DRAINAGE + LEACHING

Best Management Practices to reduce water pollution with Plant Protection Products from Drainage and Leaching

TOPPS

Water Protection

About TOPPS

TOPPS stands for "Train Operators to Promote best management Practices & Sustainability".
The TOPPS projects started in 2005 with a 3-year EU-Life programme co-funded project by ECPA and the EU Commission to reduce losses of Plant Protection Products (PPPs) to water from point sources. The initial point sources project was conceived as a multi-stakeholder project including 15 EU Member States, twelve local partners and nine subcontractors. Follow-up phases of the TOPPS project since 2008 have extended into more countries (point source projects in 23 countries), and broadened the scope of the project to also address the reduction of diffuse sources (spray drift & run-off) in seven countries). TOPPS water protection (2015 to 2018) now offers a broad set of Best Management Practices (BMPs) covering point and all diffuse source entry pathways into water. With the last part of the Best Management Practices how to reduce water contamination via drainage and leaching, TOPPS offers a complete framework of practical recommendations to mitigate the risk of PPP losses to ground and surface water. Aspects such as sprayer optimisation and improvements of infrastructure are also included in the context of their potential to reduce the risk for water contamination through Plant Protection Product losses.

Further information for farmers, advisers and stakeholders (booklets, flyers, presentations, training courses, as well as a picture and video gallery) can be found on the TOPPS websites:

www.TOPPS-life.org (documents site)
www.TOPPS-drift.org (online tool for drift risk and mitigation)
www.TOPPS-eos.org (education tool on how to optimise sprayers for more water protection)

TOPPS projects develop and recommend BMPs developed together with European experts and stakeholders. Intensive dissemination through information, training and demonstration is conducted in European countries to create awareness and help implement better water protection.

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Photos:
Pictures which are not referenced originate from TOPPS Partners.

Contents

FOREWORD

ECPA sees the protection of water as a key pillar of its work and is determined to continuously improve the correct use of pesticides to help underpin sustainable and productive agriculture.

We therefore set ourselves the task of working together with our own national associations and a broad group of international partners to develop and disseminate appropriate measures, recommendations and training materials to ensure that all relevant aspects of water protection are addressed, and that a broad consensus is achieved on the recommended measures (referred to as Best Management Practices – BMPs).

This collaborative effort to build and improve available tools for water protection also fits very closely with the UN Sustainable Development Goals (SDGs) which have become a global reference for driving sustainable human development, and with the objectives contained in relevant EU legislation such as the Water Framework Directive (WFD) and the Sustainable Use of Pesticides Directive (SUD). This effort has resulted in the multi-stakeholder TOPPS projects, which have now been running for more than 12 years.

The first phase of the project was launched in 2005 in 15 EU countries with a focus on reducing point sources (such as spills, or inappropriate equipment cleaning practices), and this was 50% co-funded by the EU-Life programme. The ongoing multi-partner TOPPS project phases have now extended the work to 23 countries, and broadened the available BMPs, diagnosis tools and training materials beyond point sources. These now also cover the key diffuse emission routes to water (primarily spray drift and run-off/erosion).

The BMP package is now complemented with this BMP booklet on how to reduce PPP losses from drainage and leaching. The TOPPS BMPs package therefore now offers a complete practical framework of recommendations to help protect groundwater and surface water.

The TOPPS projects' approach seeks to address the whole crop protection process, and to raise awareness of the potential to reduce losses to water through the correct behaviour of the operator and optimised sprayers and infrastructure. It is our hope that the BMPs will be used as a basis to inform, educate and train operators, advisers and stakeholders in a range of different ways – in the classroom, in the field and through demonstration. ECPA is committed to promoting the implementation of these BMPs.

I would like to thank all the partners and experts for their great efforts and contributions to the TOPPS projects, both in terms of the technical know-how they have brought to the table and their willingness to work together to achieve our common goal to protect water. I also hope that these BMPs will help spark the enthusiasm that will be needed to implement these recommendations "on the ground" and help create awareness and spread the knowledge which is necessary for the sustainable use of pesticides and a high level of water protection.

Jean-Philippe Azoulay
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European
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Introduction

Leaching is the process of pesticide movement with water flowing down in the soil profile. In this document, two terms – drainage and leaching – are used to distinguish where the water flows. Hence, drainage covers the case when this water flows into a subsurface drainage network connected to surface water, while leaching covers the case when it flows into groundwater. Downward water flow within soil profiles moves soil nutrients and fertilisers toward surface water and groundwater, which can lead to water contamination if not managed properly. The focus of this document is to provide information about the Best Management Practices (BMPs) to minimise pesticide water contamination by reducing pesticide movement by drainage and leaching. This BMP approach can also be used to reduce the movement of soil nutrients and fertilisers into surface water and groundwater.

In order for pesticide uses in crop protection to be acceptable to society in general, they need to deliver their benefits safely. With regard to drainage and leaching, this means not resulting in unacceptable contamination of surface water or groundwater. The strict procedures for registering pesticide use in the EU ensure that this is the case under most circumstances. For example, passing EU FOCUS modelling risk assessment scenarios demonstrates that unacceptable levels of pesticides in surface water or groundwater have a low likelihood of occurring due to drainage and leaching transport.

However, unacceptable concentrations from drainage and leaching sometimes occur for a limited number of pesticides in more extreme scenarios. This is usually due to pesticide product use patterns and pesticide properties combining adversely with local soil and climate characteristics, as well as field management practices. Hence, the BMPs about pesticide use in this document are largely meant to be used as risk management tools, in reaction to unacceptable findings of specific pesticides in surface water or groundwater. Crop protection specialists and water advisors can thus use this document as a guide to developing practical advice to reduce and prevent unacceptable pesticide concentrations in water due to drainage and leaching transport under adverse local conditions.

In contrast, selected agronomic BMPs (e.g. cover crops, crop rotation) in this document can be used proactively, since they are less product- and site-specific: they are a part of general advice about sustainable agriculture and protection of farmed land and its surrounding water bodies. This is similar to TOPPS advice to reduce spray drift and run-off. These BMPs apply generically to all pesticides and can thus be applied proactively (Ref. 1). Farmers, policymakers and other interested stakeholders can use this document to raise awareness and to support measures reducing pesticide contamination of water through leaching and drainage. Implementation of methods for practical risk diagnosis and appropriate BMP measures benefit farmers, the environment and society, minimising the risk of unacceptable pesticide concentrations in water.

BACKGROUND INFORMATION TO FURTHER UNDERSTAND DRAINAGE AND LEACHING BMPs

1 TERMS AND DEFINITIONS

a) The soil profile

The soil profile represents the soil's vertical development from the soil surface down to the underlying geological material such as solid rocks or unconsolidated geological material like glacial till. Soil profile development results in a set of more-or-less distinct soil horizons, which is a reflection of how soil properties vary with depth. These properties are vital, because they determine the behaviour and characteristics of different soils, e.g. how water flows through the soil, the ability to retain chemicals against this flow, how microbial activity levels vary (as a broad indicator of the ability to break down organic chemicals like pesticides) and their potential for crop productivity. Well-developed arable soils normally comprise three main horizons (A, B, C), as seen below in Figure 1.

Figure 1: Typical soil profile (Ref. 2)

A Horizon:
Also known as topsoil, it is the layer characterised by the accumulation of organic matter (i.e. the decayed remains of plants and animals as humified substances), so it is usually darker than the subsoil layers below. In arable soils, this horizon is often disturbed and homogenised via mechanical soil management practices (e.g. ploughing).

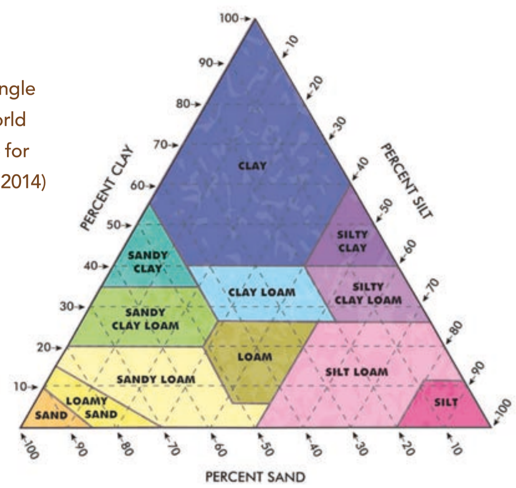
B Horizon:
Also called the illuvial horizon to denote the movement and accumulation of material from the topsoil into the B horizon, such as clay and metal oxides, or even organic matter. The biological activity levels are generally lower than in topsoil, and on average it contains less than half as much organic matter as topsoil and typically has fewer roots and hosts fewer earthworms. It is also not subject to agricultural operations, unless the soil is subsoiled or has a subsurface drainage system installed.

C Horizon:
This is the transition zone between soil and geological material, comprising largely weathered geological material, with biological activity and organic matter content typically dropping further in comparison with the B horizon. The C horizon overlies unchanged bedrock or geological deposits such as glacial till.

b) Soil Texture and Structure

The distribution of sizes for mineral particles (clay: <2 µm diameter; silt: 2 to 63 µm; sand: 63 to 2,000 µm) in soil determines the texture of the soil, which is classified in various ways as a convenient short-hand terminology (see Figure 2). Soil texture is one of the most stable soil properties and a useful index of several other properties that determine a soil's agricultural potential, particularly its water-holding capacity and its permeability that affect water flow through soil.

Figure 2: Soil texture triangle (Ref. 3: FAO World Reference Base for Soil Resources, 2014)



The permeability of soil for water is also strongly affected by soil structure – the way soil particles are arranged geometrically in the form of soil aggregates – because this affects the nature of the resulting pores between the aggregates, especially larger pores which are highly permeable. Soil aggregation is strongly influenced by soil texture and soil organic matter content.
Several types of soil structure can be identified and related to water flow (see Figure 3), as well as air movement, biological activity, root growth and seedling emergence.
Key types of soil structure include:

Granular and crumb structure

These structures comprise sand, silt and clay particles that resemble small grains or larger crumbs of soil, which are separate and loosely held together. This structure is often present in the A horizon, which enables water and air to circulate easily.

Blocky and sub-angular blocky structure

These structures comprise particles strongly bound together to form square or angular blocky aggregates with sharp edges. They are most common in B horizons with higher clay contents, which can restrict the water flow without the presence of sufficient cracks between the aggregates.

Prismatic and columnar structure

These structures comprise particles that form vertical columnar aggregates from 1 to 10 cm long, separated by narrow vertical cracks and bounded by flat or slightly rounded vertical faces. This structure is commonly found in B horizons with clay accumulation in more arid regions and in shrink-swell clays. It often restricts water flow, unless there are sufficient cracks between the aggregates.

Platy structures

These structures comprise soil particles aggregated horizontally in flat plates or sheets, piled on top of each other. Platy structures often severely restrict water flow and root development. They are commonly found at the soil surface, particularly due to heavy rainfall on bare cultivated silty soils in the form of a "soil crust", or in subsurface soil subject to compaction by heavy machinery traffic, soil cultivation or excessive animal grazing.
Soils with no visible aggregation are referred to as single grain, mostly comprising sand, or as massive, mostly comprising clay.

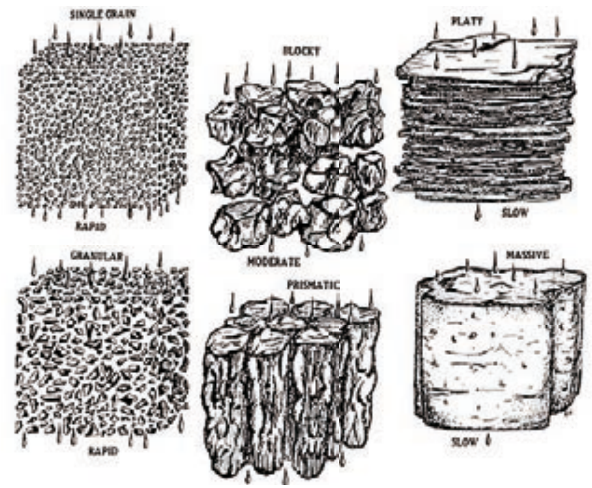


Figure 3: Classification of soil aggregates and their average water flow properties (Ref. 4)

c) Soil Pores

Similar to the distribution of particle sizes, soil pore sizes vary and pores are classified by their size and resulting function in the soil, particularly concerning water flow. The soil pore size classes can be distinguished based on average pore diameters. Pores of different sizes make water available for plants, support leaching by gravity, or bind water (see Table 1 for overview):

Coarse macropores (>50 µm diameter) are large soil pores formed by cracks between soil aggregates, earthworm channels and old plant roots; water flow in these pores is rapid due to gravity. These pores often contain small soil animals and facilitate aeration and plant root penetration.
Fine macropores (10 to 50 µm) exist within and between soil aggregates; much of the water flow and aeration in soils takes place via these pores. They store water for plants and living organisms, while this water is more slowly mobile in these pores via gravitational force. Fine macropores can be occupied by fine roots and small soil fauna.

Intermediate pores (0.2 to 10 µm) occur within soil aggregates, being associated with the storage of water in soil for plants via capillary force. These pores may still contain fine lateral roots of plants, fungal hyphae and microorganisms.

Micropores (<0.2 µm) are mostly associated with clay particles or highly humified organic matter. They contain water that is generally not available for plants and microorganisms, due to the strong capillary forces that hold the water within these small-sized pores.

d) Soil Organic Matter

Soil organic matter is the decayed remains of plants and animals, as well as humified matter. It is generally more concentrated in topsoil and declines over depth. Soil organic matter is key to soil health. Chemically, it stores organic carbon and soil nutrients, releasing them when it is mineralised (e.g. magnesium, nitrate). Biologically, it drives the life of the soil, stimulating activity in the soil through the cycle of its formation and mineralisation back to soil nutrients for plants, and physically, it affects soil structure, permeability and water-holding capacity (organic matter may hold approximately 20 times its weight in water), so it can strongly affect water storage and how water flows through soils. Good management of soil organic matter is thus seen as a key success factor at the heart of sustainable agriculture, by farming in a way that maintains or increases soil organic matter.

Table 1: Pore types in soil, water movement and plant availability of water (Ref. 5)

<table>
<tr><th>Pore classification</th><th>Coarse macropores</th><th>Fine macropores</th><th>Intermediate pores</th><th>Micropores</th></tr>
<tr><td>Diameter in µm</td><td>>50</td><td>50 to 10</td><td>10 to 0.2</td><td><0.2</td></tr>
<tr><td>pF value[1]</td><td><1.8</td><td>1.8 to 2.5</td><td>2.5 to 4.2</td><td>>4.2</td></tr>
<tr><td>Pore function</td><td>Fast moving</td><td>Slow moving</td><td>Plant available</td><td>Not plant available</td></tr>
<tr><td></td><td colspan="4">Total pore volume</td></tr>
<tr><td></td><td colspan="2">Gravitational water</td><td colspan="2">Bound water</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">Air capacity</td><td colspan="2">Plant-available water capacity</td><td>Unavailable water</td></tr>
<tr><td colspan="3">Water-holding capacity (field capacity)</td></tr>
</table>

[1] Soil moisture tension (log cm water head pressure)

e) Soil Water

Soil water storage is dependent on the pore size distribution within soils and is thus largely correlated with soil texture and organic matter content (see Figure 4). When a soil is saturated with water, all the pores are full of water, but after 1 to 3 days, all gravitational water drains out, leaving the soil at field capacity (= water-holding capacity ÷ soil water not lost by gravity). Plants then draw water out of the capillary pores (fine macropores + intermediate pores) until no more can be withdrawn against capillary forces. The soil is then at wilting point and without water additions, plants will die. Plant-available water is defined as the difference between the soil water contents at field capacity and the unavailable water, which cannot be used by plants (see Table 1). The soil moisture tension deriving from the pore size distribution in soils can be measured and is expressed as hydraulic head pressure (pF - value).

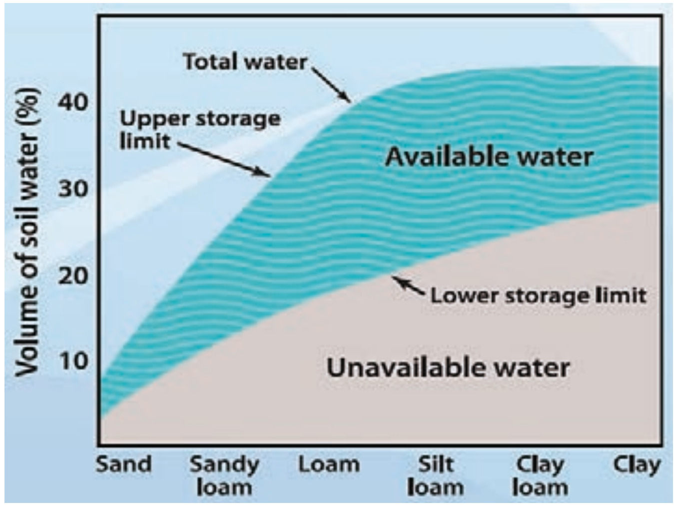


Figure 4: Water storage and plant-water availability depend largely on soil texture (Ref. 6)

Unavailable water largely bound in the micropores cannot be extracted by plants and cannot leach downwards in the soil. This water volume is highest in clay soils, which have the most micropores, and lowest in sandy soils. Only a part of water in the plant-available water fraction can move downwards in the soil profile (fine macropores). Organic matter content also influences water storage in soils, mainly through water binding to organic matter particles and higher soil pore volume due to more strongly developed soil aggregates.

