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Risk mitigation measures for pesticide runoff: How effective are they?

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Abstract

BACKGROUND: One of the most important sources of pesticide pollution of surface waters is runoff and erosion from agricultural fields after rainfall. This study analyses the efficacy of different risk mitigation measures to reduce pesticide runoff and erosion inputs into surface waters from arable land excluding rice fields.

RESULTS: Three groups of risk mitigation measures were quantitatively analyzed: vegetative filter strips, micro-dams in row crops and soil conservation measures. Their effectiveness was evaluated based on a meta-analysis of available experimental data using statistical methods such as classification and regression trees, and exploratory data analysis. Results confirmed the effectiveness of vegetative filter strips and micro-dams. Contrary to common assumption, the width of vegetative filter strips alone is not sufficient to predict their effectiveness. The effectiveness of soil conservation measures (especially mulch-tillage) varied widely. This was in part due to the heterogeneity of the available experimental data, probably resulting from the inconsistent implementation and the inadequate definitions of these measures.

CONCLUSION: Both vegetative filter strips and micro-dams are effective and suitable, and can therefore be recommended for quantitative assessment of environmental pesticide exposure in surface waters. However, the processes of infiltration and sedimentation in vegetative filter strips should be simulated with a mechanistic model like Vegetative Filter Strip Modeling System, VFSMOD. The reduction effect of micro-dams can be modelled by reducing the runoff curve number, e.g., in the pesticide root zone model, PRZM. Soil conservation measures are in principle promising, but further well-documented data are needed to determine under which conditions they are effective.

Supporting information may be found in the online version of this article.

Keywords: plant protection products; surface water; runoff; erosion; vegetative filter strips; soil conservation measures

1 INTRODUCTION

1.1 Why is risk mitigation necessary and what are the possible drawbacks?

One of the most important pesticide transport processes into surface water bodies is runoff and erosion from agricultural fields after rainfall.[1–4] Many plant protection products (PPPs, hereafter referred to as pesticides) can cause severe harm to aquatic organisms – they can pose an unacceptable risk for aquatic organisms according to regulatory risk assessments. Therefore, many pesticides can only be authorized if risk mitigation measures are imposed. An evaluation of the European risk assessment defined by the requirements of regulation (EC) No 1107/2009[5] concerning the placing of PPPs on the market showed that 26% of all registered active substances require a risk mitigation measure for surface water (no further specification what kind of measure was given).[6] An evaluation specific for runoff risk mitigation measures shows that in Germany 28.1% of all authorized PPPs (516 out of 1836) have at least one authorized

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use with mandatory runoff mitigation measures (Federal Office of Consumer Protection and Food Safety (BVL)).[7] Appropriate risk mitigation measures can reduce the contamination of surface waters adjacent to a field by pesticides during or after their application. Only if these restrictions are adhered to in the application of these pesticides the environment, and in particular aquatic ecosystems, can be adequately protected. The effect of a risk mitigation measure is therefore an integral part of risk assessment to enable authorization of a pesticide.

However, if the effect of a risk reduction measure is overestimated during the authorization process, this may in practice lead to severe underestimation of the predicted environmental concentrations and is one possible reason why recent comprehensive surface water monitoring studies have frequently detected higher concentrations than expected from the risk assessment.[8,9] Therefore, knowledge of the effectiveness of a particular mitigation measure to reduce exposure, in this case of surface waters, is essential for risk assessment in the authorization procedure. On the other hand, risk mitigation measures that are not properly implemented in the field may also result in increased pesticide inputs to surface waters.

Risk mitigation measures can be classified according to their impact location and structure into three different major categories: edge-of-field measures like vegetative filter strips, in-field measures such as soil conservation measures (e.g., no-till, mulch-tillage, ridge tillage, strip tillage, contour cropping) and relief-forming measures (e.g., micro-dams).[6] A special case requiring its own methods is rice cultivation. Extensive literature covering the differences in American, Asian and European rice production and also models accounting for water management are available.[10–12] Due to the differences in methodology, rice paddies are beyond the scope of this study.

Vegetative filter strips (VFS) are areas covered with dense vegetation that are designed to intercept surface runoff. They are often located at the downslope field edge, but can also be established in fields.[13,14] VFS act as a physical hindrance to surface runoff: by reducing the kinetic energy of the overland flow, filtering water and retaining sediment, they reduce the passage of water, sediment and diffuse pollutants (such as nutrients and pesticides).[13] Soil conservation measures like mulch-tillage or no-till leave ample vegetation or crop residue on the field. Increased soil cover primarily reduces the impact of rainfall and thus erosion, but increased aggregate stability also reduces silting and crusting. Fields where soil conservation measures are practiced tend to have a higher infiltration capacity, so both the frequency of occurrence and the magnitude of runoff events are reduced. This effect is further enhanced if the soil is not ploughed for several years. Micro-dams, which are built vertically to the ridge-furrows, at certain distances from each other, can be applied to row crops such as potatoes or maize.[15] Micro-dams were originally developed for erosion control. Their mechanism of action is to improve the retention of rainwater at the surface, thereby increasing infiltration and reducing the occurrence and extent of surface runoff events. For example, in Germany risk mitigation measures for runoff listed in the register of PPPs comprise vegetative filter strips adjacent to fields with a minimum width of 5, 10 or 20 m, which can be omitted if soil conservation measures such as no-till or mulch-tillage are applied in the field (measure NW706 stipulated by the Federal Office of Consumer Protection and Food Safety (BVL)).[16] Accordingly, in regulatory practice it is assumed that soil conservation measures are as effective in reducing pesticide losses as vegetative filter strips of 20 m width. Although soil conservation measures, if implemented properly, are considered effective in reducing pesticides losses through runoff,[6] the extent of the reduction as currently assumed for pesticide authorization in Germany is questioned.[17–19] Also, monitoring results indicate that the runoff mitigation implemented is not as effective as expected.[20]

1.2 Current situation in runoff exposure assessment and risk mitigation

For authorization within the European Union (EU), the pesticide mass entering surface waters via runoff and erosion is calculated using the pesticide root zone model (PRZM)[21] as part of the FOCUS Surface Water package.[22] Pesticides leaving the field through runoff and erosion can either be dissolved in runoff or adsorbed to eroded soil particles. However, for most pesticides, runoff losses are much more important than erosion losses because the eroded soil mass lost from a field is typically small compared with the runoff volume.[23,24]

In PRZM, the runoff volume is calculated with the curve number (CN) approach.[25] The CN is an empirical parameter used to predict daily runoff for a given rainfall volume and depends on soil type, crop type, management practice and soil moisture status. The higher the CN, the more frequently runoff events occur and the larger the runoff volumes are.

