Plant Protection Products in Field Crops: Use and Aquatic Risks from 2009 to 2018

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Surface waters enrich the agricultural landscape. (Photo source: www.123rf.com)

Summary

Since 2009, the use of plant-protection products (PPPs) in field crops has been recorded annually as part of Switzerland's agroenvironmental monitoring scheme. This information was used to calculate the amount of active substances applied per crop from 2009 to 2018, and to determine the quantity of active substances used in field crops throughout Switzerland, based on the cultivated areas specific to each crop. The risk potential posed to surface waters by this use of PPPs was analysed using the SYNOPS model. Over this period, the use of herbicides and fungicides in field crops declined steadily. Regarding insecticides, paraffin oil – an active substance used on potato crops – accounted for the bulk of applications. Without considering paraffin oil, the amount of insecticides used has also declined since 2012. The trend of the risk potential was constant for herbicides, downward for fungicides and upward for insecticides. Where the effects of the use restrictions for aquatic risk reduction imposed by the authorisation were also taken into account, a sometimes distinct reduction in all risk potentials was observed. Over the investigated period, there was a change in the spectrum of the PPP active substances available and used in field crops. It was found that some active substances, although used in smaller quantities, can be risk-dominant, while others, though used in larger amounts, have only slight effects on the risk potential for surface waters. The study shows that in field crops, the risk potential for surface waters changed over the course of the investigated period, mainly owing to the choice of PPP active substances and the increasing number of imposed use restrictions for reducing aquatic risks. An analysis of the risk in special crops requires a larger informational basis. Broader coverage, improved accessibility and increasing digitalisation in agriculture could contribute to the creation of a representative data pool for all crops in future.

Key words: Use of plant protection products, aquatic risk, risk mitigation, time series.

Introduction

Plant-protection products (PPPs) are used to protect crops from harmful organisms. Most PPPs are 'biologically active', and intervene in the metabolism and biology of organisms. This can also result in side effects on humans, animals and the environment. In order to prevent undesired side effects, PPPs can only be sold and used once they have undergone a comprehensive authorisation process. Moreover, agricultural policy measures aim to reduce the use and risks of PPPs. Although recent decades have seen the constant refinement and adaptation of authorisation processes and agricultural policy measures, an analysis of the effects on PPP use in agriculture and the associated risk potential of the PPPs for surface waters are still lacking.

Figures for the annual amounts of PPPs sold, which are collected and published by the Federal Office for Agriculture (FOAG 2020a), highlight a general trend. From 2008 to 2018, herbicide sales decreased (–33 %) and fungicide sales increased slightly (+6 %), whilst insecticide sales (including mineral oils) fluctuated over the years with no clear trend. In percentage terms, herbicides accounted for 28 %, fungicides for 49 %, insecticides for 14 % and 'other' for 9 % of all PPP sales in 2018. However, information on the amounts of PPPs sold does not allow conclusions to be drawn about their actual use in agriculture, since they are also used for other purposes. In addition, multiyear information on the amount of PPPs used in specific agricultural crops is lacking.

Since 2009, the use of PPPs in agricultural crops has been recorded as part of the agroenvironmental monitoring scheme (SAEDN, 2020). The surveys are considered to be representative for field crops, while the sample would need to be larger for other types of crops in order to illustrate regional differences or the great variability of crops and cultivation methods in a representative manner (de Baan, Spycher and Daniel 2015). Given that field crops, including meadows and pastures, account for a large percentage of the utilised agricultural area (83 %), one would expect the sales-figure trends to be reflected in the use of PPPs in field crops, possibly even at individual-crop level. To date, we lack an analysis of the long-term trend of PPP use in field crops, and hence are unable to associate the use of PPPs with the changes in authorisation and agricultural policy measures.

The risk potential for PPPs is calculated on the basis of the amount used, the modelled concentration of the PPPs in surface waters, and the ecotoxicity of the PPPs used. Thanks to the further development of the SYNOPS model for Swiss environmental and site-specific conditions (de Baan 2020), it is now possible to present the risk potential for surface waters from 2009 to 2018 based on data on the use of PPPs in field crops. For the first time, therefore, we can investigate the important issue of whether the changes in terms of authorisation and agricultural policy measures have altered either the amount of PPPs used or their risk potential. The data also allow us to determine the contribution of the different crops to the risk potential, and whether some active substances have a higher risk potential than others.

The PPP authorisation process not only influences the risk potential for surface waters through the PPP approval itself, but also through use directives (application parameters) and use restrictions, which aim to reduce PPP input into surface waters from drift and runoff. The scientific basis of the use restrictions has been continuously improved, and since 2011 said restrictions have increasingly been issued as part of targeted reviews. The use restrictions (e.g. untreated buffer zones to reduce runoff, distance restrictions to reduce drift) aim to reduce the risk potential for surface waters arising from PPP applications in a crop to a level deemed acceptable by the Plant Protection Product Ordinance (PSMV 2020). These use restrictions are seen as crucial for reducing risk in surface waters. Their effectiveness has been investigated in numerous studies, but an analysis of their efficacy within the context of the changes in the authorisation procedure and in actual plant-protection practice is lacking.

This study also provides important findings with regard to the 'Action Plan for Risk Reduction and Sustainable Use of Plant Protection Products' (AP PPP), whose aim is to reduce risk potential by 50 % by 2027 (Swiss Federal Council 2017). Aside from trends in PPP use specific to field crops and their risk potential for surface waters, the study also examines the limitations of the interpretation of the evaluations.

Materials and Methods

This study is based on the field-calendar entries of farms taking part in the agroenvironmental monitoring scheme. The composition of the farms involved changed in part over time, since participation, although remunerated, was voluntary. These data are used to calcuate various indicators in the Swiss Agri-Environmental Data Network (SAEDN), **inter alia** on PPP use and risks. For each plot (a connected area on which one particular crop only is grown), the field calendars contain details on the PPPs used, such as product name, quantity used and date of application.