With all the variations within and between soil profiles, due to differences in texture, structure and organic matter, it is not surprising that downwards **water flow** in soils is highly variable. Broadly speaking, these variations can be characterised in three key ways:

First, the **average depth** to which water moves down the soil profile per mm water rainfall (or irrigation) is primarily a function of soil texture. In order to estimate this distance, it is commonly related to the amount of water held in the soil at field capacity (water-holding capacity) defined as mm water/cm soil depth. For our purposes, the field capacity of a soil should be estimated at least to the depth of 1 m, or down to the depth of a significant flow restriction in the soil profile, or subsurface drain level, or the groundwater table. The field capacity of soils generally increases from coarse to finer textured soils (Table 2). Farmers can influence the water-holding capacity of soils through tillage practices, enrichment of organic matter, liming to improve soil aggregation, breaking up of soil compaction, and by the cropping system (i.e. root system influence on pore systems). As for all soil properties, water-holding capacity may vary across or even within fields, so it is important to check for variations. In our risk analysis dashboards, we regard soils with a water-holding (field) capacity of e.g. <150 mm (within 1 m soil depth) as of higher risk for drainage or leaching transfer (due to their lower water-storage capacity).
Therefore, it is important to achieve an adequate estimate of the soil water-holding capacity in the various fields.

Secondly, water flow shows a high spatial **variability in soil profiles**. Water flow is dispersed in soil as it contains a wide range of pore sizes – with water in the larger pores able to move much quicker and further than the average distance of water flow in soil suggests. In part, this is related to the texture of the soil, with sandy soils showing less dispersion than clay soils. This is due to the fact that clayey textured soils form larger structural aggregates with larger pores between them, while within the aggregates the small pores between clay particles dominate. Some large pores are also formed by earthworms and in the channels of decayed roots. All these large pores are called macropores, which are associated with preferential water flow in soil that bypasses aggregates (see Figure 7 for illustration). The presence and density of macropores in soil is thus a key factor for potentially quick pesticide movement down the soil profile and they are therefore considered as a key criterion for assessing the relative pesticide drainage and leaching risk of soil profiles (see dashboards in the sections on drainage and leaching BMPs).

Thirdly, **seasonal patterns** in rainfall and irrigation are important for pesticide drainage and leaching, as they determine when downward water flow takes place in soil during the year. The main periods of water flow are related to the soil-water balance, as shown in Figure 5. Net downward water movement occurs when precipitation exceeds evapotranspiration.

SOIL TEXTURE	WATER-HOLDING CAPACITY	PLANT-AVAILABLE WATER
Sand	1.0	0.5
Loamy sand	1.2	0.7
Sandy loam	1.8	1.0
Loam	2.8	1.4
Silty loam	3.1	2.0
Silt	3.0	2.4
Sandy clay loam	2.7	1.0
Clay loam	3.6	1.4
Silty clay loam	3.8	1.7
Silty clay	4.1	1.4
Sandy clay	3.6	1.1
Clay	4.2	1.2

Table 2: Water storage (mm/cm depth of soil) for different soil textures*
(Figures are averages for soils containing 2.5% organic matter, according to USDA soil texture classes; Ref. 7)

Hence, in Figure 5, the period of net downward movement or recharge is from November to April, even though the rainfall is higher in the summer months. Winter and early spring months are thus the times when most water and thus potentially also pesticide amounts move into drainage systems and groundwater. In general, the percentage of rainfall that flows through soil to drains or groundwater increases as the amount of rainfall increases; under Central European conditions it is estimated that 20 to 30% of annual rainfall reaches groundwater, while the rest is utilised by plants or evaporates from the soil surface. Yet, even outside the main recharge period, heavy rain events may induce drainage or leaching events in vulnerable situations. For irrigated soils, it is important that large irrigation events (inducing deep percolation in soils) are avoided, particularly just after applying pesticides.

* More specific local information may be available from geological service.

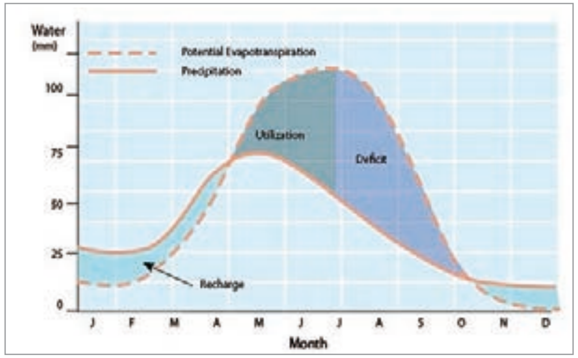


Figure 5: Seasonal soil-water balance example (Ref. 8)

2 FACTORS INFLUENCING PESTICIDE MOBILITY IN SOILS

Pesticide movement in soil is the result of the interactions between local soil and climate conditions with pesticide properties.

a) Substance Properties

There are two pesticide properties that are used as primary indicators of pesticide movement potential in soil: how strongly pesticides adsorb to soil and how quickly pesticides degrade in soil. These properties are used because pesticide movement potential is essentially a result of the competition between adsorption (an indicator of how fast pesticides can move in soil) and degradation processes (an indicator of how much can get degraded before moving out of soil).

Pesticide adsorption

The strength of pesticide adsorption to soil varies. It depends mainly on the pesticide chemical structure and on soil properties. At one extreme, pesticides only weakly adsorbed to soil particles are considered to be mobile in soil, because adsorption does little to retard the movement of pesticides as water flows through soil. At the other extreme, strongly adsorbed pesticides are considered to be immobile in soil, because adsorption results in most pesticide being "stuck" to soil surfaces, so they effectively do not move as water flows through soil. Most pesticides fall between these two extreme scenarios.

Many, if not most, pesticides are uncharged and lipophilic compounds, which means that they adsorb to lipophilic surfaces in soil, particularly those found in organic matter. The tendency to adsorb to the organic carbon fraction of organic matter is conveniently measured using the adsorption coefficient to organic carbon – K_{OC} for short. High K_{OC} values indicate that pesticides are strongly adsorbed to the organic carbon in soil and will not move easily with soil water.

Low K_{OC} values mean that pesticides are only weakly adsorbed to the organic carbon in soil and will more easily move with soil water. A rough classification of K_{OC} in terms of mobility is shown in Table 3.

Pesticide adsorption also varies among different soil types – generally increasing in soils with higher levels of organic matter in topsoil, and also generally declining with soil depth as organic matter levels decline.

Pesticide mobility	Adsorption coefficient K_{OC} (mL/g)
Low mobility	≥1,000
Medium mobility	100 to 1,000
High mobility	≤100

Table 3: General classification of pesticide mobility in soils

Some charged pesticides (i.e. acids or bases), which are not primarily lipophilic, do not adsorb readily to soil organic matter but are rather bound by clay minerals or oxides in soil. For these substances, the soil distribution coefficient (Kd) is used to characterise their sorption potential in soil. It is worthwhile to note that the adsorption of potentially charged pesticides is often also affected by soil pH, particularly in the case of weak acids and bases, which also occur in uncharged forms in soils.

In conclusion, it is possible to classify all pesticides in terms of soil mobility characteristics from mobile to immobile in soils.

Pesticide persistence in soil

The rate at which pesticides are degraded in soil varies. The degradation of pesticides into metabolites can occur by biotic processes (microbial biodegradation) and abiotic processes (hydrolysis, photolysis or catalytic oxidation). Ultimately, pesticide degradation results in their break down (mineralisation) into their simple inorganic compounds, such as carbon dioxide, ammonia and water. Rates of pesticide degradation are measured using the half-life time DT50. This is the time needed to degrade 50% of the initial amount of pesticide in the soil. It is usually measured under laboratory conditions (fixed temperature and moisture status) on a range of different topsoils to gauge what is a typical or representative value or DT50. If DT50 values are measured under field conditions, they may include contributions from other dissipation processes, such as volatilisation and photolysis. In general, pesticides can be classified as of low, medium or high persistence in topsoils, with persistence generally increasing with depth in the soil due to the general decline of microbial activity.

Combining pesticide adsorption and degradation

Pesticide movement in soil has been shown to depend on pesticide adsorption (mobility) and pesticide degradation (persistence), the latter property especially being relevant for mid- to long-term mobility in soils. Various attempts have been made to illustrate this dependence and one example is the Groundwater Ubiquity Score - GUS - index, which uses pesticide mobility and persistence to indicate the potential likelihood for pesticides to be detected in groundwater. However, the GUS index should not be used as a decision-making criterion in EU agriculture, as (i) it was developed based on US soil and climate data (ii) it ignores the differences in pesticide use rates, and (iii) in the EU registration process pesticides are only authorised that do not occur in concentrations >0.1 µg/L in groundwater under typical use conditions (determined via experimental and modelling data). Nevertheless, the GUS concept is useful to illustrate, in general, the dependency of pesticide leaching potential in soil from substance mobility and persistence (see Figure 6).

In practice, the risk of pesticide movement in soil to deeper layers also depends on the time interval between the application and the first significant rain event (inducing downward water flow in soil). If the time interval is short, there will be more substance available for leaching in topsoil, and at the same time, pesticide binding to soil is not yet so strong (many pesticides bind more strongly over time in soils). Both processes, especially if macropores exist in the topsoil, can cause a more intense downward movement of water in the soil. As a consequence, careful planning of the PPP application to avoid heavy rainfall shortly after the application is an important element of best practices to reduce the risk of pesticide leaching and drainflow transport.

b) Soil and Climate Conditions

Given that a key purpose of this document is to provide guidance on how to react to unacceptable findings of pesticides in surface water or groundwater, the main focus here is to rank the differences in local soil conditions in terms of the relative vulnerability for pesticide drainage and leaching in general. This means that only local soil/landscape factors affecting the general relative vulnerability of surface water and groundwater to pesticide movement are explicitly considered (larger geographic differences in precipitation and temperature in the EU are not considered and must be factored in for national BMP booklet versions). On this basis, three main types of soil/landscape factors were identified which affect pesticide drainage and leaching potential:

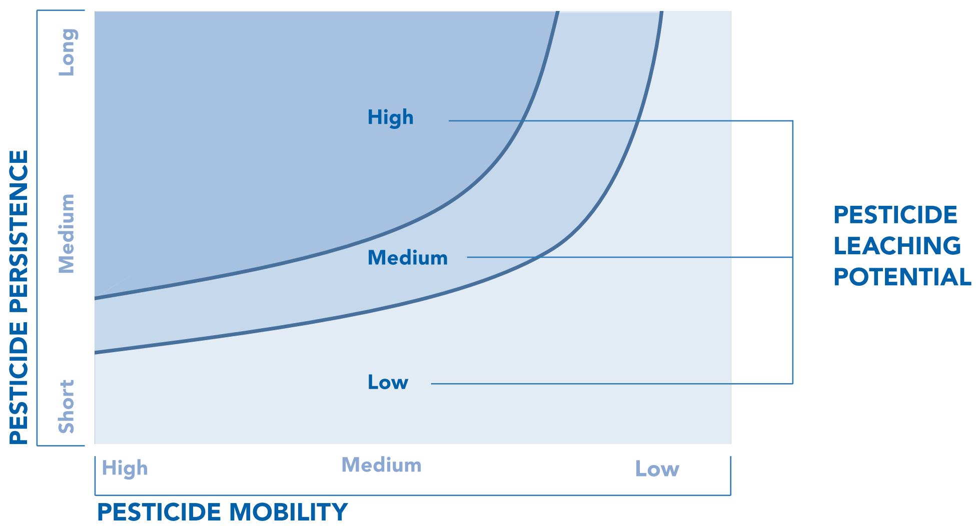


Figure 6: The link between pesticide leaching potential in soil and the persistence and mobility of pesticides in soil (based on the GUS concept)

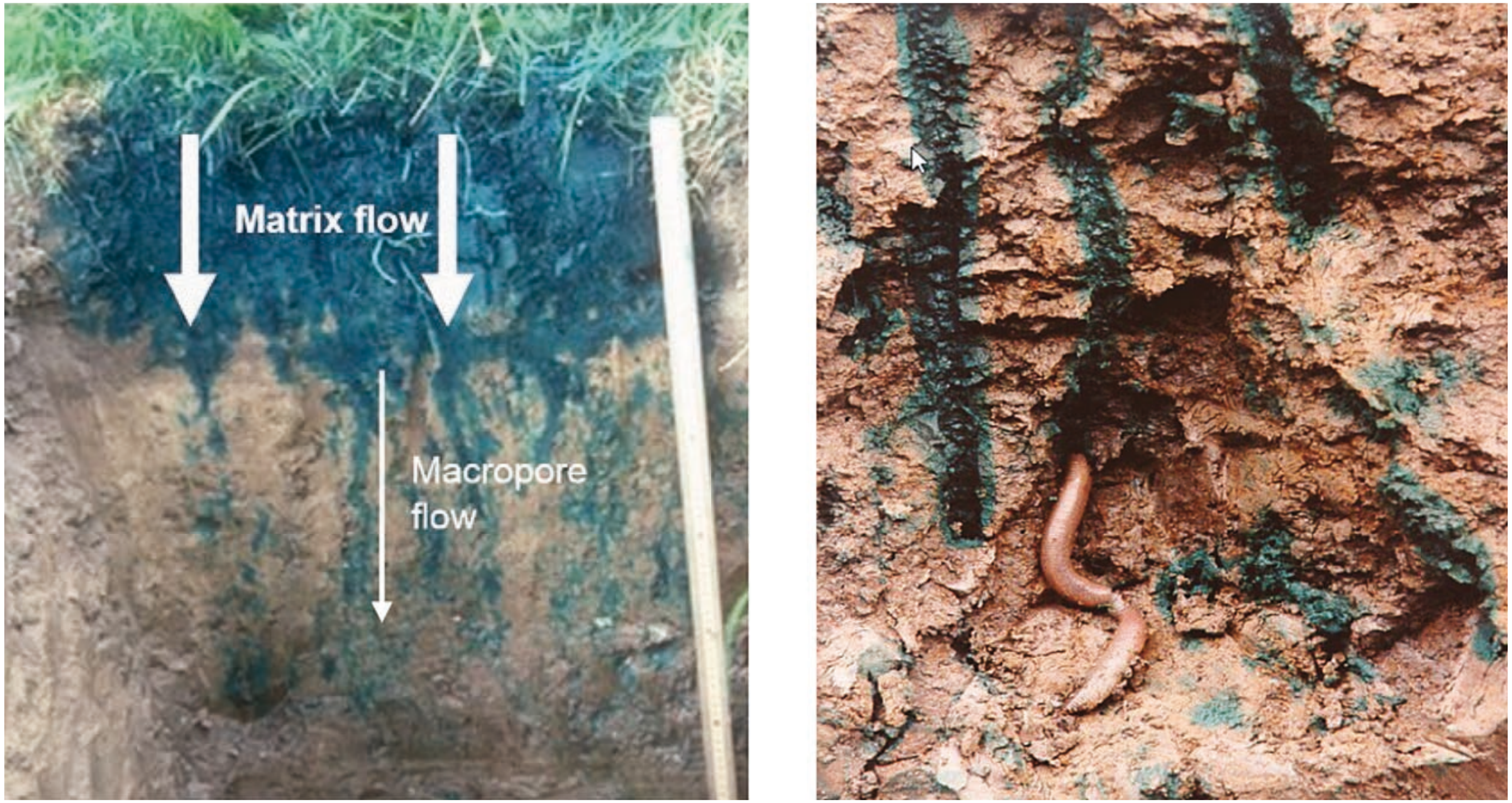


Figure 7: Water flow pattern in a soil profile (left side) and staining pattern of macropores (right side) made visible via infiltration experiments with colour tracer (Ref. 9)

Soil texture

The influence of soil texture, as given by the soil water-holding capacity, on the average water storage and flow rate through soil: This is reflected in the risk dashboards, using a <150 mm threshold of water-holding capacity in the soil profile as trigger value for higher vulnerability. Rain will penetrate deeper in these soils, leading to a higher risk of pesticide transfer to deeper soil layers.

Soil structure

The influence of soil structure on water flow in soil, as given by the presence of cracks (particularly the larger ones between aggregates) and biopores (such as earthworm burrows and old root channels): These form preferential routes for pesticide movement through soil, enabling them to quickly bypass the soil matrix (see Figure 7). Soil management practices show a heavy influence on soil structure, with no or reduced tillage favouring the development of larger and more permanent soil aggregates and its associated macropore system. Thus, the infiltration of water into the soil via macropores is enhanced, thereby reducing the potential for surface run-off, but quick transfer of water down in the soil profile is also increased. With intensive tillage, macropores are disconnected and the infiltration capacity is, in general, reduced. As a compromise, shallow tillage may be used to break up the macropores close to the soil surface, preventing some of the bypass movement, since pesticides then travel more evenly through this surface layer. Fast water and substance movement in macropores, which are generally more abundant in heavier textured soils, is considered a main factor that enhances the risk for pesticide drainage output and, to a lesser extent, also leaching (especially in case of shallow groundwater). This is reflected in the assessment of cracks at the soil surface (and tillage practices) for drainage and leaching vulnerability dashboards.

Drainage system

The type of drainage system (for surface water) and depth of the soil/unsaturated zone (for groundwater): These determine the effective distance that pesticides need to travel in soil to enter surface water and groundwater. Consequently, these factors are also considered in the risk dashboards.

Other factors were not included in order to keep the classification general, e.g. soil organic matter content (except for peaty soils) and soil pH. For further information regarding these aspects of pesticide drainage and leaching, consult your local crop protection specialist, or check if there is product-specific stewardship advice. One example of such advice can be found on the website of the Voluntary Initiative in the UK (Ref. 10).

And finally, in general, water flow through soil, particularly as affected by soil conditions, is strongly influenced by soil management practices. For example, cover crops influence soil organic matter content, microbial activity and water balance. In addition, tillage practices not only affect macropores, they also affect organic matter levels in topsoil and also microbial activity levels. No or reduced tillage is known to increase organic matter content and microbial activity in the upper topsoil layer. Hence, soil management, particularly via its impacts on macropores, should aim to strike the right balance between fostering soil health and ensuring water protection.