If the predicted environmental concentrations exceed a certain threshold derived from the ecotoxicological data submitted for product authorization, risk mitigation measures are necessary. Consideration of in-field risk mitigation measures in the exposure modelling should therefore preferably be linked to defined CN changes for the given measure. To facilitate the derivation of generic CN changes (with respect to the standard practice) for regulatory scenarios, sufficient experimental data points are needed where a CN is fitted to a given field/event combination.[15]

Since edge-of-field mitigation measures do not affect the field itself, in regulatory modelling frameworks risk mitigation at the edge of the field by VFS is considered independently of the field-scale runoff simulation. In the risk assessment at the European level the effectiveness of VFS is currently described by default reduction factors that only depend on the width (more precisely, the length in flow direction) of the vegetative filter strip.[26,27] Alternatively, vegetative filter strips can be simulated with the model Vegetative Filter Strip Modelling Sytem (VFSMOD).[28–30] Here, infiltration and sedimentation are simulated mechanistically,[31] while the reduction of pesticides is modelled using regression-based or mechanistic trapping equations.[32]

1.3 Research question

The objectives of the present study were to (i) quantify the effectiveness of various runoff mitigation measures and (ii) derive recommendations on how the measures identified as effective and suitable can be implemented in the exposure and risk assessment for the authorization of pesticides. These aims were addressed in a three-step approach. First, the economic viability, controllability, current and potential dissemination (but not the effectiveness) of these mitigation measures was assessed on the basis of a survey of key experts in Germany. In a second step, the effectiveness of the measures was analyzed quantitatively. Third and finally, it was investigated whether these risk mitigation measures are suitable for environmental exposure assessment in the authorization of pesticides in Germany and how they could be implemented there.

2 MATERIALS AND METHODS

2.1 Qualitative assessment

To get an overview of the available measures in different countries (mainly in Europe and North America), a literature analysis on available risk mitigation measures was carried out starting with measures currently in place for pesticide regulation[16,33] and complementing them with available comprehensive reports and articles,[6,17,23,25,26,33–35] grey literature[36,37] and documents from agricultural consulting services.[38,39] The resulting collection of 42 different risk mitigation measures was subsequently prioritized by their general applicability as risk mitigation measures for the authorization of plant products (as opposed to measures falling in the domain of best management practices) and narrowed down to a list of the 16 potentially most promising measures with details on the measures given in Table S1. The 16 measures were presented to five experts with in-depth knowledge not only of the scientific basis but also of the situation at the level of the farmers (their fields of expertise are given in Table S2). The objective of this expert consultation was to further narrow down the list of suitable measures and to rank them according to the following criteria: economic viability, controllability, and current and potential dissemination by the experts. Economic viability here denotes the impact on a farm's marginal income under the current Common Agricultural Policy of the EU, including subsidies and requirements. Controllability was considered as the effort needed to enforce the measures. The current dissemination in Germany was defined as the proportion of the cultivated area where the corresponding measure is already applied and was supported with statistical data if available (see Table S3 for details and Table S4 for the full list of all 16 measures). The potential dissemination in Germany was considered to be the proportion of the cultivated area where the corresponding measure could be applied in the near future. Measures that exceedingly failed in one of the mentioned criteria are not considered suitable. The study authors are aware that these criteria are difficult to define precisely but considered them useful for a qualitative discussion. Note that the effectiveness was not evaluated using this admittedly subjective approach.

2.2 Quantitative data analysis

The quantitative analysis of the selected measures was based on the effectiveness defined by the comparison of plots with and without the corresponding measure. Due to the different quality and temporal resolution of the available experimental data, different techniques were applied to different datasets for the quantitative analysis of the mitigation measures recommended by the experts.

2.2.1 Vegetative filter strips

Quantitative analysis of the effectiveness of VFS was done with classification and regression trees (CARTs)[40] using the experimental dataset ($n = 115$ for water and eroded sediment, $n = 244$ for pesticides) compiled and published by Reichenberger *et al.*[41] The dataset comprises event-based data on precipitation, volume of runoff water, mass of eroded sediment, site and experimental treatment (e.g., type of vegetative filter strip, VFS dimensions, source/strip ratio), event and active substance. A full overview of the variables included in this dataset is given in Table S5.

The aim of the CART analysis was to explain the observed reduction efficiencies with the seven available independent experimental variables: vegetative filter strip width and area, clay and organic matter content in field topsoil, runon volume, precipitation and eroded sediment yield. CART was performed in R using the package rPART[42] for three target variables shown to be most relevant for modelling the loss reduction by the vegetative filter strip[23]:

- Total water inflow (volume of runoff water + precipitation): relative reduction (%) of total inflow (ΔQ)
- Eroded sediment mass: relative reduction (%) of sediment load (ΔE)
- Pesticide load: relative reduction (%) of pesticide load (pesticides leaving the field) by the vegetative filter strip (ΔP)

Following Reichenberger *et al.*[41] the following criteria were used as measures of prediction accuracy: Pearson (r^2), coefficient of determination (R^2, corresponds to the Nash–Sutcliffe coefficient [NSE]), percentage bias (PBIAS) and root mean square error of prediction (RMSEP).

2.2.2 Soil conservation measures

For soil conservation measures, the main data sources were (i) a plot experiment database of annual surface runoff and soil loss compiled by Maetens *et al.*,[18] (ii) a field study with event-based data on surface runoff, erosion and pesticide loss,[43] and (iii) two reviews with data on pesticide loss over the whole season.[19,44] These two reviews analyzed in total 14 studies executed in the United States. Due to the heterogeneity of the available data in terms of temporal resolution and the availability of experimental variables, the evaluation had to be done separately for (i), (ii) and (iii). Furthermore, there were differing definitions of various soil conservation measures. For a substantial share of the data only the information that the plot was not tilled with a moldboard plough was available and thus crucial information for differentiating the type of measure and judging the quality of the study was missing. The efficiency of the measures was assessed by comparing runoff, soil loss (erosion) and pesticide loss with the control treatment (conventional tillage). The resulting quantities were runoff ratio (RR, runoff with soil conservation measure/runoff with conventional tillage), soil loss ratio (SLR, soil loss with soil conservation measure/soil loss with conventional tillage) and pesticide loss ratio (PLR, pesticide loss with soil conservation measure/pesticide loss with conventional tillage). The annual and seasonal data were analyzed by means of box- and scatterplots using runoff ratio, soil loss ratio and pesticide loss ratio, while for the single study with event-based results,[43] runoff CNs[25] were calculated (a detailed description of the method is given in Sittig *et al.*[15]).