Characterisation and representativeness of the AEI data

Not all growing regions and crop groups are covered equally well in the AEI-FADN (Farm Accountancy Data Network – Agri-Environmental Indicators) dataset. Many farms provide data for field crops (including meadows, pastures and fallow land), while other types of crops (fruit production and viticulture) are represented to a slightly lesser extent. Farms supplying data on outdoor-grown vegetables (salad leaves, cabbage, carrots, onions, spinach, asparagus, etc.), other crops such as berries or sunflower, and organic crops requiring complex plant protection (e.g. fruit, viticulture, vegetables, potatoes, oilseed rape) are under-represented. Apart from the field crops, it is unclear just how representative the data are for average Swiss plant-protection practice.
Consequently, all data analysed in this study (hereafter referred to as the AEI dataset) are from field crops (including meadows, pastures and fallow land), with organic farms not being taken into account. Due to incomplete data, seed-treatment products were also left out of the analysis. In the investigation period 2009–2018, there were between 231–276 farms per year (254 on average) supplying evaluable data for field crops. During these years, an average area of almost 6500 ha under field crops was recorded in the AEI dataset. This constitutes approx. 0.74 % of the entire area under field crops in Switzerland (including meadows, pastures and fallow land). For the calculation of the risk potential, the following number of farms per year and crop were analysed on average, with most farms supplying data on several crops: winter wheat, 55.8 farms per year; 'extenso' winter wheat, 94.6 farms; winter barley, 43.8 farms; 'extenso' winter barley, 45.4 farms; other cereals (summer wheat, summer barley, oats, spelt, rye, triticale), 59.7 farms; maize, 129.8 farms; oilseed rape, 55.1 farms; 'extenso' oilseed rape, 16.6 farms; potatoes, 44.5 farms; sugar beet, 55.9 farms; fodder beet, 13.7 farms; legumes (peas, field beans, lupin), 30.5 farms; and meadows (meadows, pastures, fallow land), 91.0 farms.

Calculating PPP use

The following key figures on PPP use in field crops were calculated from the AEI dataset:

The **amount of active substance** indicates the quantity (in kg/ha) of active substance applied annually per farm and crop for herbicides, fungicides and insecticides. Here, the sum of all applied active substances per active-substance group (in kg) was calculated per farm, crop and year, then divided by the surface area (in ha) occupied by the relevant crop on the farm. Untreated plots were also taken into account when calculating the amount of the active substance. The **area-weighted amount of active substance** is an extrapolation of the quantity of active substance (in tonnes) used in a crop throughout Switzerland for herbicides, fungicides and insecticides. Here, the mean value of the amount of active substance (in kg/ha) over all farms growing the crop in question was calculated, then multiplied by the total surface area occupied by this crop in Switzerland (SFSO 2020; FOAG 2019).

The **number of interventions** tells us how frequently PPPs are used. For each farm, the number of spraying passes taking place in a crop per year was calculated for herbicides, fungicides and insecticides (e.g. the number of interventions for fungicides in winter wheat). Tank mixtures with different groups of active substances (e.g. insectides and fungicides) were counted separately and treated as two interventions. Untreated plots were taken into account for the calculation of the average number of interventions.

The **percentage of PPP applications with use restrictions** indicates the number of PPP applications for which a use restriction has been imposed in the AEI dataset of a year, according to current authorisation status. For this, the PPP-related details in the AEI dataset were supplemented by the 2009–2018 use restrictions for drift and runoff listed in the index of plant protect products, with the authorisation status at the beginning of each calendar year serving as a reference (FOAG 2020b). If a PPP was authorised for various indications (i.e. harmful organisms) in a crop, the most restrictive use restriction was taken into account. Finally, the percentage of all active-substance applications for which, according to the PPP index, the relevant product was subject to a use restriction relating to runoff or drift (e.g. the percentage of PPP applications with use restrictions for insecticides on oilseed rape) was calculated per crop, year and active-substance group.

Calculating the risk potential for surface waters

The risk potential for surface waters was calculated with the SYNOPS model (Gutsche and Strassemeyer 2007; Strassemeyer *et al.* 2017). For each plant-protection product application recorded in the analysed AEI dataset, the model calculated the potential input from a treated plot into surface water (exposure) via the four routes of entry of drift, runoff, erosion and drainage. Next, the risk potential associated with the thus-modelled concentration in surface water was calculated. Consequently, the risk potential describes the local risk to aquatic organisms posed by a treated plot. For each application, the risk potential was calculated with and without the specific use restrictions relating to drift and runoff.

In SYNOPS, the risk potential per active substance was calculated as an exposure toxicity ratio (ETR), i.e. as the quotient of exposure over toxicity. For toxicity, toxic concentrations of representative organisms determined in standardised laboratory experiments were used (for example LC_{50}, i.e. the concentration at which 50 % mortality was observed; NOEC, the concentration at which no chronic effects were noted). Water fleas, fish and sediment organisms served as representative organisms for acute and chronic effects, whilst algae and duckweed were monitored for acute effects. The data on toxicity and chemical properties were taken from the Pesticide Property Database (PPDB: Lewis *et al.* 2016). These data were checked and partially corrected. In addition to the effects of individual active substances, the effects of mixtures of several active substances applied on the same plot were also taken into account. Finally, the maximum (acute and chronic) ETR per treatment programme (i.e. the series of PPP applications on one plot over the course of one growing year) was determined for all active substances of the same group and for all groups of organisms over a one-year period. Here, chronic ETRs were divided by ten in order to give equal weighting to acute and chronic effects. The risk potentials were calculated separately for herbicides, fungicides and insecticides.