3 LEGAL GOALS FOR WATER PROTECTION

The EU Water Framework directive (WFD) sets the legal framework for water policies in the European Union, aiming to protect water: groundwater, surface water and coastal marine water.

It requires the widespread and regular monitoring of water bodies with regard to chemical and biological parameters, which form the basis for classifying the status of the waterbody (good to bad chemical and ecological status). If the status is poor, this triggers the need to establish action plans to improve it using the 6 year river basin management planning cycles. At the latest, all water bodies should be in good chemical and ecological status by 2027, which means that effective plans need implementing.

a) Pesticide limit value for drinking and groundwater
In the EU, a precautionary limit value of 0.1 µg/L was established in the 1980s as a non-health-based limit for drinking water. This applies to all pesticide active ingredients and all toxicologically "relevant" metabolites of pesticide active ingredients. As groundwater is the major source of drinking water in many Member States, this limit value was extended to groundwater due to its frequent use as raw water for drinking water production, often with a minimal amount of treatment.

Non-relevant metabolites of pesticides (as defined in DG Sante guidance Sanco/221/2000) are not regulated at EU level in drinking water or groundwater. However, an upper threshold value of 10 µg/L is used in several EU member states as the cut-off criterion in regulatory assessments of their (predicted) levels in groundwater.

Regulatory water exposure assessments in the EU are done before market authorisation of products, to minimise the number of findings of pesticides and metabolites that may exceed their limit values. However, in the long term, if pesticide exceedances occur at vulnerable sites frequently, this may lead to local pesticide use restrictions or bans at national level.

b) Surface water limit values

For surface water, substance-specific environmental quality standards (EQSs) apply for individual substances (i.e. also pesticides), based on eco-toxicological endpoints to protect ecosystems from chemical pollution. EU-wide EQSs were established for a list of Priority Substances, comprising selected pesticides and other anthropogenic substances, laying down annual average limit values (EQS-AA) and maximum allowable concentration limit values (EQS-MAC). Typically, the annual average of monitored concentrations in surface water is compared with the EQS-AA for a given water-body and substance to evaluate the EQS compliance. In addition to the EU-wide Priority Substances, national or river basin "specific pollutants" (e.g. further pesticides and other anthropogenic substances) are chosen by EU Member States and listed in national surface water regulations. For these substances programmes are established as needed at country level.

For surface water bodies used to abstract drinking water, the drinking water quality standard (DWQS) is based on the existing general limit value for finished drinking water (0.1 µg/L limit value). Yet, a treatment factor should be considered, based on finished drinking water (0.1 µg/L limit value), but should also take into account a treatment factor based on substance-specific removal. However, Art. 7 of the WFD also states that Member States need to ensure that drinking water quality does not deteriorate and that the need for water purification should be reduced. To meet this aim, safeguard zones may need establishing, which can include implementing local use restrictions for pesticides.

BEST MANAGEMENT PRACTICES TO REDUCE DRAINAGE TRANSPORT OF PESTICIDES

1 DRAINAGE SYSTEMS AND KEY FACTORS

a) Introduction

Subsurface drainage systems are established to help excess water drain quickly from the soil and prevent them from remaining too wet for prolonged periods of time. Excess water lowers crop yields, particularly if too wet during crop establishment. It also damages the soil, if cultivations or other field operations are done when the soil is too wet. Water collected by drainage systems flows directly into surface water bodies, such as ditches, streams and even rivers. In Western and Central Europe, the period when drainflow is continuous usually starts in winter and lasts until spring (see Figure 8). This period is preceded by the autumn period and followed by the early summer period, both of which are periods when drains are not flowing continuously, but isolated drain flow events can be caused by heavy rainfall events. The actual drain flow period depends on the local climate (especially temporal distribution of precipitation events) and soil properties.

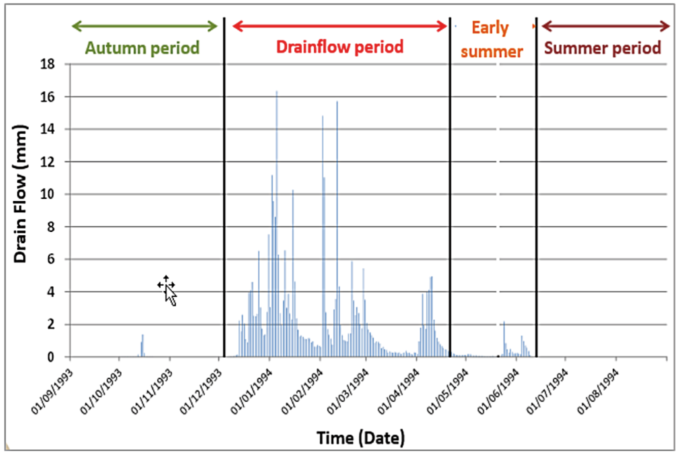


Figure 8: Example for drainflow events and periods at Arvalis research site La Jailliere in season 1993/1994 (Ref. 11)

Wet soils due to low permeability of soil profile
Soil layers with low permeability impede the downward movement of water, frequently leading to saturated conditions in the root zone. As a result, these soils take longer to dry out and warm up in spring, which adversely affects soil cultivation practices, seeding time and crop establishment. Drainage is established to remove this excess water from the soil. In addition, without drainage these soils often show surface run-off when they are saturated over winter and in early spring (see TOPPS Runoff BMP booklet; Ref. 1).

Wet soils due to shallow groundwater
In soils overlying shallow groundwater, the water table rises over winter and early spring due to groundwater recharge and comes close to the soil surface. In this situation, the soil may become too wet to be cultivated and crop establishment is poor, negatively affecting yields. The drainage system aims to mitigate this soil condition by keeping the groundwater table at an acceptable level in the soil.

Drainage of irrigated fields
In long-term irrigated fields, evaporation can lead to the accumulation of salts in the soil in drier regions. Over time, this can damage crop growth if these salts, particularly sodium, reach toxic levels in soils. In this case, more water needs to be applied than is needed for crop growth to wash out the accumulated salts from the soil via drainage systems.

b) Drainage Systems
For the three situations which require subsurface drainage (see above), two types of drainage systems are used: primary systems and secondary systems to supplement the primary ones.

Primary drainage system
Traditionally, open ditches were used to drain the surplus water from soils, connecting to the next natural surface waterbody. Modern primary drainage systems use perforated plastic (PVC) pipes buried at >50 cm soil depth to remove excess water. They account for about 80% of the primary drainage systems in the EU. These systems have the advantage that they do not interfere with field cultivation activities. The exact design of these drainage systems depends on the permeability of the soil. In general, the most common design is the ‚systematic' or ‚regular' layout,

Figure 9: Subsurface drainage outlets

Figure 10: Surface drainage system using ditches

characterised by the regular spacing of parallel lateral drainpipes. These flow into drainage ditches and streams, or they feed into a main drain (collector), which in turn discharges into a drainage channel or stream. Low-permeability soils, such as heavy clays, are drained using narrow drainpipe spacing of 5 to 15 m, while more permeable soils are drained using wider spacings of up to 40 m (Ref. 13). The spacing also depends on the depth of the drains, with deeper drains generally allow wider spacing. For soils with permeability restrictions in the soil profile, the drain depth is determined by the thickness of the more permeable upper soil layers. In many clay soils, the subsoil is so impermeable that there is little point in laying pipes deeper than 75 cm and gravel may be layered above the drainpipe to aid water flow (permeable fill). In contrast, for soils overlying shallow groundwater, the drain depth may be limited by the level of the water in the drain outfall channel. If the depth is not restricted in this way, drains may be installed as deep as 120–150 cm below the soil surface in more permeable soils.

Secondary drainage system

These systems are only needed for soil profiles with permeability restrictions that result in theoretical drainpipe spacing that is prohibitively expensive due to the needed narrow spacing. In these soils, however, subsoil drainage above the drains can be enhanced by secondary drainage practices like ‚moling' and ‚subsoiling' that facilitate water movement to drainpipes. Secondary drainage is cost-effective at spacings of 1 to 2 m, usually at right angles to the primary drainpipes that are more widely spaced at around 20 to 40 m (Ref. 13). Mole drains are created by pulling mechanical devices through the subsoil, creating channels resembling those of moles. If mole drains are created in clayey soils, when the soil is ductile, they can last 2 to 10 years. Subsoiling is done by pulling a wedge-shaped "shoe" with "side wings" on it to lift and crack the soil. Both mole drains and subsoiling are normally done at the depth of 40 to 60 cm, with subsoiling breaking up shallow impermeable layers due to soil compaction.

Secondary drainage systems collect excess water and channel it directly into the primary drainage system, particularly by intercepting the permeable fill above the primary drains. As a result, secondary drainage systems can result in higher pesticide peak concentrations than from primary drainage systems alone, since the drainage is from a shallower depth in the soil profile.

c) Considerations for Decision-making

The main reason for farmers to invest in drainage systems is to increase yield (often by double or more) and to widen the varieties of crops that can be grown (without drainage, land use is often restricted to pasture). With the awareness over the potential environmental impact of drainage, the specialised companies that install primary drainage systems need to prepare a dedicated plan for farmers, considering all the relevant factors. In many cases, the local authorities are also involved, to audit the proposed plans and to administer public funding. Furthermore, the implications of drainage activities in a catchment, including downstream effects after drainage, need to be considered. The establishment of primary drainage systems is a long-term decision (>20 years), so the impact of implementing BMPs need also longer-term considerations. However, secondary drainage systems need renewing every 3 to 5 years and require less financial investment. Hence, the impact of implementing BMPs for secondary drainage systems can be realised in the shorter term.

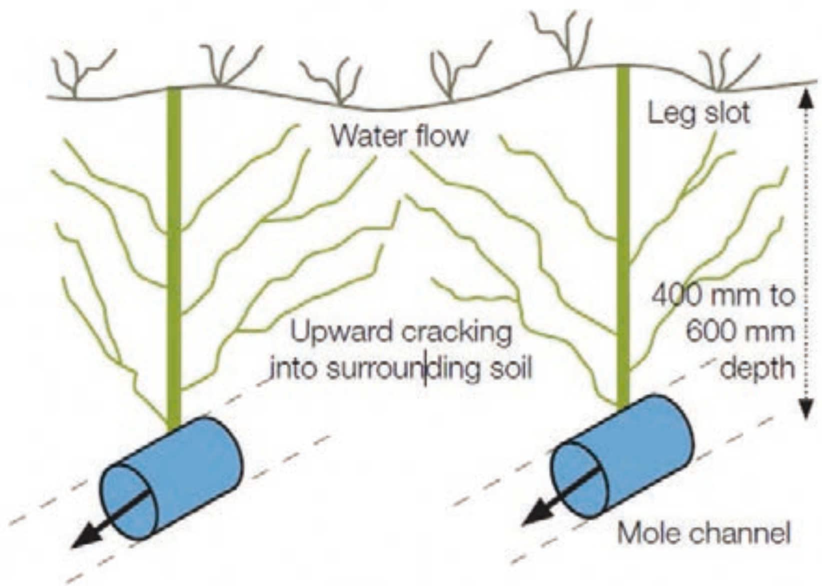


Figure 12: Schematic view of effect of mole drainage in soils (Ref. 14)

Determination of the movement of water in the soil and landscape

A lot of information relevant to understanding the water movement in the soil and catchment is usually available. Some can be received from land management authorities; some files may be directly available from the farmer. It is recommended to use these data and verify them directly by auditing the specific fields in a catchment.

Sometimes, information on old drainage systems in the fields is no longer available (e.g. due to a short term land lease, a change in ownership, lost maps). Therefore, a thorough field audit during times of drain flow should be done to verify if there is drainage and if it is fully operational. Ideally, the drain-flow should be monitored in relation to time of rain, intensity and time/amount of drainage outflow. It should be also audited where the drain outfalls are located and where the drainflow water is flowing to: Is it retained (e.g. in a wetland) or is it flowing directly into a ditch or stream?

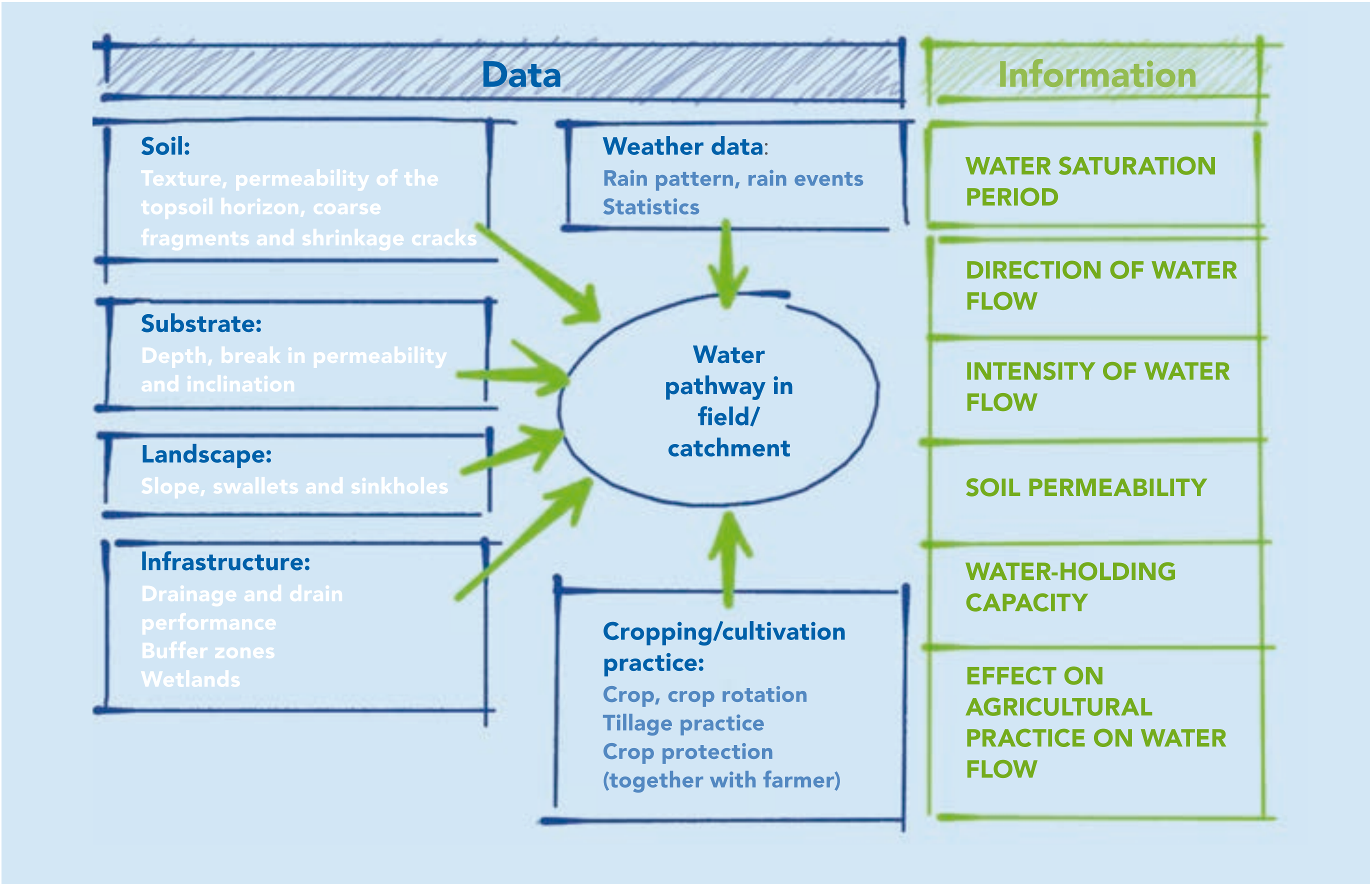


Figure 13: Information requirements to determine water contamination risks at field level (Ref. 1)

Risk evaluation dashboard

A dashboard has been developed to identify a range of drainage scenarios in the field and their associated relative risk potential for pesticide losses from drained fields into surface water. This dashboard was developed to reduce the complexity of the entire process of identifying scenarios and associated risks with a set of common criteria that apply across Europe and for pesticides in general. After diagnosing the scenario and its associated risk levels, the appropriate mitigation measures need to be selected. In particular, the local climatic conditions (e.g. rainfall pattern, temperature) need to be taken into account.

The diagnosis dashboard may need to be adapted to country-specific environmental conditions (e.g. in France, a lower vulnerability cut-off is defined with a plant-available water capacity of 120 mm, rather than a water-holding capacity of 150 mm).

BMP = RISK DIAGNOSIS + SELECTION OF BMP MEASURES (TOOLBOX)

Figure 14: Dashboard – Vulnerability diagnosis of fields causing drainflow transport of pesticides

Drainage due to low-permeability soil	Large cracks/macropores[1] occur			High risk
	Large cracks/macropores do not occur in most years	Subsoiling or moling done		High risk
		No subsoiling or moling done	Clay >35%	High risk
			Clay 25 to 35%	Medium risk
			Clay <25%	Low risk
Drainage to control shallow groundwater	Mineral soil	Large cracks/macropores occur		High risk
		Large cracks/macropores do not occur in most years	WHC[3] <150 mm	High risk
			WHC 150–230 mm	Medium risk
			WHC >230 mm	Low risk
	Peaty[2] soil			Low risk

[1] Cracks/macropores of ≥1 cm width occur at the soil surface
[2] Peaty soils: Soils with ≥30% organic matter in topsoil (plough layer)
[3] Soil water-holding (field) capacity (in upper 100 cm of soil profile or above the level of drains, whichever is shallower).

How to use the dashboard

The dashboard needs to be used from left to right, selecting the appropriate category in each column for each diagnosis parameter.