2.2.3 Micro-dams

For the analysis of micro-dams we mainly relied on the event-based data compiled by Sittig *et al.*,[15] which comprised five studies in potatoes and two in maize (in Belgium, Germany and France). CNs for each event had already been fitted by Sittig *et al.* In addition, the study of Sui *et al.*[45] on micro-dams in maize in China and the study of Keshavarz *et al.*[46] on micro-dams in furrow irrigation (bare soil) in Iran were evaluated. Again, for each event, CNs were calculated and compared between micro-dams and conventional tillage.

3 RESULTS

3.1 Qualitative analysis by expert consultation

In expert interviews, 16 mitigation measures were qualitatively evaluated (Table S4). Regarding *economic viability* two risk mitigation measures were consistently considered to be particularly applicable: no-till and reduced tillage. Six further measures primarily relating to cultivation methods (mulch tillage, strip tillage, cover crops in general, cover crops with deep roots and micro-dams) were assessed to be economically neutral. Eight measures were classified as slightly uneconomical among them various types of vegetative buffer strips (vegetative filter strip, riparian and thalweg buffers) with noticeable differences in the assessment between the different experts (Table S4).

The *controllability* was the criterion with the most positive ratings but varied between measures: while off-field measures can be controlled by remote sensing if data with a high spatial and temporal resolution are available, in-field measures usually require field inspections. Some measures have the potential for efficient record keeping, e.g., through the use of smartphone apps to determine whether a particular plot had a sufficient soil cover to be effective as a soil conservation measure.

The *current dissemination* of the different soil conservation measures was determined using data from the German Federal Statistical Office (Destatis). In 2015, 40% of arable land was managed with conservation tillage and less than 1% with no-till.[47] Quantitative information on the dissemination of riparian buffer strips in Germany is also available, as this measure is an indicator in the National Action Plan required under the Sustainable Use Directive (2009/128/EC) of pesticides.[48] According to the last progress report, the fraction of agricultural streams with buffer strips increased from 38% to 47% from 2010 to 2016.[49]

Another aspect assessed in the expert interviews was *critical factors for success*. These were weighted in the following order: the measures must be easy to integrate into agricultural practice, they must be easy to adapt to local conditions and the necessary know-how must be available or easy to acquire. In addition, it was suggested that the measures must be able to be described in a legally binding way.

Measures that not only contribute to the reduction of pesticide losses but also to soil and erosion protection are preferable. Thereby, they protect the economic production factor soil and are thus also beneficial for the farmers themselves. Labor management and economic constraints sometimes push this self-interest into the background in practice. For example, the short-term concern for a close harvest date may be weighted higher than the long-term perspective of avoiding soil compaction.

The measures finally selected for quantitative analysis based on the results of the expert assessment belong to three major groups: vegetative filter strips, soil conservation measures and micro-dams. The need for up-to-date knowledge on the first two groups is particularly high, as these measures are currently imposed during pesticide authorization in the case of Germany, but also in other countries like Switzerland. The group of soil conservation measures is heterogenous and comprises measures such as no-till, strip till, mulch-tillage and, in some reports, simply low tillage intensity. In Germany, mulch-tillage, a technique in which 100% of the soil surface is disturbed, is the most widespread soil conservation measure.

3.2 Quantitative data analysis

3.2.1 Vegetative filter strips

Results show that the width of the VFS cannot predict any of the three target variables: reduction of total inflow by the vegetative filter strip (ΔQ), reduction of eroded sediment load (ΔE) or reduction of pesticide load (ΔP) (e.g., Fig. 1 and Table S6). The total inflow Q_i (normalized to the vegetative filter strip area), i.e., the hydraulic load, has a stronger influence on the reduction of the total inflow (ΔQ; Fig. 2), eroded sediment load (ΔE; Fig. S3) and pesticide load (ΔP; Fig. S4) than the VFS width (Figs 1, S1 and S2, respectively).

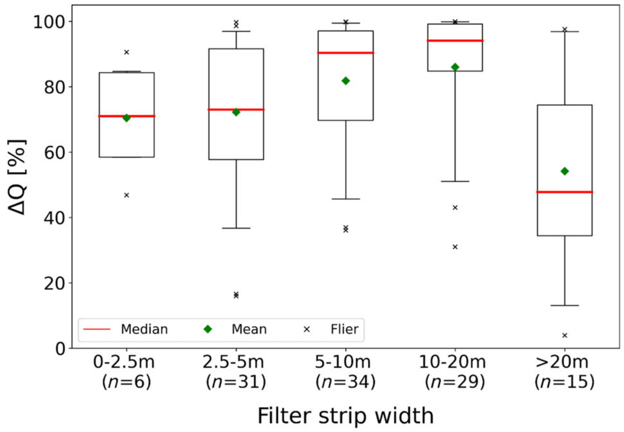

Figure 1. Relative reduction of total inflow by the vegetative filter strip ΔQ as a function of the buffer strip width (length in flow direction). The total inflow equals the runoff leaving the field and the rainfall on the vegetative filter strip. Reichenberger *et al.*[41] $n = 115$.

Using all available independent variables ΔQ can be predicted relatively well using CART, with runon volume and eroded sediment load entering the VFS being the two most important predictors ($R^2 = 0.61$; Table S6 and Fig. S6). In contrast, ΔE cannot be predicted well ($R^2 = 0.45$) and ΔQ is necessary for its prediction in CART (Fig. S7 and Table S6). Reduction of pesticide load (ΔP) can be predicted well from ΔQ, ΔE and the other independent variables using CART ($R^2 = 0.78$; Figs S8 and S9, and Table S6), with ΔQ and ΔE being by far the most important predictors (Table S6). However, this also means that uncertainties in ΔQ and ΔE are further reflected in ΔP.

3.2.2 Soil conservation measures

Not as much or as well-documented data were available for quantifying the effectiveness of soil conservation measures as for vegetative filter strips. Only one study by Erlach[43] contains event-based data on pesticide load, runoff and soil loss reduction, as well as data on cover over the course of the season. The remaining studies contain only more general data on a seasonal or annual basis.