Since PPP input into surface waters is affected by environmental conditions (e.g. slope or climate), representative environmental scenarios were defined for Switzerland. As part of a sensitivity analysis, 618–9193 different environmental scenarios were tested per crop group studied, allowing the definition of a representative set of environmental conditions for each crop (de Baan 2020). For field crops, 79 environmental scenarios were defined, which were used to calculate the risks for each treatment programme in the AEI dataset. Finally, for each treatment programme the 90th percentile was determined from the 79 risk potentials calculated, taking the frequency of these environmental conditions in Switzerland as a weighting factor. The 90th percentile is based on a specific combination of environmental conditions and soil properties considered to be a realistic worst-case scenario. Surface waters were defined as being 1 m wide and 30 cm deep, with a constant volume of water. In order to identify the risk-**dominant active substances**, we calculated which active substance had the highest risk potentials for each treatment programme and plot (without taking mixing effects into account).

Where a farm grew the same crop on several fields, the **risk potential** per crop, farm and active-substance group was first calculated. In a subsequent step, the median of the risk potentials was determined for all farms growing this crop. Thus, the mean risk potential of a crop was calculated for all SAEDN farms. Lastly, the median value per crop was multiplied by the area (in ha) occupied by this crop over the year in question (**area-weighted risk potentials**).

In order to reduce the risk potential of PPPs, use restrictions were stipulated as part of the authorisation procedure for PPP applications where potential inputs via drift and runoff pose a risk for aquatic organisms. The distance restrictions for reducing drift inputs vary according to the possible risk associated with PPP use, and can be 6, 20, 50 or 100 m, depending on the product; in previous years, there were also use restrictions of 10 m in individual cases. Likewise, there are use restrictions that aim to reduce PPP risk from possible runoff inputs on plots less than 100 m from surface waters, if the PPPs are not applied on a level plot with < 2 % slope, or if the plot is lower-lying than the surface waters. Up until 2018, the use of products posing a potential risk owing to runoff was subject to the establishment of a 6 m-wide, untreated buffer strip of vegetation along watercourses. In order to highlight the **effect of use restrictions** on risk potentials, two distinct SYNOPS calculations were made: one with and one without taking into account the use restrictions stipulated in the PPP index of the relevant year in order to reduce drift and runoff for the different PPP applications. It was assumed here that a 6m-wide, vegetation-covered buffer strip reduced inputs from runoff by 50 % (FOAG Instruction 2020c; based on Hanke *et al.* 2013). Calculated on the basis of drift measurements made by Rautmann, Streloke and Winkler (2001), the drift-reducing effect of untreated buffer strips ranged between 0 % and 94 %, depending on the distance between the field and the water bodies.

Results

Area-weighted quantities of active substances

Area-weighted amounts of active substances in field crops (Fig. 1) vary significantly according to crop and PPP active-substance group. Depending on the survey year, between 328 and 476 t of herbicides were used in field crops over the period of the study, with the amounts of active substances used falling steadily by nearly 31 % from 2012 to 2018. In general, a reduction in herbicide use can be observed in almost all crops, with a greater decrease between 2009 and 2018 for meadows and pastures (–16.9 t) and in the maize (–28.4 t), winter wheat (–20.1 t) and 'extenso' winter wheat (–19.8 t) crops. Fungicide use in field crops ranged between 99 and 146 t per year. Compared to 2009, the quantity of fungicides used in 2018 fell by almost 27 %. Whereas fungicide use in winter wheat decreased overall by almost 19 t despite the annual fluctuations, fungicide use in sugar beet rose steadily during this period by over 8 t. Insecticides, which are often highly effective even at low dosages, were used in far smaller amounts than the herbicides and fungicides. The use of paraffin oil in potato crops was an exception, accounting for over 99 % of the amount of active substances used per year. Apart from insecticide use in potatoes (grey in Fig. 1), an increase in insecticide use to 10.8 t in all other crops combined was observed up to 2012, followed by a decrease to 4.0 t until 2018. This corresponds to a reduction of 63 % since 2012.

Area-weighted risk potential of PPPs in surface waters

The area-weighted risk potentials (ETR × areas of the field crops) showed that herbicides have greater risk potentials than insecticides, and insecticides have greater risk potentials than fungicides (Fig. 2). The highest area-weighted risk potentials for herbicides were in maize, oilseed rape and winter barley (including extenso). By contrast, herbicide applications on meadows and pastures led only to a very slight area-weighted risk potential. The highest area-weighted risk potentials for fungicides were observed in winter wheat and winter barley; the use of fungicides in potatoes and in 'other cereals' accounted for a fairly low percentage of the risk potential. The area-weighted risk potential for insecticide applications was mainly the result of PPP applications in oilseed rape. Insectide applications in potatoes and sugar beet had only very slight effects on the area-weighted risk potential.