First, a decision must be taken about the purpose of the drainage system: (a) to manage wet soils with low permeability; or (b) to manage soil influenced by a shallow groundwater table.

a) In low-permeability soils, fast transfer of water is influenced by cracks, which mainly occur in clayey soils due to strong aggregate formation, exacerbated in soils with swelling clays that crack on drying. If no cracks are observed, the water movement in such soils is usually slow. Subsoiling or moling, as well as the clay content, increase the amount of macropores and the speed of water flow and, therefore, can increase drain outflow and consequently worsen the risk class of the field.

b) In fields influenced by shallow groundwater, soils with high organic matter content (peaty soils) have a low vulnerability to cause drainage transport of pesticides. Mineral soils may have high vulnerability, depending on whether large cracks are formed regularly in the topsoil. Risk levels in soils without apparent cracks are classified from low to high risk, depending on the available water-holding capacity in the top 100 cm of soil.

The diagnosis dashboard may need to be adapted to country-specific conditions with regard to local soil and climate conditions or because of compatibility with existing risk-diagnosis systems. It should be stressed again that drainage risk diagnosis and implementation of BMPs should be done primarily in reaction to unacceptable findings of specific pesticides in catchment water bodies. As this transfer pathway depends on pesticide properties and overall use in a catchment, most BMPs should not be applied proactively to all drained fields and pesticides, but should be targeted to reduce the frequency of unacceptable findings of specific pesticides.

3 DEVELOP BMPS BY LINKING RISK DIAGNOSIS WITH BMP MEASURES

The starting point for developing BMPs for drainage risk mitigation typically is the occurrence of unacceptable water pollution in a catchment, caused by a "critical" pesticide in this regard. If this pesticide is used on drained fields in the catchment, the drainage risk profile should be determined for all drained fields in the catchment. Linking the risk diagnosis to appropriate (and implementable) measures forms the overall BMP for the risk management in this field.

BMP = DIAGNOSIS + MEASURES

Fields diagnosed with a low risk may require none or only a few general measures to maintain the low risk profile, while high risk situations may require the application of most or even all mitigation measures available. It is recommended to conduct the risk diagnosis and discussion of potential measures together with the advisor and the farmer, ensuring that mitigation measures are evaluated also based on their fit with the current farming system and any future options for it. The example shown in Table 4 can be used as a starting point to discuss suitable (combinations of) measures. In the end, defining the suitable measure(s) is also an iterative process, which may need to be repeated based on the achieved water-monitoring results, if still not acceptable.

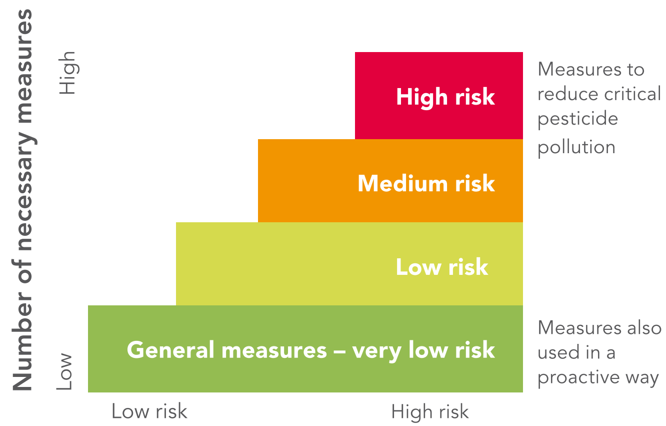


Figure 15: Visual concept of how to build risk-adapted BMPs by selecting appropriate mitigation measures

Measures categories	General measures	Low-risk* measures	Medium-risk* measures	High-risk* measures
Adapt application timing	Do not spray if heavy rainfall is forecast		Avoid spraying during drainflow period	Consider alternative PPPs
Reduce substance load per field	Consider seed treatment options Consider spot treatment techniques	Use split applications Reduce rate to a minimum that maintains efficacy	Reduce rate via pesticide mixture	
PPP selection and rotation		Widen crop rotation in catchment	Rotate pesticide use in specific crop	Restrict use of critical pesticide(s)
Optimise crop rotation	Select rotation to optimise plant health	Consider crops with tap- & fibrous-root systems Alternate winter & spring crops		
Adapt tillage practice				Consider tillage to disconnect soil macropores
Grow cover crops	Select suitable cover crops			
Optimise drainage practice		Avoid over drainage		
Water-retention structures				Use retention structures to collect drainflow
Optimise irrigation practices	Calculate needed irrigation volume	Optimise irrigation scheduling based on soil moisture		

Table 4: Example matrix how to link BMP measures to the field diagnosis risk levels

* For these risk levels also measures listed for lower risk levels can be considered (see Figure 15).

1. Adapt Pesticide Application Timing

Timing of pesticide application is important, as the highest pesticide concentrations in the drainage outflow are typically measured with the first induced drainage events after application. Drained fields often show a distinct drainage season of more or less continuous drain flow during winter and early spring. This is due to low evapotranspiration rates at this time of the year, leading to a downward directed water flow in soils. Due to the variability of yearly rainfall, the beginning and end of the drain flow period may shift by a few weeks at a given site from year to year. In the case of macropore-rich topsoil (e.g. cracking clay soils), fields may show some isolated drainage events in autumn and summer, when heavy rainfall can induce a quick percolation of water to drains.

What to do

In general, apply critical pesticides (i.e. pesticides known to cause unacceptable water concentration in the catchment via drainage) outside of main drain flow season. If necessary, select more appropriate PPPs, giving a wider time window for application. Do not apply PPPs when heavy rainfall is forecast.

How to do it

Study PPP label carefully, to determine whether seasonal application timing requirements exist or restrictions for use on drained fields apply. Check also for product stewardship advice from the manufacturer.

For critical pesticides, avoid spraying, as far as possible, from late autumn until early spring (main drainflow period), when soils are wet. Make sure drains are not flowing before you start spraying.

Check the weather forecast for rain in your area (the first rain event after application is the most critical): Do not apply critical products when heavy rainfall (>20 mm) is forecast for your region within the next 48 h.

Check soil moisture levels in the field you intend to spray and avoid spraying on moist soils (near field capacity), unless no rainfall is forecast for the next days.

2. Reduce Substance Load per Field

a) Reducing the application rate of a pesticide (incl. via mixture products)

Efficacy of PPPs depend on the specific properties of the pesticide active ingredient, but also on a number of external factors, e.g. climatic conditions, application techniques, soil type, soil moisture, crop, plant varieties, target organisms, development stages of pests. The rates that are recommended on the label need to guarantee good efficacy considering the variability of the external factors. Rate reductions are sometimes possible without a loss of efficacy, if external factors are favourable for the PPPs activity.

In practice, farmers at times can reduce PPP application rates, but in these cases the risk of reduced PPP efficacy needs to be considered, as the external factors are not always easy to predict. However, based on farmer's experience with PPP use on each of their fields, a rate reduction may result in acceptable risk to secure crop yields. Also, plant traits, specifically bred for higher pest resistance/resilience, may be a factor that allows reduction of plant protection intensity. Yet, it should also be considered that reduced rates can increase the risk of resistance formation in pests, due to decreased effectiveness (i.e. pest mortality) after application. An increasing pest resistance may result in the need for increased rates at consecutive applications or a change of the PPP to break resistance. Rate reductions should therefore be discussed with advisors and, if possible, should focus on preferentially using mixture products (or tank mixes), combining different modes of action.

What to do

Reduce the application rate of critical pesticides (i.e. pesticides known to cause unacceptable water concentration in the catchment via drainage) to the minimum necessary on the respective field, considering mixture products whenever possible.

How to do it

Consult with the advisor and/or the respective company stewardship managers about the minimum effective

MEASURES CATEGORIES	MEASURE
Adapt PPP application timing[1]	Avoid spraying ***during drainflow season*** and shortly before heavy rainfall is forecast ***Consider available treatment alternatives***
Reduce substance load per field[1]	Reduce overall rate per area ***Use pesticide mixtures (different active ingredients)*** Use split applications (stretch PPP load) Use pest-monitoring techniques (manual; automatic sensors) and only treat infested areas (spot treatment) Use seed treatment
Optimise PPP selection and rotation in catchment[1]	Widen crop rotation to reduce the load of specific pesticide ***Rotate pesticide for a specific crop in the catchment*** ***Restrict pesticide applications in vulnerable fields***
Optimise crop rotation	Select crop rotation to optimise plant health and - alternate winter and spring crops - consider plants with tap- and fibrous-root systems
Adapt tillage practices[1]	***If drainflow is a problem: consider using at least shallow tillage to disconnect soil macropores in vulnerable fields***
Grow cover crops	Select cover crops to fit with the rotation of main crops - pay attention to good cover crop - maintain and manage cover crop - ensure cover crop does not interfere with cash crop
Optimise drainage practices	Design drainage professionally (follow guidance) to avoid over-drainage
Use water-retention structures[1]	***Use retention structures (e.g. ponds, wetlands) to capture drainage water for retention, dilution and dissipation of high-concentration drainflow pulses in autumn or summer***
Optimise irrigation practices	Calculate the necessary irrigation volume (balance) Soil moisture monitoring to optimise irrigation scheduling

Table 5: Overview on measures to reduce losses of PPP to surface water through drainage

[1] Some BMP measures (in bolt italics) should only be used reactively for reduction of unacceptable concentrations of critical pesticides.

application rates of a critical pesticide. If possible, select mixing partners which allow to reduce the rate of a critical pesticide without compromising efficacy or resistance development. Make sure that a reduced rate or pesticide mixture is sufficiently effective to solve the crop protection problem. Before mixing several PPPs as tank mixes, it is recommended to check label recommendations and ask for specific advice, such as if PPPs can be mixed and what results can be expected.

b) Reduction of application rate via split applications

Split applications are successive applications of the same or different PPPs in a sequence. These repeated applications exploit the higher sensitivity of small weeds to the herbicide (e.g. a first flush of emerged weeds) and have shown good effects also for the molluscicide metaldehyde. Split applications reduce the PPP concentration in topsoil/on plants directly after application and spread the load of active ingredient on the field over a longer time period. Therefore, it decreases the risk for high concentrations of pesticides in drain flow, especially if rainfall occurs shortly after application.

What to do

Split the application of critical PPPs into several applications (usually two half-doses), which need to be timed and dosed according to label requirements.

How to do

Split applications require good monitoring of the growth stages of pests and a very good knowledge of the specific PPP activity and properties. Application timing therefore needs to be chosen very precisely and agronomic advice should be sought.

Constraints

Split applications have the disadvantage that applications have to be done at least twice, resulting in additional costs and soil trafficking (soil compaction). In late autumn and early spring, such practices are sometimes difficult to realise as the soils are too wet to drive on.

c) Reduction of overall application rate via spot application

In practice, crops and pests are not evenly distributed in a field but occur in clusters (e.g. crop rows) or different densities (e.g. pest hotspots). Spot application methods direct pesticide applications to parts of the infested field only, where pesticide treatment is needed. This means that a certain part of the field remains untreated, thereby reducing the overall pesticide application rate per field.
It can be differentiated between banded applications (typically targeting the area between rows only) and variable subarea applications (either map-based or sensor-based).

Further technical options may be offered via the use of digital farming: Digital farming technologies are currently being developed to predict, secure and enhance yields while optimising the application of plant protection products (PPP) in a more targeted, controlled and efficient manner (precision farming). The fast development of these platforms and applications will provide ample opportunities to tackle environmental exposure issues by reducing the drainage and leaching risk of plant protection products due to spatial and temporal refinement of application rates.

Decision support tools, in combination with disease risk models that map the infestation risk and pressure, can help to optimise rates of fungicides on specific spots in a field, thus minimising the total load of PPP. Targeted weed control by weed patch spraying based on automated weed recognition and mapping provides a further opportunity to achieve highly efficient PPP application.

Vulnerability mapping is a further promising approach to delineate the leaching and drainflow risk based on site-specific risk indicators such as organic carbon content, texture or infiltration capacity. These maps can help farmers, advisors and regulators to identify high-risk areas and to target site-specific risk mitigation measures.

What to do

Banded application

Annual and perennial crops, which are grown with large enough row spacing, can be treated only for weed control by a special sprayer. The sprayer is designed so that the crop cannot be hit by the spray through shielding devices (chemical hoe). These techniques are most often used with herbicides in orchards and vineyards. However, also in field row crops (e.g. maize, sunflower) banded application of herbicides has recently become more frequent.

Variable subarea applications

The aim is to only treat infested (insects, fungi, weeds) parts of the field. Such a strategy can only be recommended when precise pest monitoring is possible and a consecutive targeted treatment via a sprayer can be realised (either manually/or by automatic sensors).

How to do

Sprayer technology needs to be adapted to enable application between the crop rows. Side-shielding may be necessary to prevent crop damage if non-selective herbicides are used. Dose and spray volume calculations need to consider the area actually treated.

Key is a reliable monitoring/sensoring system which allows to indicate the areas/positions to be treated. If a pre-application monitoring of pest infestation is done (manually or via drone/satellite sensoring), the treatment areas are usually transferred to digital GPS maps, which modern sprayers use for targeted spraying during application. Pests which have a high moving capability (e.g. some insects) are more difficult to treat effectively using map-based application systems. Sensor-based application relies on the online signal of sprayer-mounted sensors (i.e. in front of the spraying machinery), which detect pests while passing. For weed control, sensor-based techniques already exist; for other applications, sensors are mostly still in a research stage.

Constraints

The adaptation of monitoring and spraying technology requires investments in machinery/software which may not be justified for smaller farms and for limited application scenarios.

d) Reducing application rates via seed treatment

Seed treatments are the most effective PPP application in terms of environmental contamination, as only the seed is treated before sowing. Often, overall PPP loads to the field are then significantly less than via broadcast pesticide use (to be substantiated case by case). This technology is targeted towards soil-born pests, as well as systemic protection of plants (i.e. complete foliage). For the latter target, only systemic pesticides are used, which can be translocated after germination to the above-ground parts of the plant.

What to do

Use specific treated seeds to minimise exposure of the environment for a targeted pesticide, and use appropriate equipment to avoid any dust drift.

How to do

In most cases, seeds are treated in specialised treatment plants and the treated seed is bought by the farmer, coated with the desired pesticide(s). Make sure to avoid dust drift during seeding, and buy high-quality seed products (with low dust abrasion) and use appropriate technology to direct the exhaust of seeding machinery towards the ground.

Constraints

Seed treatments combine the choice of seeds with the choice of plant protection. This technology should only be used if there is a high probability for needing the respective chemical crop protection within the season (pre-determination of pest management tool).

3. Optimise Pesticide Selection and Rotation in Catchment

a) Rotate pesticide at catchment level

In a catchment area, all drained fields may contribute contaminated water during the drain flow season or at times after heavy rainfall events. Pesticide findings in surface water often correlate with the overall use of certain pesticides in a catchment. A suitable crop rotation (e.g. 3- to 4-year cycles) on the fields in the catchment will reduce the overall treated area of a single pesticide used in a season (as compared to mono-cropping or 2-year cropping cycles), as PPPs are mostly specific for certain crops and pests (the available herbicide product toolboxes, e.g. for sugar beet, cereals and corn, do not overlap much). PPP use can be rotated, if several PPPs are available in a certain crop for a certain pest. This practice will decrease the probability of the development of pest resistance against any specific PPP long term.

What to do

In areas where drainflow contamination is an issue, it is recommended to implement wide crop rotations by varying seeding dates (autumn/spring), making sure that no critical PPP is used predominantly in any season (see also BMP on Crop Rotation for more information). If one or two crops are dominant in a catchment, PPP use on these crops should also be rotated among all farmers, who cultivate these crops.

How to do

Based on agronomic and economic evaluations, the crop rotation in catchments with pesticide drainflow issues should be optimised by the farmer to achieve the longest crop rotation cycle feasible. In order to avoid a too high share of one crop in a catchment, a basic understanding should be sought among growers at catchment level to achieve an adequate crop heterogeneity in any season. In case one or two crops remain dominant in a catchment, a PPP rotation should be implemented for this crop (agreement needed amongst growers), so that simultaneous applications of any critical pesticide are minimised. Naturally, the basis for selecting and applying pesticides on each crop and pest are the use recommendations listed on the label, which guarantees biological performance and compliance with the legal requirements.

Constraints

Achieving a high crop variability in a catchment may be hampered by economic (e.g. marketing of harvest) and agronomic (e.g. available machinery) factors, which need to be addressed first. A rotation of PPPs for specific crops is sometimes restricted by the limited availability of effective and registered PPPs for certain crop-pest combinations. Coordination at catchment level, which could be led by the water authorities, drinking water providers or advisors (in collaboration with farmers) is needed for this BMP.

b) Select pesticides/restrict their use on vulnerable fields

In a limited number of catchments normal adherence to good agricultural practices and general stewardship advice for pesticides will not prevent some pesticides from contaminating surface water bodies via drainflow, in exceedance of legal limit values (i.e. environmental quality standards – EQSs) or levels acceptable for local drinking water producers (taking into account existing water treatment processes). Water-monitoring data will provide catchment managers with information on which pesticides lead to unacceptable concentrations in surface water under the current use practices. Besides point source pollution, which needs to be addressed as the first priority, such situations arise due to worst-case combinations of pedo-climatic (sub-)catchment or field features and pesticide environmental fate characteristics. In such situations, special requirements are needed to ensure that water bodies meet the necessary quality standards.

- Local restrictions (voluntary or mandatory) on PPP use in certain vulnerable areas, where restriction of use beyond that stated on the label are considered to be necessary and sufficient to meet the necessary standards for surface water.
- Local non-use (voluntary or mandatory) of critical pesticides in certain vulnerable areas because the risk of exceeding the standards for clean water from any use is considered to be too high.

  Vulnerable areas/fields for drainflow contamination can be roughly assessed using the TOPPS drainage risk dashboard and should be substantiated with local advisors.

