereal crops that can establish well in coarse seedbeds
quantified (classes):	Unknown
Adoptability of the measure	Low, due to pest (particularly slug) and weed control issues.
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	-
(Phosphorous)	Limited field evidence indicates that particulate P and associated sediment losses can be reduced by up to 20%.
(Carbon / CH4)	CO_2 emissions would be reduced by a small amount from less cultivation.
Disadvantages	Yes, decreases crop quality and contributes to (more) pest and diseases
References	DEFRA report

Type of measure	Soil management
Measure	Use tines to disrupt tramlines or delay their establishment until the spring

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

Type of measure	precautionary measure
Measure	Drift-reducting technology
Targetted pollutant	pesticides
Mode of action	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.
Target of measure	quality of surface and groundwater
Expected effectiveness	
	Moderate: 10-25% decrease in concentration/load
Expected implementation costs	
cost class:	Unknown
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Yes (on more than 75% of the agricultural land)
Adoptability of the measure	
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
Disadvantages	
References	Otto, S, D Loddo, C Baldoin, and G Zanin. 2015. "Spray drift reduction techniques for vineyards in fragmented landscapes." Journal of environmental management 162:290-298.

Type of measure	precautionary measure
Measure	Wash basin voor cleaning etc
Targetted pollutant	pesticides
Mode of action	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
Target of measure	quality surface water resources
Expected effectiveness	
	Low: 5-10% decrease in concentration/load
Expected implementation costs	
cost class:	Unknown
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Yes (on more than 75% of the agricultural land)
Adoptability of the measure	
quantified (classes):	No (on <25% of the addressees)
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
Disadvantages	0

References	https://voluntaryinitiative.org.uk/media/1085/design_manual_updated_922015.pdf; http://edepot.wur.nl/211455; http://edepot.wur.nl/213674

Type of measure	precautionary measure
Measure	Biobeds
Targetted pollutant	pesticides
Mode of action	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
Target of measure	quality surface water resources
Expected effectiveness	
	Unknown
Expected implementation costs	
cost class:	Unknown
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Unknown
Adoptability of the measure	
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
Disadvantages	
References	https://voluntaryinitiative.org.uk/media/1085/design_manual_updated_922015.pdf

Type of measure	precautionary measure
Measure	Biofilters
Targetted pollutant	pesticides
Mode of action	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.
Target of measure	quality surface water resources
Expected effectiveness	
	Unknown
Expected implementation costs	
cost class:	Unknown
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Unknown
Adoptability of the measure	
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	

Disadvantages	
References	https://voluntaryinitiative.org.uk/media/1085/design_manual_updated_922015.pdf

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

Type of measure	Land use and management
Measure	Rotation improvement
Targetted pollutant	pesticides
Mode of action	Respect for an annual maximal proportion of surfaces. This leads to the imporvement of crop rotation to minimize the pesticide use.
Target of measure	quality groundwater resources
Expected effectiveness	
	Moderate: 10-25% decrease in concentration/load
Expected implementation costs	
cost class:	High: 50-100 euro per ha
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Partly (on 25-75% of the agricultural land)
Adoptability of the measure	
quantified (classes):	No (on <25% of the addressees)
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
(Other)	Yes, contributes to landscape diversity
Disadvantages	No
References	Reichenberger, Stefan, Martin Bach, Adrian Skitschak, and Hans-Georg Frede. 2007. "Mitigation strategies to reduce

	pesticide inputs into ground-and surface water and their effectiveness; a review." Science of the Total Environment 384 (1):1-35.