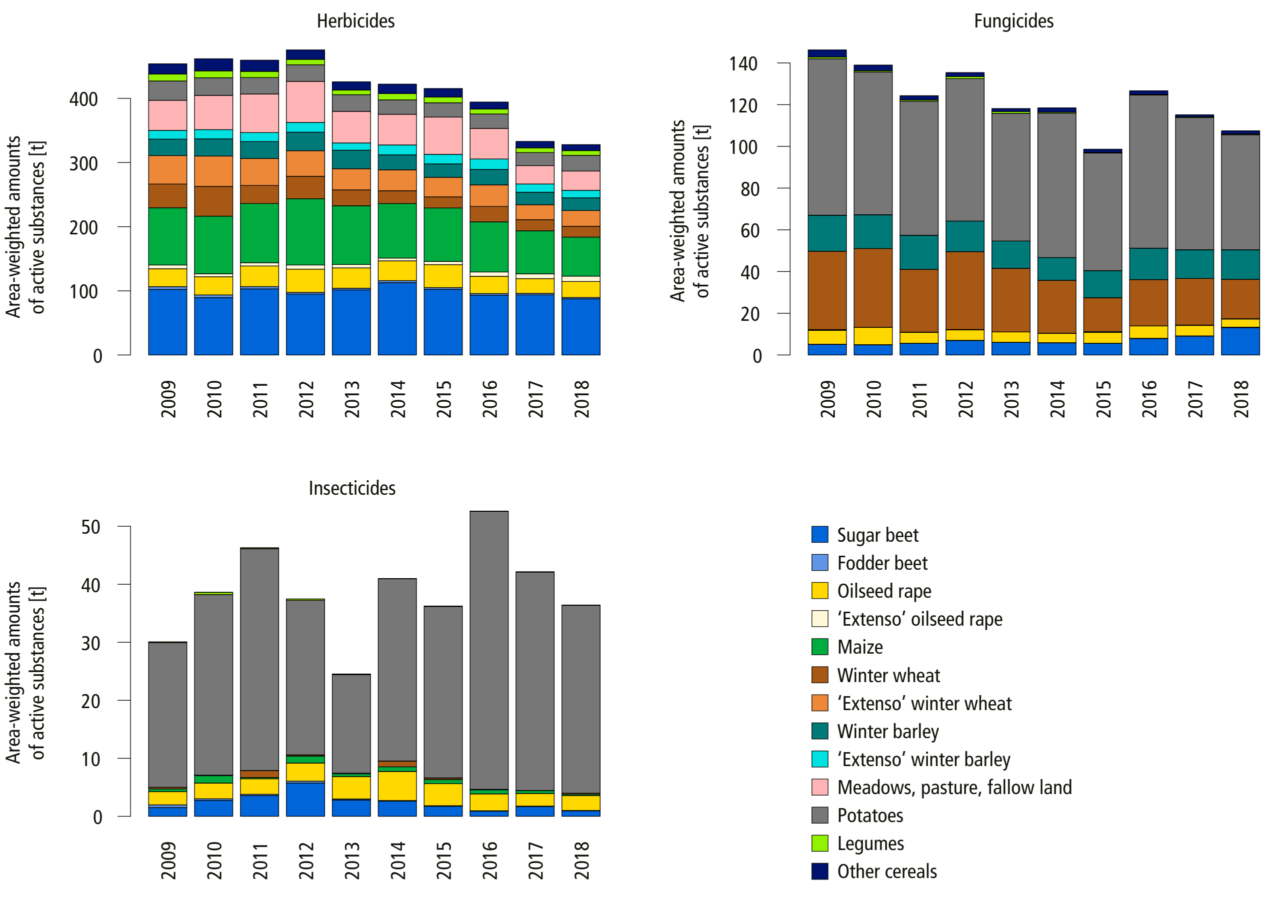

Fig. 1 | Area-weighted amounts of active substances in field crops from 2009 to 2018, separated into herbicides, fungicides and insecticides.

Without considering the use restrictions of the PPP authorisation (Fig. 2, left), the risk potential from herbicides remained relatively unchanged between 2009 and 2018, but with annual fluctuations. The use restrictions of the PPP authorisation had a significant risk-reducing effect, with the risk potential falling steadily since 2012 and a more significant reduction in 2013 for almost all crops. Thanks to the use restrictions, in 2018 the risk potential for maize was reduced by 42 % compared to a calculation without the use restrictions; for winter barley and extenso winter barley, the risk potential in 2018 was 49 % and 44 % lower, respectively, and for potatoes it was 44 % lower than a calculation without the use restrictions (Fig. 2; right, with the use restrictions). In the case of fungicides, no clear trend could be observed; the only noticeable thing here was a greater reduction of