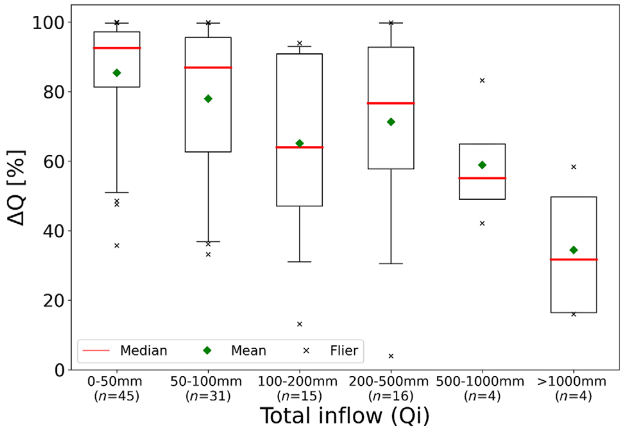

Figure 2. Relative reduction of total inflow by the vegetative filter strip ΔQ as a function of total inflow normalized to the vegetative filter strip area Q_i. The total inflow equals the runoff leaving the field and the rainfall on the vegetative filter strip. Reichenberger *et al.*[41] $n = 115$.

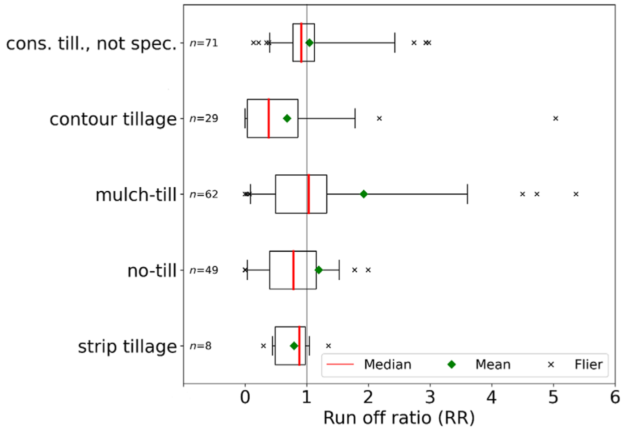

Figure 3. Ratio of annual surface runoff volume with soil conservation measures to the runoff volume without measure (runoff ratio, RR) in arable crops for the data compiled by Maetens *et al.*[18] Hence, if the runoff ratio is <1, the runoff volume with a particular soil conservation measure is lower than without the measure. The label 'Cons. till., not spec.' stands for 'conservation tillage, not specified'.

The effectiveness of mulch-tillage in reducing runoff and pesticides was found to be very variable. Erlach[43] found from event-based data that mulch-tillage clearly reduced runoff, both in terms of occurrence and magnitude (complete elimination of runoff for experiment with winter oilseed rape, clear reduction for maize, slight reduction for winter wheat; Table S7). On the other hand, the data by Maetens *et al.*[18] indicate no difference between annual runoff volumes of mulch-tillage and conventional tillage (Fig. 3). Also, soil loss was substantially reduced by mulch-tillage in the event-based data of Erlach[43] (Table S8) but was unaffected at seasonal level in Maetens *et al.*[18] As expected, in Erlach,[43] pesticide losses due to runoff were reduced for most compounds by mulch-tillage (Tables S9–S11). The only exception was isoproturon, increasingly lost after mulch-tillage in winter wheat, suggesting desorption from the mulch during runoff events.

In the data of Maetens *et al.*[18] with no-till (zero tillage), the efficacy of runoff reduction was also variable but higher than with mulch-tillage (Fig. 3). No-till showed a clear reduction in runoff (median runoff ratio 0.78), especially at high annual runoff volumes (fig. 21 in Klein *et al.*[50]), and erosion (median soil loss ratio 0.39). In the experimental plots of Erlach,[43] no-till even led to a complete elimination of runoff and hence pesticide loss. Analysis of the available annual data on pesticides losses ($n = 79$; $n = 29$ for artificial and $n = 50$ for natural rainfall)[19,44] demonstrated that no-till reduced pesticide loss via runoff and erosion by 54% after artificial rainfall and by 90% after natural rainfall (median values, see Tables 1 and 2). The condensed evaluation of conservation tillage measures such as ridge till or chisel showed a median pesticide loss reduction by 25% for artificial rainfall ($n = 69$) and 55% under natural conditions ($n = 26$) (see further details in Tables 1 and 2).

For a large part of the data, the exact type of soil conservation measure was not specified, neither in the data compiled in Maetens *et al.*[18] nor in the original publications. Thus, information on the degree of soil cover as well as on the intensity and frequency of the soil cultivation method is missing.

The measures referred to as contour tillage in Fig. 3 were also quite heterogeneous and ranged from the formation of ridges along contours, e.g., for potatoes, to more subtle methods such as a seed placement along contours. This aggregated group had the lowest median runoff ratio, implying high effectiveness in reducing runoff. Contour tillage therefore seems to be a recommendable method when the plot size and orientation allow cultivating along contours. The information on slope gradient shows that there is a large fraction of rather steep slopes. This could explain why forming ridges along contours resulted in a substantial reduction in annual runoff and erosion. However, due to the heterogeneity of the data and the lack of event-based data, only limited conclusions can be drawn for this type of measure as well.

Table 1. Pesticide loss ratios for various soil conservation measures and no-till under artificial rainfall conditions (according to Dönges[44] and Fawcett *et al.*[19])

Measure	Measure category	Median	5th percentile	25th percentile	75th percentile	95th percentile
Ridge till, $n = 19$	Conservation tillage	1.06	0.24	0.39	1.28	1.94
Chisel, $n = 19$	Conservation tillage	0.91	0.18	0.69	1.37	1.45
Till plant, $n = 9$	Conservation tillage	0.89	0.62	0.72	1.26	1.47
Disk, $n = 18$	Conservation tillage	0.61	0.13	0.38	0.93	1.21
Strip till, $n = 4$	Conservation tillage	0.03	0.02	0.02	0.05	0.05
Conservation tillage (all), $n = 69$	Conservation tillage	0.75	0.12	0.45	1.19	1.58
No-till, $n = 29$	No-till	0.46	0.04	0.17	0.89	1.62

Table 2. Pesticide loss ratios for various soil conservation measures and no-till under natural rainfall conditions (according to Dönges[44] and Fawcett *et al.*[19])

Measure	Measure category	Median	5th percentile	25th percentile	75th percentile	95th percentile
Ridge till, $n = 16$	Conservation tillage	0.45	0.11	0.25	0.62	1.00
Chisel, $n = 10$	Conservation tillage	0.44	0.09	0.21	0.49	0.52
Conservation tillage (all), $n = 26$	Conservation tillage	0.45	0.09	0.20	0.55	0.79
No-till, $n = 50$	No-till	0.10	0.00	0.04	0.26	0.77

For strip tillage, eight data points were available, all from the same study. The observed maximum annual runoff volume for the control treatment was very low in this study (4.5 mm), which impairs comparability with the other measures.