No set process can be outlined here for deciding which local restrictions or non-use requirements need to be applied, since this depends on the details of each specific situation. Yet, based on existing experience, solutions can often be found ensuring that adapted pesticide use integrates the need for both clean water and crop productivity.

PPP manufacturers also provide stewardship advice for pesticides with critical substance properties (e.g. mobility in soil, persistence in soil) to avoid excessive drainflow output from treated fields. This advice can either be found on the product label or may be communicated to users via the advisory or PPP distribution system (country-specific). Growers and advisors should adhere to such voluntary stewardship recommendations and, in addition, consult their official plant protection advisors for further information.

What to do

In areas where surface water drainflow contamination with a specific pesticide is an issue, seek advice on specific PPP use and follow recommendations/restrictions for vulnerable areas.

How to do

Based on the identified pesticide of concern and relevant vulnerable areas, recommended use restrictions for the critical PPP(s) should be implemented on these specific fields. Official advice (e.g. by an advisory system or water advisers) and, if relevant, company stewardship recommendations should be followed in this regard. Yet, the legal basis for selecting and applying pesticides on each crop is the use recommendations listed on the label, which guarantees biological performance and compliance with the legal requirements.

Constraints

Use restrictions (especially non-use advice) for a PPP may sometimes limit the effectiveness of the remaining crop protection alternatives for a given crop. Consider also changes of the crop rotation on vulnerable fields to avoid these situations in the future.

4. Optimise Crop Rotation

Crop rotation is an agronomic practice based on the subsequent cultivation of different crops on the same field over the years. The rationale of this practice is to achieve agronomic, economic and environmental benefits, compared with continuous mono-cropping systems. The main goal of the crop rotation is to maintain the fertility of the soil and good plant health.

For a farmer, the selection of the crop rotation is an important management decision. It decides on workloads during the year, short- and longer-term profitability, machines needed, fertility and structure of the soil, tillage practices, build-up of organic matter and pest pressure, and has consequences for environmental aspects such as water movement in the soil and at landscape level. Generally, crop rotation is understood as sequential cultivation of different crops on a field, but it can also be extended and understood as a variety of crops on different fields in a landscape/catchment (which is usually the result if farmers do different crop rotations on different fields).

With regard to mitigation of pesticide transfer to drains, optimised crop rotations provide the following advantage:

Figure 16: Crop rotation reduce the dominance of certain crops which increase the variety of PPP being used

Enhancing PPP sorption and degradation in soil

Most of the biological activity in the soil is located in topsoil, which is rich in organic matter. High levels of organic matter favour the degradation of PPP in the soil and increase the soil adsorption capacity for PPP. Enriched soils with high levels of crop residues and the inclusion of cover crops in the crop rotation contribute to increased soil organic matter content.

Reduce overall PPP use by exploiting IPM benefits

Narrow crop rotations tend to accumulate crop-specific diseases, pests and weeds. Therefore, it is good practice to consider a diverse crop rotation also from the perspective of plant health. This helps to better target the use of PPPs. Crop rotation decisions depend very much on economic parameters which are often out of the farmer's direct influence.

What to do

Establish a crop rotation which is most diverse and which fits with your farming system and economic needs. Alternate between winter and spring crops, tap- and fibrous-root crops, cereals and broad-leafed crops. Legumes in crop rotations can provide additional benefits with regard to increased nitrogen contents and the biological activity of soils. Suitable rotations depend very much on the local climate and soil types. An example of a diverse crop rotation would be, for instance, winter wheat/barley, followed by maize, soybean and peas/sugar beets.

How to do

The soil organic matter content needs to be managed by leaving ample crop residues after harvest in the field (root system, straw residues, additional cover crops). Depending on the yield harvested, the volume of organic residues in the soil and stable remnants can be calculated to maintain or increase the organic matter in the topsoil (consult agronomic look-up tables).

The number of crops in the rotation which are hosts of the same pathogens/pests should be minimised, otherwise this could lead, for example, to the build-up of nematodes or fungal reservoirs. Weed control aspects need to be considered for the rotation, as in some crops weeds can be easier controlled than in others. Seek local advice on tested crop rotation options and known benefits for pest control.

5. Adapt Tillage Practices

Conservation tillage (reduced or no-till) is effective in reducing surface run-off, erosion and pesticide transfer from treated fields via these processes. However, with regard to drainflow, current knowledge suggests that conservation tillage can lead to higher drainflow output of pesticides in fine-textured soils, due to quicker and more intensive macropore transport of pesticides to drains within undisturbed soil profiles. Consequently, the tillage regime influences the transfer speed of solutes, as well as their distribution between run-off and drainage pathways.

This means the influence of reduced tillage/no-till on run-off mitigation and drainage mitigation result in contradicting effects. If surface run-off occurs on a drained field, its prevention takes precedent over drainflow mitigation, as pesticide concentrations and short-term loads are typically higher for surface run-off events. In addition, erosion control is of utmost concern for farmers. As a consequence, no-till should be discouraged on a field only if:

(i) surface run-off is not an issue (which usually is of top priority)
(ii) drainflow transfer via macropores must be mitigated for pesticides applied to this field.

(Literature review Ref. 16 to 43)

Figure 17: Tillage practices influence the porosity of the soil (less tillage – less disturbed soil structure)

What to do

If applied pesticides cause problems via drainflow in a catchment, at least shallow tillage should be done before sowing on vulnerable drained fields to minimise fast macropore transport of pesticides in the soils. This only applies to fields where conservation tillage is not needed for surface run-off mitigation.

How to do

As a first step a surface run-off risk diagnosis of the field must be done to exclude the need for conservation tillage in this respect. If one of the applied pesticides is of concern in the catchment due to the drainflow output and the field is diagnosed as being a high risk for drainage (see drainage risk diagnosis tool), then no-till should be discouraged. This is especially important for fields where the soil tends to form cracks at the surface.

Reduced or no-tillage is, besides run-off mitigation, also beneficial to soil fertility due to conservation of soil organic matter. Therefore, the decision to change to shallow tillage should be made only if the application of the pesticide(s) of concern on the relevant drained fields is known to contribute to unacceptable surface water pollution.

6. Use Cover Crops

Cover crops can be seen as an integral part of the crop rotation system and need to fit in between the needs of the "cash crops" and the farming system. In arable cropping systems, they are often grown after harvesting a winter crop in summer/autumn and before planting a spring crop. In perennial crops, like vineyards and orchards, they are also grown between the plant rows.

Cover crops provide benefits to farmers and the environment:

- Minimisation of fallow period: Protects soil from direct exposures to atmospheric processes (rainfall, radiation, wind), thereby increasing aggregate stability and reducing erosion
- Balances soil moisture by evapotranspiration and protects soils from drying out through shading
- Increases organic matter content in soils and thereby enhances nutrient levels (green manure), cation exchange capacity, soil water-holding capacity and soil structure

- Stimulates biological activity in soils and may help to manage certain pests
- Reduces nutrient and pesticide transfer risk to groundwater or drainage system via increased soil sorption and water-holding capacity
- Improves cash crop productivity and potentially farming profitability, depending on the cost of establishing and managing cover crops

What to do

Four key aspects should be considered for green cover crops to deliver benefits for farmers and the environment:

a) Cover crop must fit

Green cover crop mixes must be chosen to fit to the farming system to provide the benefits the grower is looking for. Cover crops are often based on brassicas, legumes, grasses and cereals, or some combination of these plant species. Cover crops must fit with the crop rotation or the perennial crop and sowing dates must be chosen to ensure good establishment, while minimising any negative impacts on the cash crops (e.g. competition for nutrients).

b) Only well-established cover crops deliver the full benefits

As green cover crops often involve a mixture of seeds, special care is needed to ensure that they are sown properly. Cover crops can be drilled or broadcast sown. The specific methods to establish them depend on the choice of cover crops, the type of equipment and field conditions.

c) Cover crops need to be managed

Realising full benefits requires good management of the cover crops, involving, for example, mowing (or grazing), application of fertilisers or pesticides, depending on the cover crops in the seed mix.

d) Cover crops should not interfere with the following cash crop

Cover crops often need to be destroyed before establishing the following cash crops, which can be achieved naturally by frost during winter, burn-down by herbicides, grazing, flattening, or soil incorporation. This has important consequences on the establishment of the following crops. For example, cover crop destruction on heavier soils in spring often needs to open up the canopy earlier, so the soil can dry out and warm up to enable a timely cash crop establishment.

Figure 18: Main crop growing in remnants of a cover crop

How to do

Consultation with a professional agronomist is always advised when introducing cover crops into the crop rotation/perennial crop. Local agronomists should be able to give specific advice on adapting them to local soil and weather conditions, considering also the cropping systems used. Local seed houses can also give specific advice, while general advice is available online (e.g. Ref. 44, 45).

In arable cropping, cover crops will often be sown in late summer or autumn, after harvesting winter crops (such as wheat, barley, oil seed rape), and grown until spring crops (such as maize, sunflower, wheat, barley and sugar beet) are sown. Grasses like oats and ryegrass can be key components in cover crop mixes. They establish quickly and are shallow rooted, which leads to effective transpiration and promotes the development of a granular crumb structure at the soil surface. Grasses often mix well with cover crop species that form deeper root systems to improve soil structure lower down. These include brassicas like mustard and radish, but can also include legumes, particularly those suited to autumn sowing, which also enhance microbial activity.
However, after the harvest of spring crops in late autumn, it is often too late to sow a cover crop. Alternatively, a cover crop can be under sown in the cash crop: For example, ryegrass and legumes can be drilled in maize at the eight to ten leaf stage, when competition with the more advanced maize crop is already limited.

In perennial crops, ground cover is more often needed to prevent run-off and erosion than drainage transfer, particularly in drier climates. In places where there is water excess rather than water scarcity, grass-clover mixes can fit well with perennial crops, such as orchards and vineyards.
As interest in cover crops grows, the number and availability of cover crop seed mix options from seed suppliers are growing rapidly. Part of the increased use of cover crops is driven by the fact that they are included in the Ecological Focus Areas of the EU CAP and may also be suitable for complying with increased crop diversification on farms.

The effectiveness of cover crops to reduce nitrate leaching in fields is well documented. The two key processes to explain the reduced N leaching are N uptake into the cover crop, and transpiration of water from the soil (which lowers overall soil moisture and drainflow). Pesticides are in principle subject to the same processes, though the effectiveness of pesticide uptake is less certain than that of lowering overall soil moisture. In addition, increasing the microbial activity of topsoil will also generally enhance pesticide degradation and reduce leaching in soil.

Constraints

Cover crops do not come without constraints, so it is important to be aware of them and manage them, to ensure their use produces net benefits for farmers.
The increase in productivity/profitability of the following crops must outweigh the costs to sow, manage and destroy the cover crop (including discounted costs due to any subsidies).

The additional labour to manage cover crops may not be available, particularly if it is limited around sowing time, so this must fit with farm management requirements.
Cover crops generally increase transpiration from soil, which means their use must be critically evaluated in areas with water deficit, particularly if they dry the soil out too much before the following cash crops. The earlier destruction of the cover crop before cash crop sowing may be a solution here.
In moister areas, the presence of a cover crop close to sowing the cash crop in spring may result in the topsoil being too moist and hence not warm enough, delaying emergence. Also in these cases, the earlier destruction of the cover crop may need to be considered.

The residues from cover crops may be an issue for plant health for the following cash crops (e.g. increasing fungal or slug pressure). On the other hand, well-selected cover crops can suppress weeds, nematodes, or other pests and diseases.

	BRASSICAS	LEGUMES	GRASSES AND CEREALS
EXAMPLE SPECIES	**Mustards, radishes, turnips**	**Vetch, clovers**	**Oats, rye, ryegrass**
BENEFITS	Brassicas can grow rapidly in the autumn. There is a good understanding of brassica agronomy (from oilseed rape experience) and establishment systems tend to fit with farm equipment.	Legumes fix nitrogen, which can benefit following crops and raise fertility; the amount of nitrogen fixed depends on species, growth and temperature but is likely to be small with an overwinter cover crop.	Cereals and grasses can deliver good early ground cover (important where erosion is a concern) as well as other benefits, including vigorous rooting.
CHARACTERISTICS	While there are many types and growth habits, autumn-sown brassicas often provide good ground cover and deep rooting. This can mitigate leaching risks and improve soil structure. Some have trap crop and biofumigant activity.	In addition to nitrogen fixing, like most cover crops, legume roots can help to improve soil structure; rooting will vary depending on species, field conditions and cover crop duration.	For autumn sowing, these species can establish quickly and some types offer a wider range of sowing timings than brassicas or legumes.
SOWING	They are often late summer-sown at similar timings to oilseed rape. Field conditions and variety should guide specific sowing dates.	Legumes tend to be slower growing than brassicas and, for autumn use, often need to be sown earlier (late July–August) to aid growth and promote nitrogen fixation.	Sowing times vary with species and may range from July through to September.
CONSIDERATIONS	Good autumn establishment is critical to maximise growth, particularly where soil structure or nitrogen capture are key objectives. Think about potential rotational conflicts, e.g. clubroot, where vegetable brassicas or oilseed rape are grown in the rotation.	Consider management around the sowing and establishment of small-seeded legumes (used alone or in mixtures). There are also potential rotational conflicts, especially where other pulses and legumes are grown in the rotation.	Management tends to be similar to autumn cereals and grasses. They may act as a green bridge for cereal pests and diseases.

Table 6: Considerations for selection of cover crops (Ref. 44)

7. Optimise Drainage Practices

In soils where crop growth and/or trafficability are adversely affected by excess water in the soil profile, subsurface drainage can be an essential tool to maintain or enhance productivity. Subsurface drains may be required where slowly permeable or impermeable layers in the subsoil impede the vertical transfer of excess water away from the surface or in situations, such as river valleys, where a shallow groundwater table is often present within the soil profile. Subsurface drains can be effective in reducing soil saturation and this can have benefits in reducing the initiation of surface run-off. While subsurface drains are important for soil management, 'over drainage' (i.e. more intensive drainage than needed for cropping purposes) should be avoided, as this can increase the transfer of pesticides into surface waters. Secondary drainage at intervals (e.g. every 4–6 years) is necessary in some clay- and silt-rich soils where permeability is particularly low. Subsoiling involves pulling a blade through the soil to shatter the structure and create a network of fissures. When moling is done, a steel torpedo is pulled through the subsoil to create channels, thus establishing an additional drainage system. Secondary drainage, done perpendicular to primary drainage lines, facilitates the transfer of water to the main drainage system. Yet, this can increase pesticide transfer, particularly in the seasons soon after the practice is undertaken.

What to do

The drainage system (primary and any secondary drainage) of a field should be designed to remove only the minimum amount of soil water to ensure that soil management via machines can be conducted when needed and that crop growth conditions are suitable.

How to do

When installing a new drainage system, seek agronomic guidance on design to ensure that both the depth and spacing are appropriate to the soil and site characteristics. Refer to national guidance on the design of drainage systems or consult FAO guidelines (Ref. 46).

Drains should not be shallower or closer together than they need to be to provide effective management of soil water in the field.

Where secondary drainage is required, try to maximise the period between undertaking subsoiling or pulling moles, as shorter intervals will increase the vulnerability of soils for quick pesticide transfer.

Try to avoid high-risk crop/pesticide combinations immediately after undertaking secondary drainage operations.
For example, if a crop in the rotation requires the use of pesticides with higher risk for transfer to water, try to ensure that it is not grown in the season immediately after secondary drainage operations.

Constraints

The drainage design for fields can only be adapted/changed when a new drainage system is installed, or the old one is not functional and must be replaced. For an existing secondary drainage system, this may occur every 5+ years, while for deeper tile/pipe drains this may only be necessary every few decades.

8. Use Water Retention Structures

Water retention structures, such as artificial wetlands, are typically created in the catchment to protect downstream man-made structures from storm water run-off and/or water bodies from substance inputs via surface run-off. In principle, existing retention structures in the landscape can also be used to capture drainflow water. Such retention structures serve a specific purpose and usually do not contain water the whole year, but are only inundated when surface run-off (or drainage) occurs. Their primary function is

(i) to retain, evaporate and infiltrate run-off or drainage water,
(ii) to facilitate the dissipation of nutrients and pesticides from the water phase, and
(iii) to retain any eroded sediment (less relevant if dominant water source is drainage water).

In comparison to surface run-off retention, drainflow mitigation via vegetated retention structures will be less effective as more water (typically >100 mm from the contributing area over a season) with lower pesticide concentrations reaches the structure during winter and spring (drainflow season). For drainflow mitigation, retention structures are therefore a measure more suited for vulnerable sub-catchments/fields only, causing a number of sporadic and/or smaller drainflow events (e.g. beginning of autumn, spring and summer), which could then be retained (mitigated) to a higher degree. Typically, existing retention systems for surface run-off mitigation would be used to also capture drainflow in a catchment. A separate construction of wetlands for drainflow mitigation only will often result in disproportionate costs in comparison to the mitigation effectiveness.

Artificial wetlands often resemble temporarily flooded ponds, which are constructed in such a way as to maximise the water pathway in it (e.g. by structures causing a meandering of low water fluxes) and are also regulated by a weir at their outlet. For more information on retention systems see the respective BMP in TOPPS Run-off BMP booklet (Ref. 1). Natural wetland areas in catchments can also be suitable to retain drainage water and should therefore be maintained and used. As these wetlands are sometimes classified as "nature protection areas", a use for drainage flow mitigation should be clarified with authorities in advance. Such natural wetlands include, for instance, riparian meadows or forests, which are regularly inundated.