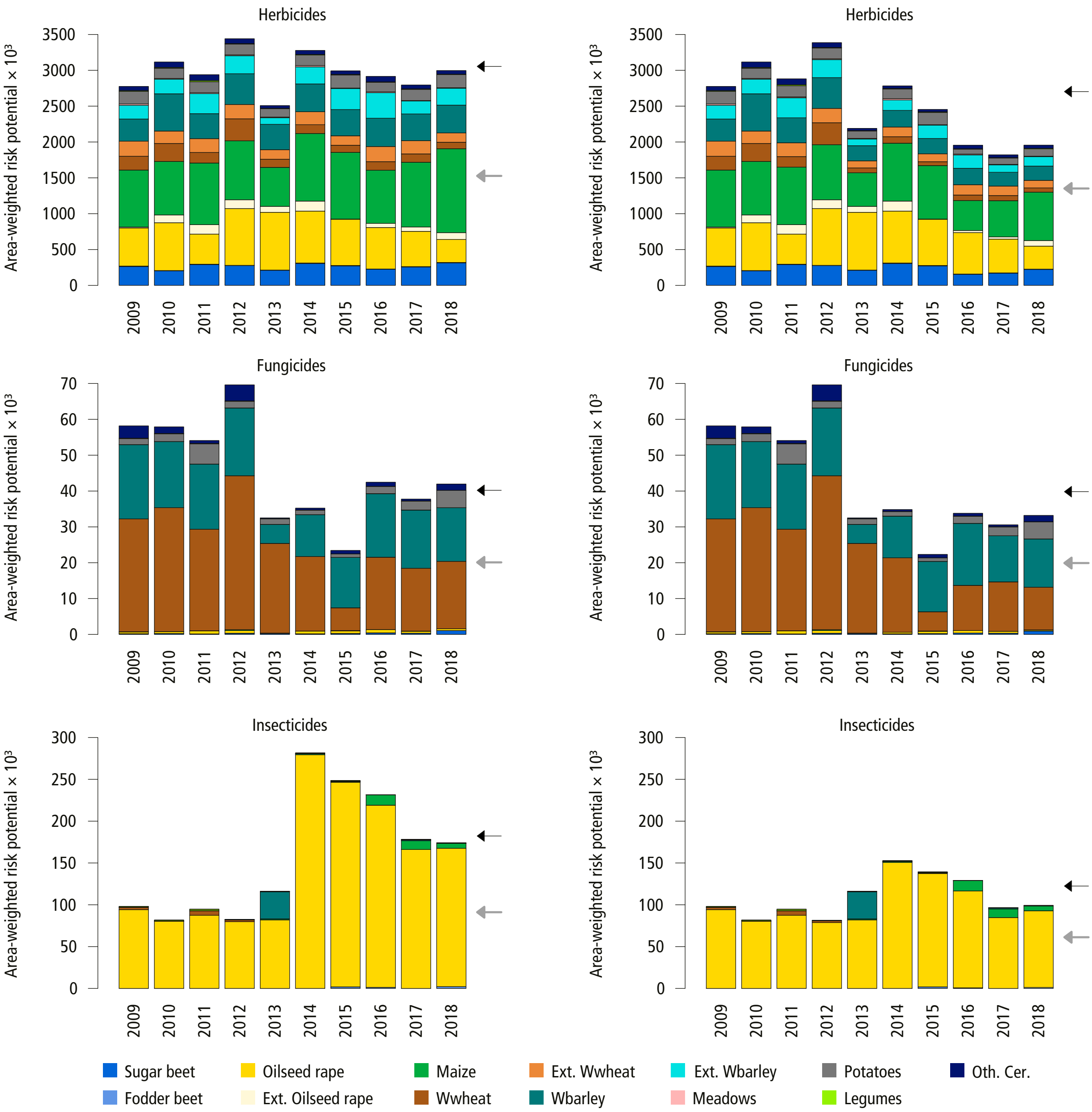

Fig. 2 | Area-weighted risk potentials for surface waters from 2009 to 2018, based on herbicide, fungicide and insecticide applications without use restrictions (left) and with use restrictions (right). The black arrow indicates the mean of the risk potential between 2012 and 2015; the grey arrow indicates 50 % of this mean (Wwheat = Winter wheat; Wbarley = Winter barley; Ext. = Extenso; Oth.Cer. = Other cereals).

the risk potential from 2012 to 2013, obvious both with and without consideration of the distance restrictions associated with PPP authorisation. For fungicides, the risk potential was reduced by around 37 % in 2018 by the application of the distance restrictions, especially for winter wheat, compared to the risk potential calculated without restrictions. For insecticides, there was a sharp increase in risk potential in 2014 compared to 2013. This increase was clearly visible without considering the use restrictions, but less obvious when they were taken into account, since the risk potential associated with insecticide use in oilseed rape was greatly reduced by the use restrictions associated with PPP authorisation. In 2018, the risk potential in oilseed rape calculated with use restrictions was 45 % lower than without restrictions.

Use of PPPs in field crops with distance restrictions

From 2009 to 2018, many new use restrictions were imposed. For all crops, the percentage of PPP applications in the AEI dataset for which the PPPs used were subject to use restrictions for the avoidance of drift and runoff rose significantly, including e.g. for the insectides used in oilseed rape (Fig. 3). Between 2009 and 2012, the percentage of insecticide applications in oilseed rape subject to use restrictions for reducing drift ranged between 13.2 % and 15.8 % (Fig. 3, left), the majority being PPPs with 20m distance requirements. From 2013 onwards, there was a clear increase in the percentage of applications subject to use restrictions for preventing drift, with the percentage ranging between 76.5 % and 85.3 % from 2015 on. Since 2015, moreover, many insecticides with very high distance requirements have been used, with almost 20 % of the insecticides used in 2015 and 2016 being subject to a 100m distance requirement.

Since 2013, insecticides have been used in the treatment of oilseed rape which are subject to a 6m use restriction for preventing runoff (Fig. 3, right). Between 2013 and 2016, their share rose from 19 % to almost 62 %. In 2018, around 50 % of all products used were subject to such a use restriction.

Risk-dominant active substances

A crop can be treated with a range of different PPPs. Depending on the treatment programme, different active ingredients dominated the risk potential. Using three examples, Figure 4 shows which active substances were risk-dominant, and how the percentage of treatment programmes dominated by them changed between 2009 and 2018.

Among the herbicides used in winter barley crops, the urea herbicide isoproturon was the risk-dominant active substance at the outset of the study period (maximum 44.7 % of plots in 2009, Fig. 4, top left). Whereas its share has been decreasing steadily (8 % in 2018), the percentage of treatment programmes dominated by diflufenican, a pyridinecarboxamide, increased over the same period (from 13.7 % in 2009 to 44.2 % in 2018). The phenylurea chlorotoluron was the dominant active substance in an average 18.5 % of treatment programmes (minimum 4.3 % in 2010, maximum 24.1 % in 2014).

On many plots, the risk-dominant fungicides in winter wheat were chlorothalonil, a chloronitrile fungicide (maximum 33.3 % of plots in 2014), spiroxamine from the spiroketalamine family (maximum 33.8 % in 2011), the piperidine fungicide fenpropidin (maximum 18.7% in 2009) and prochloraz, an imidazole fungicide (maximum 11.6 % in 2009; Fig. 4, top right). In almost all analysed years, these four active substances were risk-dominant