3.2.3 *Micro-dams*

Micro-dams in potatoes were able to substantially reduce the occurrence and magnitude of runoff from the field.[15] The event-based reduction of the runoff volume was up to 100%, while the reduction in the CN ranged between 1 and 36 points (Table S12).[51] It should be noted that the reduction in the CN for a given event strongly depends on event characteristics, notably the antecedent (i.e., pre-event) soil moisture status.

The micro-dams studied were also found to be effective in terms of soil losses (seasonal reduction efficiency 66–99.8%)[51,52] and pesticide losses from the field (mean seasonal reduction efficiency of 91% and 84%)[51,52] (see Tables S13 and S14).

For the studies of Sui *et al.*[45] in maize and Keshavarz *et al.*[46] for furrow irrigation, mean CN reductions of 7 (Table S15) and 9 (Table S16) were found, respectively. The micro-dams in these studies had larger spacings than the micro-dams typically used in potatoes, however, and are thus not directly comparable.

4 DISCUSSION

Risk mitigation measures can have two different purposes: Either they prevent the occurrence and extent of runoff leaving the field as so-called in-field measures or, as edge-of-field measures, they reduce runoff at the edge of the field if it has already occurred. The regulatory exposure assessment should consider the effect of both types of measures using different approaches.

4.1 Vegetative filter strips

VFS are among the established risk mitigation measures for runoff and erosion in the authorization process. As they usually are located at the edge of the field, they do not interfere with agricultural operations in the field. In the exposure assessment for authorization of pesticides, their effectiveness is linked to the width of the filter strip: It is assumed that reductions in runoff, erosion and pesticide load are a function of the filter strip width alone.[26,27] However, the evaluation in this study showed that the width of the filter strip is not sufficient to predict for the three target variables (reduction in total inflow, eroded sediment load or pesticide load; Figs S1–S3). Note that the weak dependency of pesticide reduction efficiency on filter strip width has been shown previously[23] (Fig. S5). Instead, it was found that the hydraulic load (the total water inflow into the vegetative filter strip [runon and precipitation], normalized to the VFS area) is the most important predictor of VFS effectiveness. This implies that VFS effectiveness is not a constant, but strongly varies from event to event and needs to be estimated on an event basis. Therefore, a constant reduction factor depending solely on the filter strip width, as recommended by FOCUS,[26,27] does not seem reasonable: with fixed reduction factors the true reduction efficiency of a VFS will be underestimated for small runoff events and overestimated for large runoff events.

The weak dependency of VFS effectiveness on VFS width has been noted before (e.g., Reichenberger *et al.*[23]) and also been predicted based on hydrological considerations (e.g., in Schulz[53]). The fact that VFS effectiveness has a stronger dependence on hydraulic load than on VFS width is closely linked to the issue of VFS performance under concentrated flow conditions (where the runoff enters the VFS in concentrated form and flows over only a small area fraction of the VFS) because it is essentially equivalent whether the volume of water entering the VFS is doubled or the area of the VFS over which runoff flows is halved: the hydraulic load on the VFS is the same in both cases. The impact of flow concentration/convergence on VFS performance has been investigated in several publications (e.g., Arora *et al.*[54] Boyd *et al.*[55] Poletika *et al.*[56] Helmers *et al.*[57]), several of which have been included in the dataset compiled by Reichenberger *et al.*[41] Even though flow concentration was clearly found to impact the effectiveness of VFS (e.g., Poletika *et al.*[56]), this impact can be well predicted with modelling (e.g., Muñoz-Carpena *et al.*[14]).

Our evaluations have demonstrated that the reduction of pesticide load (ΔP) by the vegetative filter strip can only be predicted well if accurate estimates of the reduction of total inflow (ΔQ) and the reduction of sediment load (ΔE) are available. Hence, both quantities, ΔQ and ΔE, should be calculated with a dynamic, event-based model like VFSMOD.[28] VFSMOD calculates infiltration and sedimentation mechanistically as a function of precipitation, runoff and eroded sediment yield (e.g., provided by PRZM), VFS dimensions and slope, filter media (grass) properties, VFS soil-hydraulic properties and antecedent soil water content, and properties of the eroded soil material (median particle size, organic matter content etc.).[14] It can also simulate the degradation of pesticide residues in the VFS between events and the remobilization of residues at the next event.

4.2 Soil conservation measures

A number of soil conservation measures were assessed for their potential to reduce the frequency of occurrence and the magnitude of runoff events in the field. Only no-till showed a clear reduction in all variables assessed, i.e., runoff, sediment load and pesticide losses. As for the other soil conservation measures, no effect on annual runoff was found in the data of Maetens *et al.*[18] while median pesticide losses decreased by about 25–50%.[19,44] These limited effects do not mean that soil conservation measures have no potential to reduce runoff, but this would require further event-based studies that additionally include relevant parameters such as soil cover. In the event-based study[43] evaluated, soil cover was monitored throughout the whole season, which confirms that this particular study was performed in an exemplary manner (see details in Tables S7–S11). The fact that the soil cover remained above the threshold of 30% throughout the growing season was probably the main reason for the good efficacy in this particular trial. This lack of more comprehensive data is the main reason why no-till can only be recommended as a regulatory mitigation measure to reduce runoff and erosion to some extent but not as a substitute for a VFS.

There is therefore an urgent need for more precise definitions of the terms reduced tillage (e.g., used in TOPPS[58]), conservation tillage (e.g., used by Destatis[47]) and specific conservation tillage measures such as mulch-tillage (specified by Brunotte[59]), both in the scientific literature and in practice. A more precise definition of conservation tillage would, on the one hand, generate more comprehensive data sets that include information on important variables such as the degree of soil cover. On the other hand, it would also allow a more precise and controllable application of what some authors called a thunderstorm-resistant mulch-tillage.[60] In Germany, mulch-tillage is by far the most widespread soil conservation measure, with 40% of the cultivated area managed with this technique.[48] However, exemplary monitoring data of fields with mulch tillage in maize crops from the German federal state of Bavaria[60] show that the degree of soil cover is often low: Only one plot was covered with more than 30% mulch, which is a recommended value for effective protection against erosion.[35,61,62] The majority of the maize plots examined (75%) had a soil cover of less than 10%. Nevertheless, according to the German regulation all these plots are officially considered to be cultivated with soil conservation measures with a runoff reduction comparable to a 20-m wide vegetative filter strip.