Type of measure	Dosage reduction
Measure	Application rate reduction
Targetted pollutant	pesticides
Mode of action	Respect for an maximal IFT fixed for year. Reduction of the maximun pestidide load by the farmer during the cropping season.
Target of measure	quality groundwater resources
Expected effectiveness	
	Moderate: 10-25% decrease in concentration/load
Expected implementation costs	
cost class:	High: 50-100 euro per ha
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Partly (on 25-75% of the agricultural land)
Adoptability of the measure	
quantified (classes):	No (on <25% of the addressees)
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
Disadvantages	No
References	1. Reichenberger S et al, 2007

Type of measure	precautionary measure
Measure	Selection of alternative pesticide
Targetted pollutant	pesticides
Mode of action	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...... 2nd example 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)

Target of measure	quality surface water resources
Expected effectiveness	
	Unknown
Expected implementation costs	
cost class:	Unknown
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Unknown
Adoptability of the measure	
quantified (classes):	Yes (more than 75% of the addressees)
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
Disadvantages	Unknown
References	M Le Gall, J F. Tooker (2017)Developing ecologically based pest management programs for terrestrial molluscs in field and forage crops. J Pest Sci (2017) 90:825–838;

Type of measure	Dosage reduction
Measure	Prohibition of pesticide
Targetted pollutant	pesticides
Mode of action	Prohibits the use for the health and environment harmful PPPs. Has to be scientificly confirmed. In use all over the country with stricter list of prohibited PPP on drinking water protection zones. OR Farmers cannot use pesticides which will exceed the treshold of 0,1 µg / l.
Target of measure	quality surface and groundwater
Expected effectiveness	
	High: >25% decrease in concentration/load
Expected implementation costs	
cost class:	Moderate: 10-50 euro per ha
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Yes (on more than 75% of the agricultural land)
Adoptability of the measure	
quantified (classes):	Yes (more than 75% of the addressees)
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
(Other)	Positive effect on biodiversity
Disadvantages	Yes, decreases crop yield
References	3. Rosenbom, et al. 2016: http://pesticidvarsling.dk/xpdf/vap-results-99-16.pdf

Type of measure	precautionary measure
Measure	Windbreaks
Targetted pollutant	pesticides
Mode of action	Main aim is to prevent the drift of the pesticides to offsite locations. The windbreaks decrease the wind speed, and

	thus transport potential. They also function buffer to catch the drifting pesticides.
Target of measure	quality surface water resources
Expected effectiveness	
	High: >25% decrease in concentration/load
Expected implementation costs	
cost class:	Unknown
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Yes (on more than 75% of the agricultural land)
Adoptability of the measure	
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
Disadvantages	Yes, decreases crop yield
References	Otto, S, D Loddo, C Baldoin, and G Zanin. 2015. "Spray drift reduction techniques for vineyards in fragmented landscapes." Journal of environmental management 162:290-298.

Type of measure	Land use and management
Measure	No spray zones/buffer
Targetted pollutant	nitrate & pesticides
Mode of action	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
Target of measure	quality surface water resources
Expected effectiveness	
	Moderate: 10-25% decrease in concentration/load
Expected implementation costs	
cost class:	Unknown
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	
quantified (classes):	No (on <25% of the agricultural land)
Adoptability of the measure	
quantified (classes):	No (on <25% of the addressees)
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
Disadvantages	Yes, decreases crop yield
References	

Type of measure	application method
Measure	IPM, precision farming and timing
Targetted pollutant	nitrate & pesticides
Mode of action	Spatial and temporal targeted nitrate and pesticides application
Target of measure	quality groundwater resources

Expected effectiveness	
	High: >25% decrease in concentration/load
Expected implementation costs	
cost class:	Low: < 10 euro per ha
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Unknown
Adoptability of the measure	
quantified (classes):	Partly (on 25-75% of the addressees)
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
(Other)	Yes, decreases greenhouse gas emissions
Disadvantages	
References	http://www.endure-network.eu/endure_publications/papers_in_scientific_journals2

Type of measure	precautionary measure
Measure	Pesticide storage unit
Targetted pollutant	pesticides
Mode of action	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.
Target of measure	quality surface water resources
Expected effectiveness	
	Unknown
Expected implementation costs	
cost class:	Unknown
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Unknown
Adoptability of the measure	
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
(Other)	
Disadvantages	No
References	https://voluntaryinitiative.org.uk/media/1085/design_manual_updated_922015.pdf

Type of measure	Dosage reduction
Measure	Economic (tax) measure
Targetted pollutant	pesticides
Mode of action	Variable tax on different pesticides depending on their impact on the environment
Target of measure	quality groundwater resources