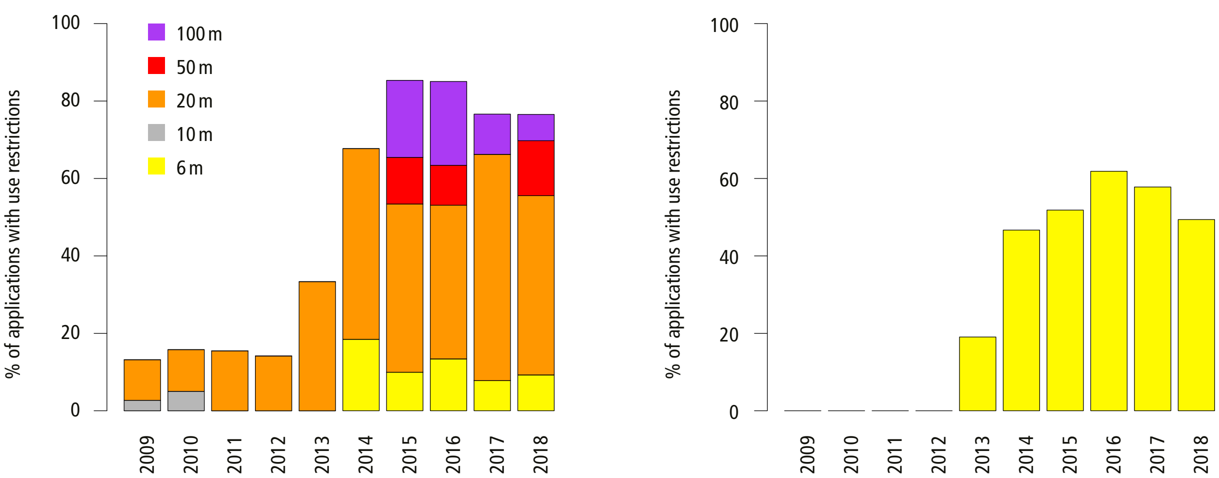

Fig. 3 | PPP applications with use restrictions, 2009–2018, based on the example of insecticide use in oilseed rape. Left: drift; Right: runoff.

on 58 to 70 % of winter-wheat plots, as opposed to just 42 % of the plots in 2015. By contrast, the percentage of plots on which the polysaccharide laminarin was risk-dominant rose from 3.7 % (2014) to 12.8 % in 2015. Among the insecticides used in oilseed rape crops, the pyrethroids bifenthrin and cypermethrin and the neonicotinoid thiacloprid were the most common risk-dominant substances until 2011 (Fig. 4, below). The percentage of plots on which bifenthrin was risk-dominant stood at a maximum of 40.5 % (2011), while for cypermethrin and thiacloprid the figures were 41.5 % (2009) and 18.3 % (2011), respectively. From 2013, the organophosphates chlorpyrifos and chlorpyrifos-methyl were authorised as insecticides in oilseed rape crops, and were frequently risk-dominant in the treatment programmes of the following years (combined maximum of 58.7 % in 2017).

Variability of use and risk between farms

Both the use and risks of PPPs varied significantly not only from one year to another, but also between the individual farms in the same growing year. Figure 5 shows this based on the example of the use and risks of fungicides in winter-wheat crops, with an average of 55.8 farms being evaluated per year (42 to 70 farms, with only non-extenso farms taken into account). The frequency of fungicide application on farms cultivating wheat ranged from 0 to > 3.5 interventions per year. Fungicides were most frequently applied once or twice a year. During the period 2009–2018, the frequency of fungicide use changed: the percentage of farms with ≤ 0.5 interventions rose from just a few percent between 2010 and 2012 to over 20 % in 2018 (Fig. 5, left). Over this period, the quantities of active substance used and the risk potentials (medians per farm) also fell (Fig. 5, centre and right). In some years, the differences were greater; for example, the percentage of farms carrying out ≥ 1.5 fungicide applications in 2012 was 63.3 %, but only 35.7 % in 2015. Moreover, in 2012 the median value of the quantity of active substance used per farm was 1.17 kg/ha and the median value of the risk potential was 1.23, whist in 2015 both values were much lower (0.42 kg/ha and median ETR of 0.13). Even within a single year, however, the quantity of active substances used per farm and the risk potential associated with fungi-