Although the effectiveness of soil conservation measures alone to reduce runoff could not be quantified in this study, the authors generally advocate a combination of different measures in the risk assessment. It should be recognized that any measure that reduces runoff formation *in* the field will always contributes to the efficiency of a vegetative filter strip *outside* the field. This is because the effectiveness of the vegetative filter strip depends on the hydraulic load imposed on it. This applies both to the reduction of pesticide losses and to soil losses during heavy rainfall events.

4.3 Micro-dams

Finally, the assessment demonstrated that micro-dams as an in-field measure can also substantially reduce the occurrence and magnitude of runoff events and the associated soil and pesticide losses. Our analysis was limited to potatoes and, to a lesser extent, maize. However, micro-dams can also minimize water loss through runoff in furrow irrigation systems.[46] It can be concluded that micro-dams are an effective mitigation measure, provided that agricultural machinery is available to establish the dams and the soil texture is suitable for dam formation. For crops such as potatoes, where soil structure is already severely compromised, the formation of micro-dams does not cause any additional disturbance. The applicability to other crops needs to be further investigated, also in terms of how to avoid possible conflicts with the basic idea of soil conservation measures, namely, to minimize soil disturbance and thereby increase water infiltration.

As mentioned before, for the authorization of pesticides in the EU (exposure through runoff is assessed with the model PRZM),[21] which uses the CN technique[25] (section 1.2). Since the CN determines the occurrence and magnitude of surface runoff as a function of a given rainfall volume, it makes mathematically more sense to describe the reduction effect on surface runoff with a reduction of the runoff CN than as a fixed percentage of runoff volume. With the CN approach, the reduction efficiency automatically depends on the amount of precipitation and can be modelled directly in PRZM. In irrigated agriculture, micro-dams can also substantially reduce the loss of irrigation water via surface runoff and thus increase irrigation efficiency.[46] Therefore, in-field risk mitigation measures should be included in the exposure assessment by changing the runoff CN for reference soil moisture conditions. However, elaborating a CN table for, for example, the FOCUS scenarios would require an in-depth analysis of the available data, considering site hydrology, soil texture and the antecedent soil water content for each event.

5 CONCLUSION

After having evaluated various risk mitigation measures for runoff exposure, only the following two measures can be proposed as measures with a sufficient basis of quantitative data.

Vegetative filter strips are already considered in quantitative risk assessment and hence in the context of regulatory decision-making. However, the calculation of their effectiveness should be changed in regulatory practice. Instead of the current approach, which uses fixed reduction factors for runoff, soil loss and pesticide reduction as a function of filter strip width, infiltration and sedimentation in a vegetative filter strip should be simulated with a mechanistic model such as VFSMOD. The pesticide load reduction by the VFS can then be calculated based on the predicted runoff and sediment reduction using mechanistic or regression-based trapping equations.

Micro-dams in row crops are also recommended as a regulatory mitigation measure in a quantitative risk assessment. Yet, sufficient data as well as specific technology to create micro-dams are only available for potatoes. Their effect can be modelled with a reduction of the runoff CN.

The effectiveness of the various soil conservation measures (e.g., mulch-tillage) could not be quantified sufficiently well due to the high variability of results and limited availability of data comprising essential aspects such as soil cover and loss of pesticides. Although these measures have the potential to reduce runoff, they cannot be currently recommended as regulatory mitigation measures to reduce surface runoff and erosion unless a better data basis of event-based data is established and more specific guidelines are developed on how soil conservation measures should be applied to effectively reduce pesticide losses.

The current German regulatory approach, that mulch-tillage can replace a vegetative filter strip of 20 m width, implying that these two measures are equally effective, therefore cannot be corroborated with the available data. However, mulch-tillage and soil conservation techniques in general might be particularly effective in combination with VFS as the reduction of runon volume to the vegetative filter strip by soil conservation measures might result in a synergistic effect.

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CONFLICT OF INTEREST

The authors declare there is no conflict of interests regarding the publication of this article.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

REFERENCES

1 Burgoa B and Wauchope RD, Pesticides in run-off and surface waters. in *Progress in Pesticide Biochemistry and Toxicology*, ed. by Roberts TR and Kearney PC. Volume 9, Environmental Behaviour of Agrochemicals. Wiley, New York, pp. 221–255 (1995).

2 Müller K, Bach M, Hartman H and Spiteller M, Point – and nonpoint-source pesticide contamination in the Zwester ohm catchment, Germany. *J Environ Qual* **31**:309–318 (2003).

3 Leu C, Singer H, Stamm C, Müller SR and Schwarzenbach RP, Simultaneous assessment of sources, processes, and factors influencing herbicide losses to surface waters in a small agricultural catchment. *Environ Sci Technol* **38**:3827–3834 (2004).

4 Leu C, Schneider MK and Stamm C, Estimating catchment vulnerability to diffuse herbicide losses from hydrograph statistics. *J Environ Qual* **39**:1441–1450 (2010).

5 European Union, Regulation (EC) No 1107/2009 of the European Parliament and of the council of 21 October 2009 concerning the placing of plant protection products on the market and repealing Council Directives 79/117/EEC and 91/414/EEC (2009). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009R1107). 15 May 2023.

6 Alix A ed, MAgPIE. Mitigating the Risks of Plant Protection Products in the Environment. From the two-part SETAC Workshop Mitigating the Risk of Plant Production Products in the Environment. 22–24 April 2013 Rome, Italy, 13–15 November 2013 Madrid, Spain. SETAC (2017).

7 Federal Office of Consumer Protection and Food Safety (BVL), Verzeichnis zugelassener Pflanzenschutzmittel (2023). https://apps2.bvl.bund.de/psm/jsp/index.jsp). 9 March 2023.

8 Spycher S, Mangold S, Doppler T, Junghans M, Wittmer I, Stamm C *et al.*, Pesticide risks in small streams – how to get as close as possible to the stress imposed on aquatic organisms. *Environ Sci Technol* **52**:4526–4535 (2018).

9 Liess M, Liebmann L, Vormeier P, Weisner O, Altenburger R, Borchardt D *et al.*, Pesticides are the dominant stressors for vulnerable insects in lowland streams. *Water Res* **201**:117262 (2021).

10 Capri E and Karpouzas D, *Pesticide Risk Assessment in Rice Paddies: Theory and Practice*. Elsevier, Piacenza, Italy (2007).

11 Capri E and Karpouzas D, Risk analysis of pesticides applied to rice paddies using RICEWQ 1.6.2v and RIVWQ 2.02. *Paddy Water Environ* **4**:29–38 (2005).

12 Boulange J, Watanabe H, Inao K, Iwafune T, Zhang M, Luo Y *et al.*, Development and validation of a basin scale model PCPF-1@ SWAT for simulating fate and transport of rice pesticides. *J Hydrol* **517**:146–156 (2014).