Expected effectiveness	
	High: >25% decrease in concentration/load
Expected implementation costs	
cost class:	Moderate: 10-50 euro per ha
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Yes (on more than 75% of the agricultural land)
Adoptability of the measure	
quantified (classes):	Yes (more than 75% of the addressees)
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
(Other)	Other environmental effects and human health
Disadvantages	Unknown
References	

Type of measure	precautionary measure
Measure	Network engagement
Targetted pollutant	pesticides
Mode of action	'Network engagement' embedding information and communication at all levels from supply chain to agronomist to farmers to stimulate change of practice. This is being done by an Anglian Water agricultural adviser. In partnerships with Anglian Water(AW), UoL is conductiong a farmer survey to review the effectiveness of knowledge transfer, using AW catchment advisors, to promote on farm best pracice for Metaldehyde use.
Target of measure	quality surface water resources
Expected effectiveness	
	Unknown
Expected implementation costs	
cost class:	Unknown
Underpinning of the measure	Unknown
Applicability of the measure: qualitative	
quantified (classes):	Unknown
Adoptability of the measure	
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
Disadvantages	Unknown
References	1. J. Mills et al (2017). Engaging farmers in enviromental management through a better understanding of behaviour. Agric Hum Values(2017) 34:83-299; 2. K Prager, Rl Creaney (2017) Achieving on-farm practice change through facilitated group learning:Evaluating the effectiveness of monitor farms and discussion . Journal of Rural Studies 56(2017) 1 -11

Type of measure	application practise
Measure	Biological pest control
Targetted pollutant	pesticides
Mode of action	The use of natural enemies, or other biological methods to manage and reduce pest impact on yield. Often as a part of IPM.
Target of measure	quality surface and groundwater
Expected effectiveness	
	Unknown
Expected implementation costs	
cost class:	Unknown
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	there is a lot of literature, but often they do not compare with a pesticide system in terms of pollution. So still data availability may be low.
quantified (classes):	Unknown
Adoptability of the measure	
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
Disadvantages	Unknown
References	

Type of measure	Dosage reduction
Measure	mechanical weed control
Targetted pollutant	pesticides
Mode of action	Mechanical measures based on GPS techniques, infrared or laser techniques based on GPS techniques. These measures are well studied for organic agriculture and IPM systems. However the negative aspects of this methods in terms of workload, accuracy etc, should be taken into account during evaluation.
Target of measure	quality surface and groundwater
Expected effectiveness	
	Unknown
Expected implementation costs	
cost class:	Unknown
Underpinning of the measure	Yes (> 5 reports)
Applicability of the measure: qualitative	there is a lot of literature, but often they do not compare with a pesticide system in terms of pollution. So still data availability may be low.
quantified (classes):	Unknown
Adoptability of the measure	
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
Disadvantages	Unknown
References	

Type of measure	Land use and management
Measure	constructed wetlands
Targetted pollutant	pesticides
Mode of action	Promising method to reduce inputs via runoff/erosion and drift into surface waters. As a negative effect it requires a lot of area to be really effective. The better results are shown for strongly sorbing pesticides, however the size of the wetland has to increase if less sorbing pesticides are at aim
Target of measure	quality surface water resources
Expected effectiveness	
	Moderate: 10-25% decrease in concentration/load
Expected implementation costs	
cost class:	Unknown
Underpinning of the measure	Partly (1-5 reports)
Applicability of the measure: qualitative	
quantified (classes):	Unknown
Adoptability of the measure	
quantified (classes):	Unknown
Other benefits, qualitative assessment (Nitrogen)	
(Phosphorous)	
(Carbon / CH4)	
(Other)	Increases biodiversity, and landscape diversity.
Disadvantages	Yes, decreases crop yield
References	Moore, MT, R Schulz, CM Cooper, S Smith, and JH Rodgers. 2002. "Mitigation of chlorpyrifos runoff using constructed wetlands." Chemosphere 46 (6):827-835.; Tournebize, Julien, Cedric Chaumont, and Ülo Mander. 2017. "Implications for constructed wetlands to mitigate nitrate and pesticide pollution in agricultural drained watersheds." Ecological Engineering 103:415-425.