What to do

Capture drainflow of vulnerable areas contributing to surface water pollution in existing retention structures in the landscape. A new establishment of retention structures is usually initiated by catchment managers or local authorities to improve or maintain good water quality in a catchment (e.g. reduce nutrient and pesticide input to streams). A thorough diagnosis is necessary to identify suitable locations in the catchment (covering the maximum of high-risk fields) and to determine for each the necessary retention volume needed, depending on climatic and associated drainage flux conditions of the connected area. As such structures may retain drainage water (and run-off) from several fields belonging to various owners, a common management approach is sometimes necessary, to organise the construction and maintenance of the retention structures.

How to do

Retention structures should be sufficiently large to retain the drainage water of a defined "flow event" (e.g. 2 to 5 mm of drainage from connected fields), depending on climatic conditions and the size of the contributing area draining into the retention structure. In the event that enough land is available, vegetated retention structures may be sized to cover a surface area representing up to 1 to 2% of contributing catchment area. Yet, unlike for run-off, it cannot be expected that retention structures can capture and retain the larger part of the incoming water, as the drain flow season may extend for months (late autumn to spring) and results in >100 mm of more or less continuous water flow. However, the residence time/flow path of the water detained in the retention structure can be optimised, for example by using weirs or barriers within the structure.

The water-retention structures are constructed on the local soils/subsoils. In order to ensure that infiltration is not too rapid (and thereby potentially causing a quick infiltration of nutrients and pesticides to shallow groundwater) the banks and the bottom of the retention structures should be clad with a layer of topsoil material (if possible loamy and finer texture), put aside during the previous excavation.

The banks of the structure, as well as its bottom, should be permanently vegetated to ensure bank stability and to slow down water flow. Dense vegetation in the retention structures, which is resilient to regular inundations and anaerobic conditions in the root zone, is important for effective removal of nutrients, pesticides and suspended sediment from the water phase. The types of species to consider (e.g. reeds, grasses, etc.) for establishment of robust and resilient vegetation may be selected with support from local environmental authorities or nature conservation organisations. With time, the retention structures will develop some kind of natural vegetation, which needs to be maintained in a suitable state for optimum substance removal, water slow down, and regular removal of sediment. Usually, grassy/reedy vegetation is the preferred choice, based on current experience from storm water retention and sewage treatment ponds.

A regular removal (e.g. once per year or when >20% of retention volume filled) of deposited soil sediments may be necessary, as otherwise the accumulating deposits will reduce the water retention and infiltration capacity of the retention structure. Removed sediments will consist mainly of eroded soil particles and organic matter, making an application to nearby fields a sensible option.

Locate/use retention structures/artificial wetlands in the catchment at critical points, where drainage from vulnerable fields can be easily captured and retained. Size retension structures sufficiently to intersept a normal expected drainage volume.

- Volume: Design to accept at least 2 to 5 mm of drain flow from the contributing catchment.
  Depending on vulnerability of the drained area and associated problems with nutrients and/or pesticide transport, wetlands may need to be designed to accommodate larger volumes (>5 mm).
- Water depth: In the range of 0.2 to 1 m with an average water depth of 0.5 m when flooded (adjust by weir) at outlet of pond/wetland).
- Banks should not be too steep to provide escape routes for small animals.
- Length: If possible, maximise length of water pathway (i.e. retention time) by constructing a meandering flow pathway within the retention structure using barriers/dams to slow down water movement.
- Vegetate retention structure by seeding local species (non-invasive), which are adapted to an irregular inundation (e.g. *Typha latifolia, Sparganium erectum, Carex spp)*.

In general, expert knowledge is needed for the establishment of efficient retention structures. For more details, seek advice from local environmental advisors/authorities and also consult technical manuals, such as the technical guide "Mitigation of agricultural nonpoint-source pesticides pollution and bioremediation in artificial wetland ecosystems" (Ref. 47) from the EU-Life Artwet project (LIFE 06 ENV/F/000133).

Figure 19: Artificial wetland to collect drainage outflow in landscape

Figure 20: Vegetated ditch to collect drainage outflow

Mitigation effectiveness

The more hydrophobic pesticides are in general the better retained in vegetated retention structures, as they bind more to soil particles (suspended or bottom sediment), as well as to plant material. However, often the more polar pesticides are regarded as "of concern" in catchments used for drinking water production, as these cannot be easily removed during sorptive drinking water treatment processes (e.g. activated charcoal filtration). The elimination efficacy for polar to moderately polar compounds in vegetated retention structures is estimated to be lower (typically in the range from 20 to 70%), while for strongly sorbed compounds efficacy can reach 90 to 100%.

Constraints

Existing retention structures or dedicated space are a prerequisite for this measure and can be an obstacle to implementation. Vegetated water-retention structures are anthropogenic, infrastructural installations, which are constructed to retain and clean drainage (and run-off) water of sediments, nutrients and pesticides. Therefore, any regulation regarding the protection of ecosystems/habitats, potentially interfering with the functionality of the retention structure, should be checked in advance with local environmental authorities. It needs to be ensured that the original purpose of the structure can be maintained even if, for example, endangered species enter the retention structure, since the purpose was to provide wider protection of water quality rather than to establish an ecosystem requiring protection.

9. Optimise Irrigation Practices

Irrigated fields may contribute to drainflow output of pesticides in a catchment if irrigation is applied in excess of crop water requirements and soil water-holding capacities.
On drained fields, sprinkler or drip irrigation may typically be used, with the latter technology being more water-efficient during normal use. Drip irrigation is mostly used in high-value crops due to the high investment needed for its establishment.

What to do

In order to minimize water leaching in soils toward drains, correct irrigation management is key, which considers soil water content, soil water-holding capacity, and crop water requirements in relation to actual evapotranspiration.

How to do

The starting point is the daily monitoring of soil moisture and evapotranspiration, in combination with the forecasted rainfall quantity. Based on these data, the crop water requirements, remaining soil water and the necessary amount of irrigation water can be calculated. Ready-to-use technical irrigation steering toolkits, as well as IT-based decision support systems are commercially available for the management of irrigation processes. Drain outfalls should be checked regularly during the irrigation season to make sure that no artificial drainage events are triggered in the soil.

Figure 21: Optimised irrigation practice

BEST MANAGEMENT PRACTICES TO REDUCE PESTICIDE LEACHING

1 KEY FACTORS FOR PESTICIDE LEACHING

In the contect of these recommendations, leaching is defined as the downward transfer of substances with soil water into the groundwater. In agriculture, especially nitrate and some pesticides are potential leaching pollutants.

In general, most groundwater recharge takes place during winter and early spring, due to lower evapotranspiration from soil/plants, resulting in a downward flow of water in the soil profile. This seasonal pattern of water flow is especially important for more mobile pesticides, whose uses may need to be restricted in autumn in some scenarios.

Leaching tends to be stronger and faster in sandy soils, which have a low water-holding capacity and higher permeability. In contrast, water movement in heavier soils (e.g. clay loam) is typically very slow. However, in some clay soils (depending on clay types and contents) deep cracks may open at the soil surface during drying periods, which facilitate a quick preferential flow of water into deeper soil layers.

Key factors influencing leaching processes

Key parameters influencing the leaching potential of substances are described in the general introduction and are briefly summarised. Three main aspects are important:

a) Properties of the pesticide (active ingredient of PPP)

- Persistence in soil (DT50)
- Mobility in soil (sorption coefficient K_{OC})

b) Climatic conditions

- Average soil temperature after application
- Average soil moisture after application (rainfall pattern)
- Annual groundwater recharge rate

c) Soil properties

- Soil texture
- Soil structure (aggregation, macropores)
- Biological activity (organic matter content, aeration)
- Sorption capacity (presence of clay and organic matter as key constituents)

Hence, it is important to note that pesticide leaching is affected by many factors and their complex interactions, making it difficult to determine the exact leaching potential of pesticides in a particular situation. In this context, independent from substance properties, we recommend focusing on the key factors influencing the relative risk of pesticide leaching in terms of the soil and climate conditions, namely the

(i) depth to the groundwater,
(ii) soil structure, including the effects of soil management on it,
(iii) special soil types, and
(iv) soil water-holding capacity, as influenced by soil texture.

2 RISK DIAGNOSIS

It is recommended to conduct a catchment and field diagnosis before selecting BMPs to manage pesticide leaching. A dashboard has been developed to identify a range of leaching scenarios in the field and their associated relative risk potential for pesticide losses from fields to groundwater. This dashboard was developed to reduce the complexity of the entire process of identifying scenarios and associated risks with a set of common criteria that apply across Europe and for pesticides in general. After diagnosing the existing situation, the associated leaching risk can be estimated. In the next step, the appropriate mitigation measures need to be selected. In addition, the local climatic conditions (e.g. rainfall pattern, temperature) need to be taken into account. This concept of Best Management Practice (BMP) to prevent unacceptable pesticide leaching requires a risk diagnosis and subsequent selection of appropriate BMP measures. BMP = risk diagnosis + selection of BMP measures (toolbox).

The diagnosis dashboard may need to be adapted to country-specific environmental conditions (e.g. in France, a lower vulnerability cut-off is defined with a plant-available water capacity of 120 mm, rather than a water-holding capacity of 150 mm).

Figure 22: Dashboard – Vulnerability diagnosis dashboard for pesticide leaching potential in fields

Shallow[1] groundwater	Large cracks/macropores[2] occur		High risk
	Large cracks/macropores do not occur in most years	Sowing under no-till	High risk
		WHC[3] <150 mm	High risk
		WHC of 150 to 230 mm	Medium risk
		WHC >230 mm	Low risk
		Peaty soil[4]	Low risk
No shallow groundwater	Shallow soil[5] on fractured rock		High risk
	Other soil	Sowing under no-till	Medium risk
		WHC <150 mm	Medium risk
		WHC >150 mm	Low risk

[1] Groundwater ≤1 m below soil surface at some time of the year.
[2] Cracks/macropores of ≥1 cm width occur at the soil surface.
[3] Soil water-holding (field) capacity (in upper 100 cm of soil or above groundwater level, whichever is shallower).
[4] Peaty soil: Soil with ≥30% organic matter in topsoil (plough layer).
[5] Soils with ploughable profiles <30 cm depth: normally just topsoil horizon overlying fractured rock (e.g. rendzina soils on karst).

How to use the dashboard

The dashboard needs to be used from left to right, selecting the appropriate category for each column, progressing stepwise to define the risk category for each field. First, a decision needs to be made about the depth to groundwater, if it is ≤1 m (shallow groundwater) or deeper (no shallow groundwater).

Secondly, decisions need to be made about the presence of macropores in case of shallow groundwater. For deeper groundwater, high-risk soils are identified with a shallow topsoil, when overlying fractured rock.

Thirdly, decisions need to be taken based on the water-holding capacity of the soil, the tillage regime during sowing and the existence of peaty topsoil.

Besides these factors, local climatic conditions (rainfall pattern, temperature) will influence the absolute vulnerability of groundwater to pesticide leaching.

In general, implementation of BMPs can reduce the risk of pesticide leaching and should be applied especially in vulnerable areas, where pedoclimatic conditions and agricultural practices favour water transfer to groundwater. Exceedances of the pesticide threshold value in groundwater can lead to use restrictions or ultimately the ban of relevant PPPs via the environmental or regulatory authorities long term. Pesticides in groundwater (low microbial activity, no sunlight, slow water flow) persist longer than in surface water, and thus may cause a mid- to long term issue in catchments. Yet, pesticide groundwater contamination risks are evaluated during the EU regulatory process and safe uses under typical worst-case conditions are thereby ensured. In some cases, use restrictions for vulnerable areas or further stewardship advice are stated on the PPP label.

The diagnosis dashboard may need to be adapted to country-specific conditions with regard to local soil and climate conditions or because of compatibility with existing risk-diagnosis systems.

It should be stressed again that leaching risk diagnosis and BMP implementation should be done in reaction to unacceptable findings of specific pesticides in groundwater bodies of a catchment. As pesticide leaching very much depends on pesticide properties, use rates and local climatic conditions, leaching BMPs should not be applied to all fields and pesticides in a proactive way, but rather only to specific pesticides causing unacceptable findings in groundwater.

The risk profile for leaching can be defined by conducting a dashboard analysis (Fig. 22).

Fields diagnosed with a low risk may require none or only a few general measures to maintain the low risk profile, while high-risk situations may require the application of most or even all mitigation measures available. It is recommended to conduct the risk diagnosis and discussion of potential measures together with the advisor and the farmer, ensuring that mitigation measures are evaluated also based on their fit with the current farming system and any future options for it. Most of the mitigation measures for leaching are similar to those proposed for drainage.

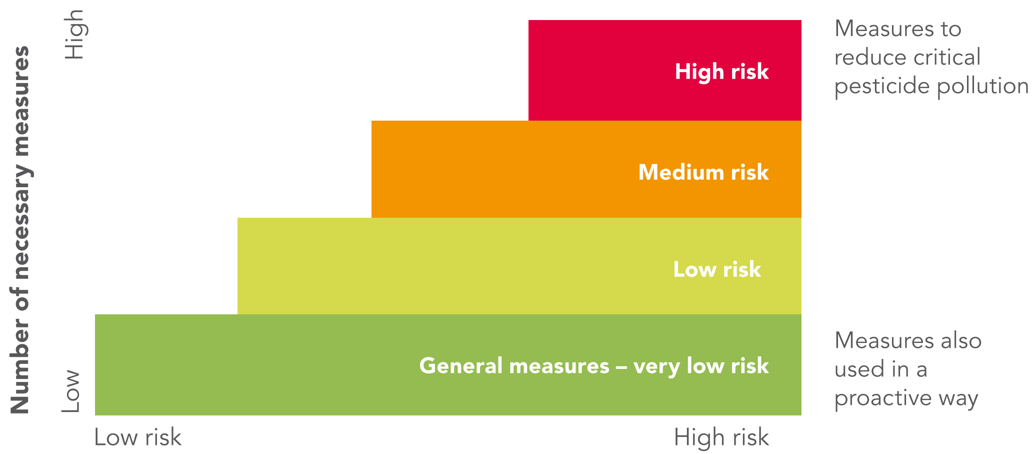


Figure 23: Concept of how to build risk-adapted BMPs by selecting appropriate mitigation measures

The example shown in Table 7 can be used as a starting point to discuss suitable combinations of measures. In the end, defining the suitable measure(s) is also an iterative process, which may need to be repeated based on the achieved water monitoring results (i.e. in this case groundwater data), if still not acceptable. However, as pesticide leaching to groundwater can be a mid- to long-term process, changes in groundwater quality are unlikely to not be seen within one year.

1. Adapt Pesticide Application Timing

The timing of pesticide application in respect to the yearly groundwater recharge season (winter and early spring) is critical, as during this time there is a continuous downward-directed water flow in soil and degradation conditions are not favourable. Due on the variability of yearly rainfall, the beginning and end of the groundwater recharge period may shift for a few weeks for a given site from year to year.

What to do

In general, apply critical pesticides (i.e. pesticides which are known to cause unacceptable groundwater concentrations in the catchment) outside of the main groundwater recharge season whenever possible; if needed, select more appropriate PPPs according to the possible time window for application.

How to do

Study the PPP label carefully, if seasonal application timing requirements exist. Check also for product stewardship advice from the manufacturer.
Avoid the spraying of critical pesticides as far as possible from late autumn until mid-spring (main groundwater recharge period).

2. Reduce Substance Load per Field

a) Reducing the application rate of a pesticide (incl. via mixture products)

The efficacy of PPPs depend on the specific properties of the pesticide active ingredient, but also on a number of external factors, e.g. climatic conditions, application techniques, soil type, soil moisture, crop, plant varieties, target organisms and the development stages of pests. The rates that are recommended on the label need to guarantee good efficacy considering the variability of the external factors. Rate reductions are sometimes possible without the loss of efficacy if external factors are favourable for the PPP's activity.

In practice, farmers at times can reduce PPP application rates, but in these cases the risk of reduced PPP efficacy needs to be considered, as the external factors are not always easy to predict. However, based on a farmer's experience with PPP use on each of their fields, a rate reduction may result in acceptable risk for crop yields. Besides, also plant traits, specifically bred for higher pest resistance/resilience, may be a factor that allows the reduction of plant protection intensity.
However, it should also be considered that reduced rates can increase the risk of resistance formation in pests, due to lower pest mortality after application. Increasing pest resistance may result in the need for increased rates at consecutive applications or a change of the PPP to break resistance. Rate reductions should therefore be discussed with advisors and, if possible, should rather focus on using mixture products (or tank mixes), combining different modes of action.

What to do

Reduce the application rate of targeted pesticide to the minimum necessary on the respective field, considering mixture products whenever possible.

How to do

Always consult with the advisor and/or the respective company stewardship manager about the minimum effective application rates of a pesticide. If possible, select mixing partners which allow one to reduce the rate of a critical pesticide without compromising efficacy or the risk of resistance development. Make sure that the reduced rate or pesticide mixture is sufficiently effective to solve the crop protection problem. Before mixing several PPPs as tank mixes, check label recommendations and ask for specific advice, such as if PPPs can be mixed and what results can be expected.

Table 7: Example to define BMPs related to their estimated efficacy linked with the risk diagnosis

Measures categories	General measures	Low-risk* measures	Medium-risk* measures	High-risk* measures
Adapt application timing			Avoid spraying during ground-water recharge period	Consider alternative PPPs
Reduce substance load per field	Consider seed treatment options Consider spot treatment techniques	Use split applications Reduce rate to a minimum that maintains efficacy	Reduce rate via pesticide mixture	
PPP selection and rotation			Rotate pesticide use from year to year on field Rotate pesticides at catchment level	Restrict use of critical pesticide(s)
Optimise crop rotation	Select rotation to optimise plant health	Consider crops with tap- & fibrous-root systems Alternate winter & spring crops		
Adapt tillage practice				Consider tillage to disconnect soil macropores
Grow cover crops	Select suitable cover crops			
Optimise irrigation practices	Calculate needed irrigation volume	Optimise irrigation scheduling based on soil moisture		

* For these risk levels also measures listed for lower risk levels can be considered (see Fig. 23).

b) Reduction of application rate via split applications
Split applications are successive applications of the same or different PPP in a sequence to a crop. These applications exploit the higher sensitivity of small weeds to the herbicide (e.g. a first flush of emerged weeds). Split applications have been shown to be effective to protect water for the molluscicide metaldhyde. Such applications reduce the PPP concentration in topsoil/on plants directly after application and thus spread the load of active ingredient on the field over a longer time period. It therefore decreases the risk for high concentrations of pesticides being leached into deeper soil layers, especially if rainfall occurs shortly after application.