13 Brown C, Balderacchi M, Beinum WV, Capri E and Trevisan M, *Definition of Vegetative Filter Strip Scenarios for Europe*. Final Rep Univ York, Heslington York UK (2012).

14 Muñoz-Carpena R, Fox GA and Sabbagh GJ, Parameter importance and uncertainty in predicting runoff pesticide reduction with filter strips. *J Environ Qual* **39**:630–641 (2010).

15 Sittig S, Sur R, Baets D and Hammel K, Consideration of risk management practices in regulatory risk assessments: evaluation of field trials with micro-dams to reduce pesticide transport via surface runoff and soil erosion. *Environ Sci Eur* **32**:86 (2020).

16 Federal Office of Consumer Protection and Food Safety (BVL), Kodeliste für Kennzeichnungstexte und sonstige Auflagen zugelassener Pflanzenschutzmittel (2023). https://www.bvl.bund.de/SharedDocs/Downloads/04_Pflanzenschutzmittel/PSM_Kodeliste.html). 9 March 2023.

17 Bach M, Guerniche D, Thomas K, Trapp M, Kubiak R, Hommen U *et al.*, Bewertung des Eintrags von Pflanzenschutzmitteln in Oberflächengewässer – Runoff, Erosion und Drainage, GERDA – GEobased Runoff, erosion and Drainage risk Assessment for Germany, Final report (Project No. 3711 63 427). *Umweltbundesamt, Dessau-Roßlau* **72/2017**, p. 553 (2017).

18 Maetens W, Poesen J and Vanmaercke M, How effective are soil conservation techniques in reducing plot runoff and soil loss in Europe and the Mediterranean? *Earth-Sci Rev* **115**:21–36 (2012).

19 Fawcett RS, Christensen DR and Tierney DP, The impact of conservation tillage on pesticide runoff into surface water: a review and analysis. *J Soil Water Conserv* **1994**:126–135 (1994).

20 Brinke M, Szöcs E, Foit K, Bänsch-Baltruschat B, Liess M, Schäfer RB *et al.*, Umsetzung des Nationalen Aktionsplans zur nachhaltigen Anwendung von Pestiziden – Bestandsaufnahme zur Erhebung von Daten zur Belastung von Kleingewässern der Agrarlandschaft, Forschungskennzahl 3714 67 404 1. Umweltbundesamt, Dessau-Roßlau, Texte 89/2017, p. 144 (2017).

21 Carsel RF, Imhoff JC, Hummel PR, Cheplick JM and Donigian AS jr, *PRZM-3, A Model for Predicting Pesticide and Nitrogen Fate in the Crop Root and Unsaturated Soil Zones: User's Manual for Release 3.12. Center for Exposure Assessment Modeling (CEAM)*. US Environmental Protection Agency (USEPA), Athens, GA, USA (2003).

22 FOCUS, FOCUS Surface Water Scenarios in the EU Evaluation Process under 91/414/EEC. Report of the FOCUS Working Group on Surface Water Scenarios, EC Document Reference SANCO/4802/2001-rev.2. p. 245 (2001).

23 Reichenberger S, Bach M, Skitschak A and Frede HG, Mitigation strategies to reduce pesticide inputs into ground- and surface water and their effectiveness; a review. *Sci Total Environ* **384**:1–35 (2007).

24 Leonard RA, Movement of pesticides into surface waters: pesticides in the soil environment: processes, impacts, and modelling, in *SSSA Book Series*, ed. by Cheng HH. Soil Science Society of America, Madison, WI, USA, pp. 303–349 (1990).

25 USDA-NRCS, National Engineering Handbook, Part 630, Hydrology Chapter 10, Estimation of Direct Runoff from Storm Rainfall. p. 79 (2004). https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17752.wba). [22 February 2023].

26 FOCUS, Landscape and Mitigation Factors In Aquatic Risk Assessment, Volume 1. Extended Summary and Recommendations, Report of the FOCUS Working Group on Landscape and Mitigation Factors in Ecological Risk Assessment, EC Document Reference SANCO/10422/2005 v2.0 169 pp (2007).

27 FOCUS, Landscape and Mitigation Factors In Aquatic Risk Assessment, Volume 2. Detailed Technical Reviews, Report of the FOCUS Working Group on Landscape and Mitigation Factors in Ecological Risk Assessment, EC Document Reference SANCO/10422/2005 v2.0 436 pp (2007).

28 Muñoz-Carpena R and Parsons JE, VFSMOD-W Vegetative Filter Strips-Modelling System. Model documentation & user's manual Version 6.x (2014).

29 European Crop Protection Association, Surface Water Assessment eNabler (SWAN) v5.0.1, B-1160 Brussels, Belgium (2018). https://esdac.jrc.ec.europa.eu/projects/swan). [July 2023].

30 Ritter A, Muñoz-Carpena R, Chen R, Tang J, Westgate J, Henry E *et al.*, VFSMOD Input Definitions, Literature References and Sensitivity Analyses for Evaluating Vegetative Filter Strips in Pesticide Risk Assessment 58 p (2023) https://zenodo.org/record/7789811/files/VFSMOD_Parameters_3-20-2023_FINAL.pdf). July 2023.

31 Muñoz-Carpena R, Parsons JE and Gilliam JW, Modeling hydrology and sediment transport in vegetative filter strips. *J Hydrol* **214**:111–129 (1999).

32 Sabbagh GJ, Fox GA, Kamanzi A, Roepke B and Tang JZ, Effectiveness of vegetative filter strips in reducing pesticide loading: quantifying pesticide trapping efficiency. *J Environ Qual* **38**:762–771 (2009).

33 Federal Ministry of Food and Agriculture, The National Action Plan on Sustainable Use of Plant Protection Products 100 p (2017).

34 Prasuhn V, Doppler T, Spycher S and Stamm C, Reducing PPP inputs due to erosion and runoff. *Agrarforschung Schweiz* **9**:44–51 (2018).

35 Alletto L, Coquet Y, Benoit P, Heddadj D and Barriuso E, Tillage management effects on pesticide fate in soils. A review. *Agron Sustain Dev* **30**:367–400 (2010).

36 TOPPS-Prowadis, Best Management Practices to reduce water pollution with plant protection products from run-off and erosion 79 p (2014). http://www.topps-life.org/key-documents5.html). 21 October 2022.

37 Swiss Federal Office of Agriculture, Cahier de fiches techniques: Erosion – réduire les risques OR Erosion – Risiken beschränken. Merkblätter-Set 73 p (2010). https://www.blw.admin.ch/blw/de/home/nachhaltige-produktion/umwelt/boden.html). [21 October 2022].