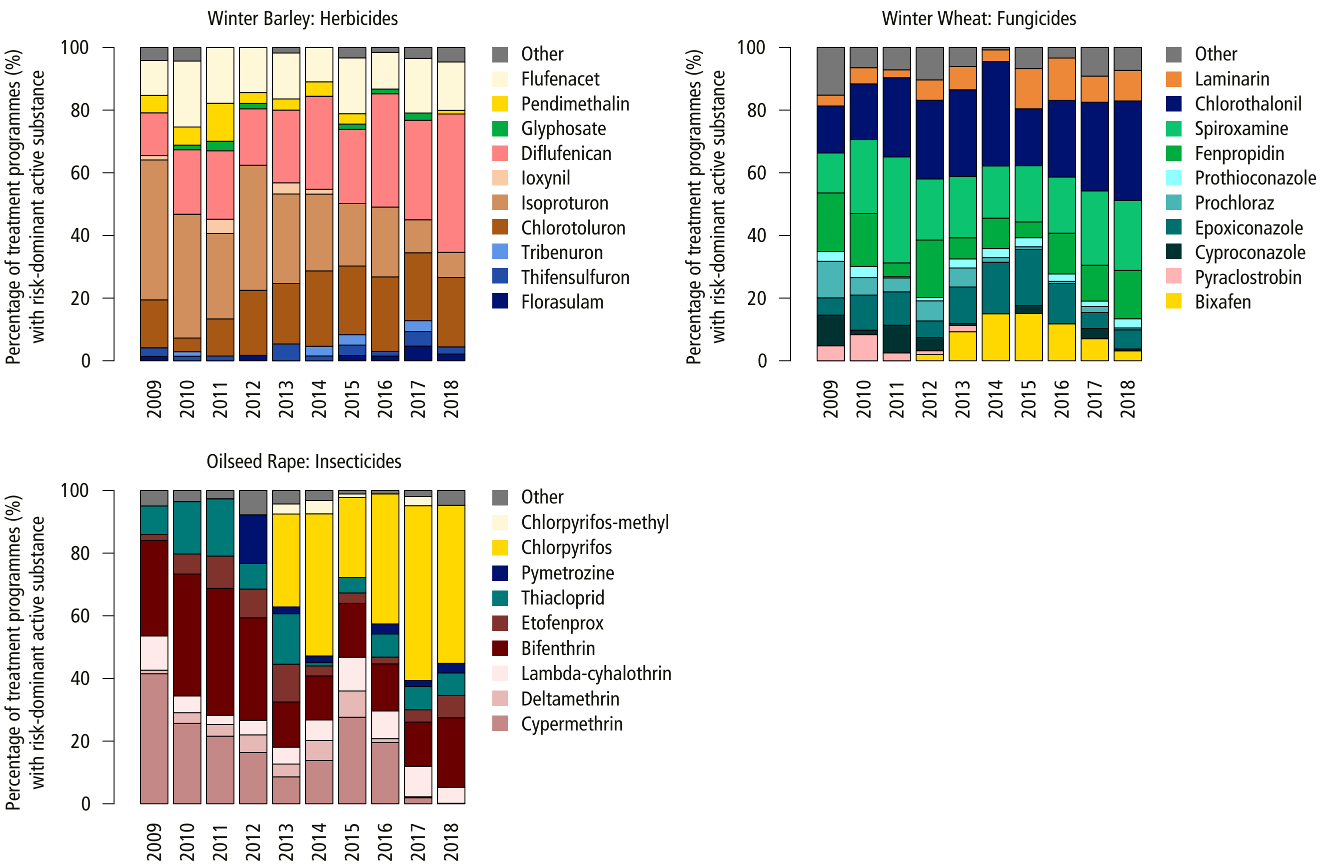

Fig. 4 | Percentage of treatment programmes (%) from 2009 to 2018 in which the active substance in question was risk-dominant, considering use restrictions, based on the example of herbicides in winter barley, fungicides in winter wheat and insecticides in oilseed rape.

cide use varied considerably. The upper quartiles (25 % of the data lies above this value) and lower quartiles (25 % of the data lies below this value) in the boxplots are sometimes very far apart. Over the study period, the quantity of active substances used by the farms in the upper quartile was 11.7 times higher on average than that used by the farms in the lower quartile. The risk potential associated with fungicide use also varied significantly from one farm to another over the course of the same year. Between 2009 and 2013 – the years with the highest lower and upper quartiles – the risk potential of the higher quartiles was 26.4 times higher on average than that of the lower quartiles. In the following years, the risk potential fell, mainly in the lower but also in the upper quartiles. On average, the risk potential of the upper-quartile farms was thus over 7,500 times higher than that of the lower-quartile farms between 2014 and 2018.

Discussion and Conclusions

PPP use

In the case of herbicides, significant decreases in both sales volumes (FOAG 2020a) and in PPP use were recorded from 2012 onwards. Since field crops are an important area of application for herbicides (depending on the year, 50–60 % of herbicides sold are used in field crops), this parallel trend is plausible. The largest volume of active substances in herbicides was used in sugar beet and maize, followed by meadows, pastures and fallow land, oilseed rape, extenso winter wheat, and potatoes. With the exception of extenso oilseed rape, the amount of active substances in herbicides decreased in all crops.

The amount of fungicides used in field crops decreased, while the quantities sold increased (FOAG 2020a). Around half of the fungicides used in field crops were applied on potatoes. The quantities of active substances in winter wheat and winter barley were slightly lower; the lowest were those applied in sugar beet and oilseed rape. It was found that in field crops, in addition to the crops with a comparatively high use of active substances per unit area (e.g. potatoes), crops grown on a large surface area (winter wheat, maize) were also relevant for the quantity of active substances used. A decrease in the amount of active substances was observed in almost all crops but sugar beet. The increase in sugar beet can probably be explained by the increased pressure from Cercospora leaf spot, whose control now requires not just one but several fungicide treatments.

Regarding insecticides, the amounts of active substances used increased up to 2012 and decreased thereafter, except for potato crops. In potatoes – the crop with the highest insecticide use – paraffin oil in particular accounted for a large part of the quantities of active substances applied. Paraffin oil, which is also approved for use in organic farming, must be applied in high doses for effective treatment. Although paraffin oil was used on potato crops in an average of only 47 % of insecticide treatments a year, its share of the area-weighted quantity of active substance used was over 99 % on average. Besides changes in PPP authorisation and the implemen-

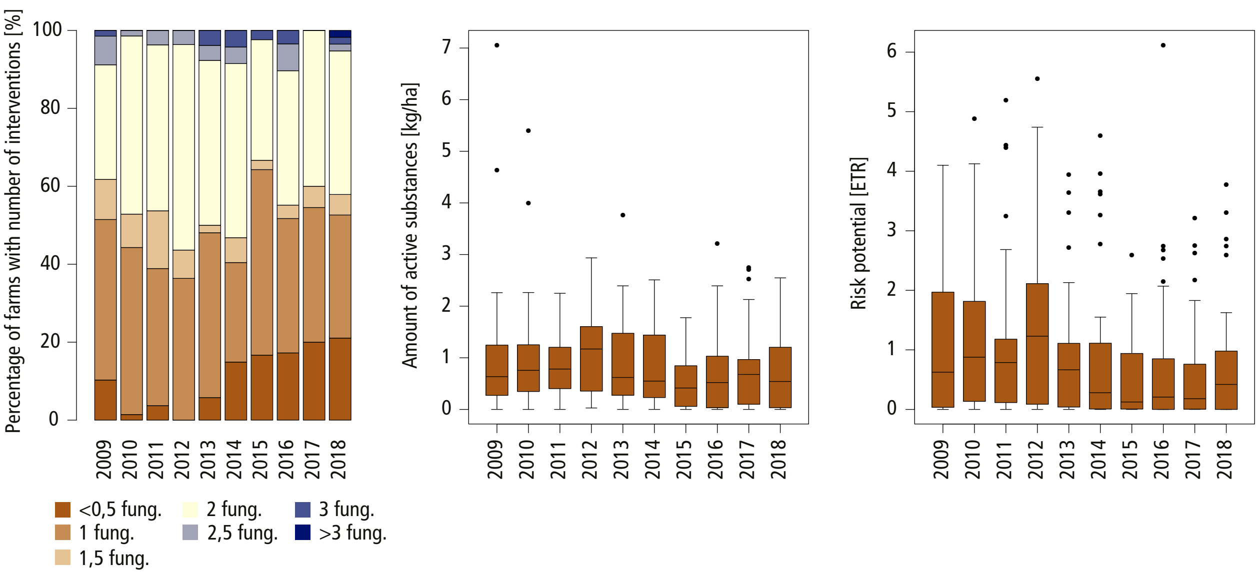

Fig. 5 | Relative frequency of the number of interventions (left), amount of active substances (centre) and risk potential (right) per farm for fungicides in winter-wheat crops. The boxplots show the respective median, the lower and upper quartile (lower and upper limit of the boxplot which covers 50 % of the farm data), the whiskers (1.5 times the interquartile distance) and individual points (outliers with > 1.5 times the interquartile distance).