What to do
Split the application of PPP into a number of applications (usually two half-doses), which need to be timed and dosed according to label requirements.

How to do
Split applications require good monitoring of the growth stages of pests and a very good knowledge of the specific PPP activity and properties. Application timing therefore needs to be chosen very precisely and agronomic advice should be taken.

Constraints
Split applications have the disadvantage that applications have to be done at least twice, resulting in additional costs and soil compaction via spraying operations. In late autumn and early spring, such practices are sometimes difficult to realise if the soils are too wet to drive on.

c) Reduction of overall application rate via spot application
In practice crops and pests are not evenly distributed in a field but occur in clusters (e.g. pest hotspots). Spot application methods direct pesticide applications to the parts of the field, where pesticide treatment is needed. This means that a certain part of the field remains untreated, thereby reducing the overall pesticide application rate per field.

Such reductions can be differentiated between banded applications (typically targeting the area between crop rows only) and variable spot applications.

Digital farming may offer further technical options. Digital farming technologies are currently being developed to predict, secure and enhance yields while optimising the application of plant protection products (PPP) in a more targeted, controlled and efficient manner (precision farming). The fast development of these platforms and applications will provide ample opportunities to tackle environmental exposure issues and reduce the drainage and leaching risk of plant protection products due to spatial and temporal refinement of application rates.

Decision support tools, in combination with disease risk models that map the infestation risk and pressure, can help to optimise rates of fungicides to specific parts in a field, thus minimising the total load of PPP. Targeted weed control by weed patch spraying based on automated weed recognition and mapping provides a further opportunity to achieve highly efficient PPP application.

Vulnerability mapping is a further promising approach to delineate the leaching and drainflow risk based on site-specific risk indicators such as organic carbon content, texture or infiltration capacity. These maps can help farmers, advisors and regulators to identify high risk areas and to target site-specific risk mitigation measures.

What to do

Banded application annual and perennial crops which are grown with large enough row spacing can be treated in-row or between-row for weed control using a special sprayer. Such application methods are most often used with herbicides in orchards and vineyards. However, also in field row crops (e.g. maize, sunflower), banded application of herbicides has recently become more frequent.

For variable subarea applications (spot applications), the aim is to only treat infested (insects, fungi, weeds) parts of the field. Such a strategy is only recommended when patch-wise precise pest monitoring is available and a targeted treatment is ensured (either manually or by automatic sensors).

How to do

Sprayer technology needs to be adapted to enable application between the crop rows. Side-shielding may be necessary to prevent crop damage. Dose and spray volume calculations need to consider the area actually treated.

Key is a reliable monitoring/sensoring system which allows one to indicate the areas/patches to be treated. If a pre-application monitoring of pest infestation is done (manually or via drone/satellite sensoring), the treatment areas identified are usually transferred to digital GPS maps. Such digital maps are used by modern sprayers for automated nozzle control during application. Pests which are mobile (e.g some insects/fungal diseases) are more difficult to treat effectively using map-based application systems. Sensor-based applications, rely on the online signals of sprayer-mounted sensors (i.e. in front of a sprayer), which detect pests during application. For weed control, sensor-based techniques already exist; for other applications, sensors are mostly still in a research stage.

Constraints

The adaptation of monitoring and spraying technology requires investments in machinery/software which may be difficult to justify for smaller farms and limited application scenarios.

d) Reducing application rates via seed treatment

Seed treatments are the most effective PPP application method in terms of environmental contamination, as only the seed is treated before sowing. Often, overall PPP loads to the field are then significantly less compared with broadcast pesticide use (to be substantiated case by case). This technology is targeted towards soil-born pests and diseases, as well as systemic protection of plants (i.e. complete foliage). For the latter target, only systemic pesticides are used, which can be translocated after germination to the above-ground parts of the plant.

What to do

Use treated seeds to minimise exposure of the environment (e.g. via spray drift) to PPP.

How to do

In most cases, seeds are treated in specialised treatment plants and the treated seed is bought by the farmer, coated with the desired pesticide(s). Make sure to avoid dust drift during seeding, and buy high-quality seed products (with low dust abrasion) and use appropriate technology to direct the exhaust of seeding machinery towards the ground.

Constraints

Seed treatments combine the choice of seeds with the choice of plant protection. This technology should only be used if there is a high probability for needing the respective chemical crop protection within the season (predetermination of pest management tool).

Table 8: Overview on measures to reduce losses of PPP to groundwater due to leaching

MEASURES CATEGORIES	MEASURE
Adapt PPP application timing[1]	Avoid spraying shortly ***before or during groundwater recharge period*** or before heavy rainfall is forecast ***Consider alternative PPPs***
Reduce substance load per field[1]	Reduce overall rate per area ***Use pesticide mixtures (different active ingredients)*** Use split applications (stretch pesticide load) Use pest-monitoring techniques (manual; automatic sensors) and only treat infested areas (spot treatment) Use seed treatment
Optimise PPP selection and rotation in catchment[1]	***Rotate pesticide year-to-year on vulnerable fields*** ***Rotate pesticide at catchment level*** ***Restrict pesticide applications on vulnerable fields***
Optimise crop rotation	Select crop rotation to optimise plant health and - alternate winter and spring crops - consider plants with tap- and fibrous-root systems
Adapt tillage practices[1]	***If leaching is a problem, consider using at least shallow tillage to disconnect soil macropores in vulnerable fields***
Grow cover crops	Select cover crops to fit with the rotation of main crops - pay attention to good cover crop establishment - maintain and manage cover crop - ensure cover crop does not interfere with cash crop
Optimise irrigation practices	Calculate the correct irrigation volume (balance) Soil moisture monitoring to optimise irrigation scheduling

[1] Some BMP measures (in bolt italics) should only be used reactively for reduction of unacceptable concentrations of critical pesticides.

3. Optimise Pesticide Selection and Rotation

a) Rotate pesticide at field level

If pesticide leaching in a catchment is an issue, a number of vulnerable fields usually contribute to groundwater contamination. Leaching to groundwater can be a long-term (i.e. multi-year) process, depending on the substance and soil properties. Therefore, a yearly application of the targeted pesticide on vulnerable fields will lead to a continuous translocation of pesticides, while a restriction to one use every other or third year, for instance, will reduce the resulting long-term groundwater concentration.

What to do

If a pesticide creates an issue with groundwater contamination in a catchment, PPPs with this substance should be used in rotation on vulnerable fields (i.e. not every season). This can be achieved by crop rotation and product rotations for individual crops, depending on farming systems.

How to do

Consult advisors and PPP distributors on alternative PPPs solutions to avoid that a single active ingredient is applied too often. Adapt the crop rotation to ensure that critical pesticides are not used every season. Also adhere to stewardship advice from manufacturers of pesticides in this regard.

b) Rotate pesticide at catchment level

In catchments with pesticide leaching issues, many fields may contribute to groundwater contamination. A suitable crop rotation (e.g. 3- to 4-year cycles) on the fields in the catchment will reduce the overall amount of a single pesticide used in a season (as compared to monocropping or 2-year cropping cycles), as PPPs are mostly specific for certain crops and pests (the available herbicide product toolboxes, e.g. for. sugar beet, cereals and corn, do not overlap much). On a given crop, PPP use can also be rotated, based on the available products registered for use in a certain crop for a certain pest. This practice will also decrease the probability of developing of pest resistance against any specific PPP in the long term.

What to do

In areas where groundwater contamination is an issue, it is recommended to implement wide crop rotations via variable seeding dates (autumn/spring), making sure that no critical PPP is used predominantly in any season (see also BMP on Crop Rotation for more information). If one or two crops are dominant in a catchment, PPP use on these crops should also be rotated among all farmers that cultivate these crops.

How to do

In catchments with pesticide groundwater issues, the crop rotation should be optimised by the farmer to achieve the longest crop rotation cycle feasible. In order to avoid a too high share of one crop in a catchment, a basic understanding should be sought among growers at catchment level to achieve an adequate crop heterogeneity. In the case of one or two dominating crops in a catchment, a PPP rotation should be implemented for this crop (agreement needed among growers), so that simultaneous applications of critical pesticides are minimised. Basis for selecting and applying pesticides is the use indications listed on the label, which guarantee biological performance and compliance with the legal requirements.

Constraints

Achieving a high crop variability in a catchment may be hampered by economic (e.g. marketing of harvest) and agronomic (e.g. available machinery) factors, which need to be addressed first. A rotation of PPPs for specific crops is sometimes restricted by the limited availability of effective and registered PPPs for certain crop-pest combinations. Coordination at catchment level, which could be led by the water authorities, drinking water providers, or advisors (in collaboration with farmer representations) is needed for this BMP.

c) Select/restrict pesticides for use on vulnerable fields
In a limited number of catchments normal adherence to good agricultural practices and general stewardship advice for pesticides will not prevent some pesticides from contaminating groundwater, in exceedance of the legal limit value (i.e. generic groundwater limit of 0.1 µg/L, which also applies to drinking water). Water-monitoring data will provide catchment managers with information on which pesticides lead to unacceptable concentrations in groundwater under the current use practices. Besides point source pollution, which needs to be addressed as the first priority, such situations arise due to worst-case combinations of pedo-climatic features and pesticide environmental fate characteristics. In such situations, special requirements are needed to ensure that water bodies meet the necessary quality standards.

- Local restrictions (voluntary or mandatory: e.g. rates, timing, application type) on PPP use in certain vulnerable areas, where restriction of use beyond that stated on the label are considered to be necessary and sufficient to meet the necessary standards for groundwater.
- Local non-use (voluntary or mandatory) in certain vulnerable areas because the risk of exceeding the standards for groundwater from any use is considered to be too high. Vulnerable areas/fields for groundwater contamination can be roughly assessed using the TOPPS leaching risk dashboard and should be substantiated with local advisors.

No set process can be outlined here for deciding which local restrictions or non-use requirements need to be applied, since this depends on the details of each specific situation. However, based on existing experience, solutions can often be found ensuring that adapted pesticide use integrates the need for both clean water and crop productivity.

PPP manufacturers also provide stewardship advice for some pesticides with critical substance properties (e.g. mobility in soil, persistence in soil) to avoid excessive groundwater contamination in vulnerable situations. This advice can either be found on the product label or may be communicated to users via the advisory service or PPP distribution system (country-specific). Growers and advisors should adhere to such stewardship recommendations and, in addition, consult their official plant protection advisors for additional information.

What to do
In areas where groundwater contamination by a specific pesticide is an issue, seek advice on specific PPP use and follow recommendations/restrictions for vulnerable areas.

How to do
Based on the identified pesticide of concern, recommended use restrictions for the critical PPP(s) should be implemented on specific fields. Official advice (e.g. from a farm advisory service or water advisors) and, if relevant, company stewardship recommendations should be followed. The legal basis for selecting and applying pesticides are listed on the label, which guarantees biological performance and compliance with the legal requirements.

Constraints
Use restrictions (especially non-use advice) for a PPP may sometimes limit the effectiveness of the remaining crop protection alternatives for a given crop. In these cases, consider changes of the crop rotation on vulnerable fields.

4. Optimise Crop Rotation

Crop rotation is the subsequent cultivation of different crops on the same field or in a catchment over the years. The rationale for this practice is to achieve agronomic, economic and environmental benefits, compared with continuous cultivation of the same crop (monoculture). The main goal of the crop rotation is to maintain the fertility of the soil and increase plant health.

For a farmer, the selection of the crop rotation is an important management decision. It determines workloads during the year, short- and longer-term profitability, machines needed, fertility and structure of the soil, tillage practices, build-up of organic matter and pest pressure, and has implications on environmental aspects like water movement in the soil. With regard to mitigation of pesticide leaching to groundwater, optimised crop rotations provide the following advantages:

Enhancing PPP sorption and degradation in soil

Most of the biological activity in the soil is found in topsoil, which is rich in organic matter. This activity is increased with the content of organic matter and favours the degradation of PPP in the soil and the soil adsorption capacity. Cropping soils with a high level of crop residues and inclusion of cover crops in the crop rotation contribute to increased soil organic matter content in soils and microbial activity levels.

Reduce overall PPP use by exploiting IPM benefits
Narrow crop rotations tend to accumulate crop-specific diseases, pests and weeds. Therefore, it is good practice to consider a diverse crop rotation also from the perspective of plant health. This helps to better target the use of PPPs. Crop rotation decisions depend very much on economic parameters which are often out of the farmer's direct influence.

What to do

Establish a crop rotation which is most diverse and which fits with the farming system and the economic needs. Alternate between winter and spring crops, tap- and fibrous-root crops, cereals and broad-leafed crops. Legumes in crop rotations provide additional benefits with regard to increased nitrogen contents and the biological activity of soils. Suitable rotations depend very much on the local climate and soils. An example of a diverse crop rotation would be, for instance, winter wheat/barley, followed by maize, soybean and peas/sugar beet.

How to do

Soil organic matter content needs to be managed by leaving ample crop residues after harvest in the field (root system, straw residues, additional cover crops). Depending on the yields harvested, the biomass of organic residues in the soil and remnants can be calculated if organic matter in the topsoil is maintained or increased (consult agronomic tables). The number of crops in the rotation which are hosts of the same pathogens/pests should be minimised, otherwise this could lead, for example, to the build-up of nematodes or fungal disease infection reservoirs. Weed control aspects need to be considered for the rotation, as in some crops weeds can be controlled more easily than in others. Seek local advice for crop rotation options and realise the benefits for pest control.

5. Adapt Tillage Practices

Conservation tillage (reduced or no-till) is effective in reducing surface run-off, erosion and pesticide transfer from treated fields, based on the resulting higher soil infiltration capacity. However, with regard to groundwater contamination, current knowledge suggests that no-till sometimes leads to higher leaching of pesticides. This is caused by faster transport of pesticides via macropores into the subsoil, and the subsequent leaching to shallow groundwater.

This means the influence of no-till on run-off mitigation and leaching mitigation may work in opposite directions. If surface run-off occurs on a field, it is in general recommended that run-off mitigation takes precedent over leaching mitigation, as pesticide concentrations and loads can be quite high for surface run-off events. In addition, erosion control is of utmost concern for farmers. As a consequence, no-till should be discouraged on a field only if

(i) surface run-off is not a critical issue
(ii) groundwater contamination via macropore transport must be mitigated for a critical pesticide applied to this field.

What to do

If an applied pesticide causes groundwater quality problems in a catchment, at least shallow tillage before sowing should be done on vulnerable fields to prevent excessive macropore transport. This should only be applied to fields where consevation tillage is not needed for surface run-off mitigation.

How to do

As first step a surface run-off risk diagnosis of the field must be done to exclude the need for conservation tillage in this respect. If an applied pesticide is of concern in the catchment due to groundwater contamination and the field is diagnosed as being a high risk for leaching (see leaching risk diagnosis tool), then no-tillage should be discouraged. This is especially important for fields where the soil tends to form large cracks at the surface.

Constraints

Reduced or no-tillage is, besides run-off mitigation, also beneficial to soil health and fertility due to the conservation of soil organic matter. Therefore, the decision to change to shallow tillage should be made only if the application of the pesticide(s) of concern on the relevant vulnerable fields is known to, or is highly likely to, contribute to unacceptable groundwater pollution.

6. Use Cover Crops

Cover crops are an integral part of the crop rotation system and need to fit in between the needs of the cash crops and the farming system. In arable cropping systems, they are often grown after harvesting a winter crop in summer/autumn and before planting a spring crop. In perennial crops, like vineyards and orchards, they are also grown between the rows.

Cover crops provide benefits to farmers and the environment:

- Minimisation of fallow period: Protects soil from direct exposures to atmospheric processes (rainfall, radiation, wind), thereby increasing aggregate stability and reducing erosion
- Balances soil moisture by evapotranspiration and protects soils from drying out via shading.
- Increases organic matter content in soils and thereby enhances nutrient levels (green manure), cation exchange capacity, soil water-holding capacity and soil structure
- Stimulates biological activity in soils and can help to manage certain pests, diseases and weeds
- Reduces nutrient and pesticide transfer risk to groundwater via increased soil sorption water-holding capacity and microbial activity
- Improves cash crop productivity and potentially farming profitability, depending on the cost of establishing and managing cover crops

What to do

Four key aspects should be considered for green cover crops to deliver benefits for farmers and the environment:

a) Cover crop must fit

Green cover crop mixes must be chosen to fit to the farming system to provide the benefits the grower is looking for. Cover crops are often based on brassicas, legumes, grasses and cereals, or some combination of these plant species. Cover crops must fit with the crop rotation or the perennial crop and sowing dates must be chosen to ensure good establishment, while minimising any negative impacts on the cash crops (e.g. competition for nutrients).