38 AID, Gute Fachliche Praxis – Bodenbewirtschaftung und Bodenschutz, aid infodienst Ernährung, Landwirtschaft, Verbraucherschutz e.V (2015).

39 Schoop J and Fischler M, *Merkblatt Schonende Bodenbearbeitung*. Herausgeber, Agridea, Eschikon 28, 8315 Lindau (2019).

40 Breiman L, Friedman JH, Olshen RA and Stone CJ, Classification and regression trees, in *Wadsworth & Brooks/Cole Advanced Books & Software*. Wadsworth International Group, Monterey, CA (1984).

41 Reichenberger S, Sur R, Kley C, Sittig S and Multsch S, Recalibration and cross-validation of pesticide trapping equations for vegetative filter strips (VFS) using additional experimental data. *Sci Total Environ* **647**: 534–550 (2019).

42 Therneau TM, Atkinson EJ and Ripley B, rpart: Recursive Partitioning and Regression Trees (2019). https://cran.r-project.org/package=rpart). [22 February 2023].

43 Erlach F, Strategien zur Minderung diffuser Einträge von herbiziden Wirkstoffen und Nährstoffen in Oberflächengewässer, in *Dissertation am Institut für Geographie*, Universität Paderborn, Paderborn, p. 255 (2005).

44 Dönges S, *On-site-Maßnahmen zur Minderung von Pflanzenschutzmitteleinträgen in Gewässer durch Runoff*. Bachelorarbeit, Gießen (2012).

45 Sui Y, Ou Y, Yan B, Xu X, Rousseau AN and Zhang Y, Assessment of micro-basin tillage as a soil and water conservation practice in the black soil region of Northeast China. *PloS One* **11(3)**:e0152313 (2016).

46 Keshavarz MS, Ebrahimian H, Abbasi F and Playán E, Effect of micro-dams on water flow characteristics in furrow irrigation. *Irrig Sci* **38**: 307–319 (2020).

47 Destatis, Land- und Forstwirtschaft, Fischerei – Bodenbearbeitung, Erosionsschutz, Fruchtwechsel/Agrarstrukturerhebung 2016, Statistisches Bundesamt, Wiesbaden. *Item no.*: 5411209169004 (2017).

48 Golla B, Neukampf R and Lodenkemper R, Anteil von Gewässern mit dauerhaft bewachsenen Gewässerrandstreifen an Oberflächengewässern in Agrarlandschaften, S. 39–43 In: BMEL 2020: Jahresbericht 2020, Nationaler Aktionsplan zur nachhaltigen Anwendung von Pflanzenschutzmitteln 126 pp (2020).

49 Bundesministerium für Ernährung und Landwirtschaft, Jahresbericht 2020 Nationaler Aktionsplan zur nachhaltigen Anwendung von Pflanzenschutzmitteln 126 pp (2020).

50 Klein M, O'Connor I, Spycher S, Reichenberger S, Sittig S, Multsch S *et al.*, Wie können Risikominderungs-maßnahmen in die Umweltrisikobewertung im Rahmen der Zulassungsverfahren für Pflanzenschutzmittel eingerechnet werden? Teilvorhaben 1: Analyse der Wirksamkeit von Maßnahmen zur Verringerung der lokalen Umweltexposition von Gewässern gegenüber Pflanzenschutzmitteln, Project No. 3719 65 409 1, Umweltbundesamt, Dessau-Roßlau, Texte 89/2022 (2022). https://www.umweltbundesamt.de/en/publikationen/wie-koennen-risikominderungsmassnahmen-in-die). 22 February 2023.

51 Olivier C, Goffart JP, Baets D, Xanthoulis D, Fonder N, Lognay G *et al.*, Use of micro-dams in potato furrows to reduce erosion and runoff and minimise surface water contamination through esticides. *Comm Appl Biol Sci* **79**:1–10 (2014).

52 Goffart JP, Poulet V and Olivier C, Study of the effects of tied ridges on water runoff and its consequences for potato crop. *Potato Agrophysiol* **15**:55–61 (2013).

53 Schulz R, Field studies on exposure, effects, and risk mitigation of aquatic nonpoint-source insecticide pollution. *J Environ Qual* **33**: 419–448 (2004).

54 Arora K, Mickelson SK, Baker JL, Tierney DP and Peters CJ, Herbicide retention by vegetative buffer strips from runoff under natural rainfall. *Trans ASAE* **39**:2155–2162 (1996).

55 Boyd PM, Baker JL, Mickelson SK and Ahmed SI, Pesticide transport with surface runoff and subsurface drainage through a vegetative filter strip. *Trans ASAE* **46**:675 (2003).

56 Helmers MJ, Eisenhauer DE, Dosskey MG, Franti TG, Brothers JM and McCullough MC, Flow pathways and sediment trapping in a field-scale vegetative filter. *Trans ASAE* **48**:955–968 (2005).

57 Poletika NN, Coody PN, Fox GA, Sabbagh GJ, Dolder SC and White J, Chlorpyrifos and atrazine removal from runoff by vegetated filter strips: experiments and predictive modeling. *J Environ Qual* **38**: 1042–1052 (2009).

58 TOPPS-Prowadis TOPPS-Prowadis, Best Management Practices to reduce water pollution with plant protection products from runoff and erosion. Field manual (2014).

59 Brunotte J, Konservierende Bodenbearbeitung als Beitrag zur Minderung von Bodenschadverdichtungen, Bodenerosion, Run-off und Mykotoxinbildung im Getreide, Landbauforschung Völkenrode, Bundesforschungsanstalt für Landwirtschaft (FAL). *Sonderheft* **305**:1–159 (2007).

60 Kistler MK, Brandhuber R and Maier H, Wirksamkeit von Erosionsschutzmaßnahmen: Ergebnisse einer Feldstudie; Bericht zum Forschungsvorhaben "Evaluierung der Cross Compliance Bestimmungen zum Erosionsschutz in Bayern", Schriftenreihe der Bayerischen Landesanstalt für Landwirtschaft, Bayerische Landesanstalt für Landwirtschaft, LfL (2013).

61 Stichler C, Abrameit A and McFarland M, *Best Managament Practices for Conservation/Reduced Tillage, Texas Cooperative Extension*. The Texas A&M University System, Texas, US, p. 7 (2006).

62 AID, *Gute Fachliche Praxis – Bodenbewirtschaftung und Bodenschutz, aid infodienst Ernährung, Landwirtschaft, Verbraucherschutz e.V.* AID, Bonn, p.120 (2015).