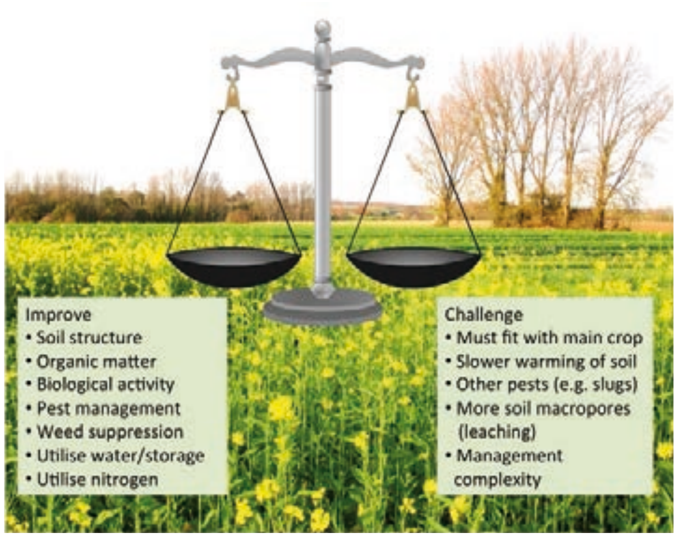


Figure 24: Cover crops can provide farmers benefits if managed correctly

b) Only well-established cover crops deliver the full benefits

As green cover crops often involve a mixture of seeds, special care is needed to ensure that they are sown properly. Cover crops can be drilled or broadcast. The specific methods to establish them depend on the choice of cover crops, the type of equipment and field conditions.

c) Cover crops need to be managed

Realising the full benefits requires good management of the cover crops, involving, for example, mowing (or grazing), application of fertilisers or pesticides, depending on the cover crops in the seed mix.

d) Cover crops should not interfere with the following cash crop

Cover crops often need to be destroyed before establishing the following cash crops, which can be achieved naturally by frost during winter, burn-down by herbicides, grazing, flattening, or soil incorporation. This has important consequences over the establishment of the following crops. For example, cover crop destruction is often needed on heavier soils in spring often needs to open up the canopy earlier, so the soil can dry out and warm up to facilitate better cash crop establishment.

How to do it

Consultation with a professional agronomist is always advised when introducing cover crops into the crop rotation/perennial crop. Local agronomists should be able to give specific advice on adapting them to local soil and weather conditions, considering also the cropping systems used. Local seed houses can also give specific advice, while general advice is available online (e.g. Ref. 44/45)

In arable cropping, cover crops are often be sown in late summer or autumn, after harvesting winter crops (such as wheat, barley, oil seed rape), and grown until spring crops (such as maize, sunflower, wheat, barley and sugar beet) are sown. Grasses like oats and ryegrass can be key components in cover crop mixes. They establish quickly and are shallow rooted, which leads to effective transpiration and promotes the development of a granular crumb structure at the soil surface. Grasses often mix well with cover crop species that form deeper root systems to improve soil structure lower down. These include brassicas like mustard and radish, but can also include legumes, particularly those suited to autumn sowing, which also enhance microbial activity.

However, after the harvest of spring crops in late autumn, it is often too late to sow a cover crop. Alternatively, a cover crop can be under sown in the cash crop. For example, ryegrass and legumes can be drilled in maize at the eight to ten leaf stage, when competition with the more advanced maize crop is already limited.

In perennial crops, ground cover is more often needed to prevent run-off and erosion than drainage transfer, particularly in drier climates. In places where there is water excess rather than water scarcity, grass-clover mixes can fit well with perennial crops, such as orchards and vineyards.
As interest in cover crops grows, the number and availability of cover crop seed mix options from seed suppliers are growing rapidly. Part of the increased use of cover crops is driven by the fact that they are included in the Ecological Focus Areas of the EU CAP and may also be suitable for complying with increased crop diversification on farms.

The effectiveness of cover crops to reduce nitrate leaching in fields is well documented. The two key processes that explain the reduced N leaching are the N uptake into the cover crop and the plant transpiration of water from the soil, which lowers overall groundwater recharge. Pesticides are in principle subject to the same processes, though the effectiveness of pesticide uptake is less certain than that of lowering overall groundwater recharge. In addition, increasing the microbial activity of topsoil will also generally enhance pesticide degradation and reduce leaching in soil.

Constraints

Cover crops do not come without constraints, so it is important to be aware of them and manage them, to ensure their use produces net benefits for farmers.
The increase in productivity/profitability of the following crops must outweigh the costs to sow, manage and destroy them (including discounted costs due to any subsidies).
The additional labour to manage cover crops may not be available, particularly if it is limited around sowing time, so this must fit with farm management requirements.
Cover crops generally increase transpiration from soil, which means their use must be critically evaluated in areas with water deficit, particularly if they dry the soil out too much before the following cash crops. The earlier destruction of the cover crop before cash crop sowing may be a solution here.

In moister areas, the presence of a cover crop close to sowing the cash crop in spring may result in the topsoil being too moist and hence not warm enough, delaying emergence. Also in these cases, the earlier destruction of the cover crop may need to be considered.
The residues from cover crops may be an issue for plant health for the following cash crops (e.g. increasing fungal or slug pressure). On the other hand, well-selected cover crops can suppress weeds, nematodes, or other pests and diseases.

7. Optimise Irrigation Practices

Irrigated fields may contribute to the leaching of pesticides to groundwater in a catchment if irrigation significantly exceeds crop water requirements.
Flood, in furrow, sprinkler or drip irrigation may typically be used, which differ in terms of water efficiency. The latter technique is mostly used in high-value crops due to the high investment needed for its establishment.

What to do

In order to minimise water leaching in soils toward groundwater or drains, correct irrigation management is key, which considers soil water content, soil water-holding capacity and crop water requirements in relation to actual evapotranspiration. Fields should not be irrigated beyond crop water requirements to prevent leaching to groundwater.

How to do

The starting point is the monitoring of soil moisture and evapotranspiration at least once a day, in combination with rain forecasts. Based on these data, the crop water requirements, remaining soil water and the necessary amount of irrigation water can be calculated. Ready-to-use technical irrigation steering toolkits, as well as IT-based decision support system are commercially available for the management of irrigation processes.

B

BMP
Best Management Practice

C

Conservation tillage
Conservation tillage practices are grouped into three types (FAO):

- no-till: planting crops directly into residue that either hasn't been tilled at all (no-till) or has been tilled only in narrow strips with the rest of the field left untilled (strip-till).
- ridge-till: planting row crops on permanent ridges about 0.1 m high. The previous crop's residue is cleared off ridge-tops into adjacent furrows to make way for the new crop being planted on ridges.
- mulch-till: any other reduced tillage system that leaves at least one third of the soil surface covered with crop residue (non inversion ploughing)

Critical pesticide
A pesticide where there have been unacceptable findings in surface water or groundwater, due to pesticide properties in combination with specific environmental factors

D

Dashboard
In our context the dashboard is a structured decision support system.

Non-available water
Water which is tightly bound in the soil by capillary force and so is unable to move and unavailable for plants

Drain outflow
Volumetric discharge (flow rate) of water that is transported by a drainage system

Drainage
Drainage is the natural or artificial removal of a soil water and subsurface water from an area. The internal drainage of most agricultural soils is good enough to prevent severe waterlogging (anaerobic conditions that harm root growth), but some soils need artificial drainage to improve production.

Drinking water quality standard DWQS
Drinking water quality standards describe the quality parameters set for drinking water, e.g. for a country/EU/WHO.

E

EQS
Environmental quality standards (EQS) are threshold concentrations set under an EU Directive for Priority Substances and certain other pollutants, with the aim of achieving good surface water chemical and ecological quality.

EU CAP
Common Agricultural Policy

Evaporation
Evaporation is the process whereby liquid water is converted to water vapour (vaporisation) and removed from the evaporating surface (vapour removal). Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation.

Exposure assessment
Exposure assessment is the process of estimating or measuring the size, frequency and duration of concentrations in the environment for chemicals such as pesticides.

F

Field capacity/water-holding capacity
Water stored in soil which is not lost by gravity few days after soil saturation
Field capacity = water-holding capacity

G

Glacial till
Soil and rock material that has been carried by a glacier as it moves and is left behind when the glacier melts (e.g. moraines)

H

Half time DT50
A parameter to characterise the rate of degradation: The time needed to reduce the concentration of a pesticide in soil or water by half

K

Kd distribution coefficient/K_{OC} organic sorption coefficient
The soil sorption coeffcients Kd and the soil organic carbon sorption coeffcient K_{OC} of pesticides are basic parameters used in describing the environmental fate and behaviour of pesticides. They are a measure of the strength of sorption of pesticides to soils and other geosorbent surfaces at the water/solid interface, and thus influence environmental mobility and persistence: (Ref. 48).

L

Leaching
As water from rain or other sources seeps into the ground, it can dissolve chemicals (e.g. excess fertiliser and pesticides) and carry them into the underground water supply.

P

Permeability
Permeability describes how fast water can seep through a soil layer. It is measured in distance/time (e.g. m/s) and depends on soil properties and soil types.

pF value
Measure how strong water is held within soil. At pF values >4.2 plants can no longer extract water.

Preferential flow
Preferential flow refers to the uneven and often rapid movement of water and solutes through soil, often via macropores (e.g. wormholes, root holes, soil cracks).

Priority substance
Substances listed in the Directive on Environmental Quality Standards (Directive 2008/105/EC)

Risk diagnosis
Identification of a problem which has the potential to lead to losses

Risk management
Risk management is the identification, evaluation and prioritisation of risks followed by coordinated and economical application of resources to minimise, monitor and control the probability or impact of unfortunate events or to maximize the realisation of opportunities. (ISO 31000)

S

Soil organic matter
Soil organic matter (SOM) is the organic matter component of soil, consisting of plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesised by soil organisms. SOM exerts numerous positive effects on soil physical and chemical properties, as well as the soil's capacity to provide regulatory ecosystem services. In particularly, the presence of SOM is regarded as being critical for soil function and soil quality.

Sorption
Process of binding a substance to a solid surface

Soil aggregates
A soil aggregate is a group of primary soil particles that adhere to one another more strongly than to surrounding soil particles.

Soil saturation
All soil pores are filled with water, no air is left in the soil

Soil texture
Classification of soils based on the portions of sand, silt and clay

Subsoiled
Soil tillage generally below ploughing depth to break soil compaction and improve drainage

T

Transpiration
Transpiration is the process of water movement through a plant and its evaporation from aerial parts, such as leaves, stems and flowers.

W

Water framework Directive
EU Directive that regulates water policy in EU member states

Wilting point
Wilting point (WP) is defined as the minimal point of soil moisture the plant requires not to wilt. If moisture decreases to this or any lower point, a plant wilts and can no longer recover its turgidity when placed in a saturated atmosphere for 12 hours.

REFERENCES

01 www.TOPPS-life.org

02 www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/office/ssr7/profile/?cid=nrcs142p2_047970

03 www.science-scene.org/blog/exploring-soil-texture

04 https://extension.psu.edu/soil-quality

05 https://de.wikipedia.org/wiki/Porenvolumen_(Boden)

06 http://soilquality.org.au

07 Saxton and Rawls, 2006

08 https://www.nature.com/scitable/knowledge/library/09soil-water-dynamics-103089121

09 http://soilandwater.bee.cornell.edu/research/pfweb/educators/intro/macroflow.htm

10 http://www.voluntaryinitiative.org.uk/

11 Arvalis pers. information

12 www.enorasis.eu/uploads/files/Water%20Governance/5.JRC46748_Report_Irrigation_EUR_23453_EN.pdf

13 M. Robinson 1990: Impact of improved land drainage on river flows, Report 113; Inst Hydrology Robinson 1990

14 www.landcareresearch.co.nz/publications/newsletters/soil/issue-24/productive-pastures

15 TOPPS_ www,TOPPS-life.org (Arvalis Institut du Végétal)

16 Alletto L, et al. (2012). Tillage and fallow period management effects on the fate of the herbicide isoxaflutole in an irrigated continuous-maize field. Agriculture Ecosystems & Environment 153:40-49.

17 Buhler DD, et al. (1993). Water quality – atrazine and alachlor losses from subsurface tile drainage of a clay loam soil. Journal of Environmental Quality 22:583-588.

18 Clay SA, et al. (1998). Application method: impacts on atrazine and alachlor movement, weed control, and corn yield in three tillage systems. Soil & Tillage Research 48:215-224.

19 Elliott, J.A., et al. (2000). Leaching rates and preferential flow of selected herbicides through tilled and untilled soil. Journal of Environmental Quality 29:1650-1656.

20 Essington, M.E., D.D. Tyler, and G.V. Wilson (1995). Fluometuron behavior in long-term tillage plots. Soil Science 160:405-414.

21 Fomsgaard, I.S., N.H. Spliid, and G. Felding (2003a). Leaching of pesticides through normal-tillage and low-tillage soil - A lysimeter study. I. Isoproturon. Journal of Environmental Science and Health Part B-Pesticides Food Contaminants and Agricultural Wastes 38:1-18.

22 Fomsgaard, I.S., N.H. Spliid, and G. Felding (2003b). Leaching of pesticides through normal-tillage and low-tillage soil - A lysimeter study. II. Glyphosate. Journal of Environmental Science and Health Part B-Pesticides Food Contaminants and Agricultural Wastes 38:19-35.

23 Fortin, J., et al. (2002). Preferential bromide and pesticide movement to tile drains under different cropping practices. Journal of Environmental Quality 31:1940-1952.

24 Gaynor JD, Mactavish DC, Findlay WI (1992). Surface and subsurface transport of atrazine and alachlor from a Brookston clay loam under continuous corn production. Archives of Environmental Contamination and Toxicology 23:240-245.

25 Gaynor JD, Mactavish DC, Findlay WI (1995). Atrazine and metolachlor loss in surface and subsurface run-off from 3 tillage treatments in corn. Journal of Environmental Quality 24:246-256.

26 Gaynor, J.D., et al. (2001). Tillage, intercrop, and controlled drainage-subirrigation influence atrazine, metribuzin, and metolachlor loss. Journal of Environmental Quality 30:561-572.

27 Gish, T.J., et al. (1991). Impact of pesticides on shallow groundwater quality. Transactions of the Asae 34:1745-1753.

28 Gish, T.J., et al. (1995). Herbicide leaching under tilled and no-tillage fields. Soil Science Society of America Journal 59:895-901.

29 Giuliano, S., et al. (2016). Low-input cropping systems to reduce input dependency and environmental impacts in maize production: A multi-criteria assessment. European Journal of Agronomy 76:160-175.

30 Hall, J.K. and R.O. Mumma (1994). Dicamba mobility in conventionally tilled and non-tilled soil. Soil & Tillage Research 30:3-17.

31 Hall, J.K., R.O. Mumma, and D.W. Watts (1991). Leaching and run-off losses of herbicides in a tilled and untilled field. Agriculture Ecosystems & Environment 37:303-314.

32 Isensee, A.R., R.G. Nash, and C.S. Helling (1990). Effect of conventional vs no-tillage on pesticide leaching to shallow groundwater. Journal of Environmental Quality 19:434-440.

33 Isensee, A.R. and A.M. Sadeghi (1995). Long-term effect of tillage and rainfall on herbicide leaching to shallow groundwater. Chemosphere 30:671-685.

34 Kanwar, R.S., T.S. Colvin, and D.L. Karlen (1997). Ridge, moldboard, chisel, and no-till effects on tile water quality beneath two cropping systems. Journal of Production Agriculture 10:227-234.

35 Logan, T.J., D.J. Eckert, and D.G. Beak (1994). Tillage, crop and climatic effects on run-off and tile drainage losses of nitrate and 4 herbicides. Soil & Tillage Research 30:75-103.

36 Masse, L., et al. (1996). Tile effluent quality and chemical losses under conventional and no tillage .2. Atrazine and metolachlor. Transactions of the Asae 39:1673-1679.

37 Masse, L., et al. (1998). Groundwater quality under conventional and no tillage: II. Atrazine, deethylatrazine, and metolachlor. Journal of Environmental Quality 27:877-883.

38 Potter, T.L., D.D. Bosch, and T.C. Strickland (2015). Tillage impact on herbicide loss by surface run-off and lateral subsurface flow. Science of the Total Environment 530:357-366.

39 Ritter, W.F., A.E.M. Chirnside, and R.W. Scarborough (1996). Movement and degradation of triazines, alachlor, and metolachlor in sandy soils. Journal of Environmental Science and Health Part a-Environmental Science and Engineering & Toxic and Hazardous Substance Control 31:2699-2721.

40 Rothstein, E., et al. (1996). Atrazine fate on a tile drained field in northern New York: A case study. Agricultural Water Management 31:195-203.

41 Steenhuis, T.S., et al. (1990). Preferential movement of pesticides and tracers in agricultural soils. Journal of Irrigation and Drainage Engineering-Asce 116:50-66.

42 Watts, D.W. and J.K. Hall (1996). Tillage and application effects on herbicide leaching and run-off. Soil & Tillage Research 39:241-257.

43 Weber, J.B., K.A. Taylor, and G.G. Wilkerson (2006). Soil cover and tillage influenced metolachlor mobility and dissipation in field lysimeters. Agronomy Journal 98:19-25.

44 https://cereals.ahdb.org.uk/media/655816/is41-opportunities-for-cover-crops-in-conventional-arable-rotations.pdf;

45 http://www.agricology.co.uk/sites/default/files/NIAB-TAG%20Cover%20Crops_lowres.pdf).

46) Van der Molen, W.H., Martínez Beltrán, J., Ochs, W.J. (2007). Guidelines and computer programs for the planning and design of land drainage systems. FAO Irrigation and Drainage Paper 62, Food and Agriculture Organisation, Rome, Italy, p230.

47 EU-Life Artwet project (LIFE 06 ENV/F/000133).

48 R Don Wauchope, Simon Yeh, Jan BHJ Linders, Regina Kloskowski, Keiji Tanaka, Baruch Rubin, Arata Katayama,Werner Kordel, Zev Gerstl, Michael Lane, John B Unsworth
Pesticide soil sorption parameters: theory, measurement, uses, limitations and reliability.
Pest Manag Sci. 2002; 58(5); 419-45.

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