tation of agricultural policy measures (increase in the area on which organic and extenso cereals were grown), the decline in the total area occupied by cereal crops between 2009 and 2018 also contributed to the decrease in the area-weighted quantity of active substances in field crops. PPPs are scarcely used in organic cereals, whilst insecticides and fungicides are prohibited in extenso farming. Moreover, observed trends or fluctuations in the quantities of active substances used are also caused by the use of other PPPs, for example the replacement of highly effective low-dose PPPs (e.g. pyrethroids) with less-effective high-dose PPPs (e.g. paraffin oil).

Between 2009 and 2018 the volume of herbicide sales fell, while there was a slight increase in the volume of fungicides sold. The volume of insecticide sales varied significantly from one year to the next, with no clear trend. In 2018, the share of the (area-weighted) quantity of active substances of PPPs in field crops (excluding organic farming) was 56 %, 11 % and 13 % of total sales for herbicides, fungicides and insecticides, respectively. It is not yet known what percentage of the sales volumes is represented by the different applications (conventional and organic field crops, fruit production, viticulture, vegetable production and non-agricultural applications). If agricultural applications alone were considered, the percentage of PPPs used in field crops would be even higher. While use in special crops tends to be characterised by the high number of treatments, in field crops the (comparatively much larger) cultivated surface area is the determining factor.

The detailed analysis of the amounts of active substances used in field crops allows us to better understand the contribution of the each individual crop within the context of plant protection. Not all crops have the same requirements; in some cases, a reduction in the quantity of active substances used inevitably results in yield losses. Furthermore, the quantity of active substances used can also increase again owing to certain harmful organisms, resistance formation, periodic climatically unfavourable years and other factors. Accordingly, crops and the surface area they occupy also play a major role in the search for strategies for reducing PPP use, as well as in understanding how reduction targets can be achieved. This knowledge, which would also be important for special crops, allows for the future targeted development and prioritisation of measures.

Risk potential for surface waters

To date, it has not been possible to calculate the risk potentials for surface waters based on the amounts of active substances used on farms and on the SYNOPS model adapted for Switzerland. The available data on quantities (sale or use) for the most part do not reflect a decrease or increase in risks. True, our study pointed out certain parallels, with e.g. herbicides having both the highest sales volumes and the highest risk potentials. In the majority of cases, however, the quantities of active substances used and the risk potentials followed different trends. The risk potential for the insecticides, for example, was higher than for the fungicides, although the converse was true for the quantities of active substances used. Moreover, from 2009 to 2018 the risk potentials of the fungicides and insecticides were subject to sharp decreases and increases, respectively, which were not observed for the quantities of active substances used. It is thus important to consider not only the quantities but also to explicity include risk potentials when evaluating environmental impact trends.

The change in area-weighted risk potentials for surface waters over time is caused by the interaction of several factors. Apart from the cultivated area, the quantities of active substances used and the choice of active substance are important input parameters for the calculations. These are in turn dependent on the efficacy of the PPP against harmful organisms, the crop and the variety cultivated, weather conditions, infection pressure, farm plant-protection strategy, authorisation guidelines, and agricultural policy. The AEI dataset is an invaluable resource, as it includes information on these factors and describes the annual changes in PPP use in different crops. A further key element is consideration of the local factors that are typical for Switzerland (soil type, temperature, slope, proximity to watercourses) for modelling PPP concentrations in surface waters (de Baan, 2020). In addition, authorisation is subject to use restrictions that reduce the discharge of PPPs from the treated fields, and hence the input into surface waters. Finally, the choice of active substances used is also important, since they do not all behave the same in the environment, and also differ in terms of ecotoxicity. These factors all play an important role in understanding the observed risk-potential trends for surface waters.

Over time, the risk potential for surface waters posed by herbicides and fungicides has declined. The influence of the use restrictions associated with authorisation were key here. For insecticides, the risk potential has increased substantially from 2014 onwards, mainly owing to the use of insecticides in oilseed rape crops. Nevertheless, the restrictions imposed with authorisation have significantly reduced this increase. For a better understanding of the changes in risk potential, it is necessary to examine the risk potentials of the groups of active substances (herbicides, fungicides and insecticides) for the different crops separately.

With fungicides in winter wheat, for example, weather-related fluctuations in disease pressure and their effects are clearly visible. In 2012, a wet year, both the quantity and risk potential of fungicides used in winter wheat were very high; chlorothalonil, fenpropidin, spiroxamine and prochloraz were dominant in almost 70% of the treatment programmes. By contrast, only one-third of the amount of active substances used in 2012 was used in 2015; the risk potential in 2015 was only one-tenth as high.

The spectrum of active substances used has changed in part from 2009 to 2018. For herbicides used in winter barley, there has been a shift over the years in risk-dominant active substances, from isoproturon to the lower-risk diflufenican. The steep increase in the risk potential of insecticides used in oilseed rape is due to the active ingredients chlorpyrifos and chlorpyrifos-methyl, approved in 2013 to control the rape pollen beetle in oilseed rape crops after the pest developed a resistance to pyrethroids. Chlorpyrifos and chlorpyrifos-methyl have since been withdrawn from the market because of environmental concerns, and as of July 2020 may no longer be used. In 2015, a relatively high percentage of fungicide-based treatment programmes were dominated by the fairly low-risk laminarin, whilst the percentage of treatment programmes dominated by the active substances chlorothalonil, fenpropidin, spiroxamine and prochloraz, which posed a 3-to-4-times-greater risk, was nearly 30% lower than in 2012. The use of chlorothalonil has been prohibited since 1 January 2020. PPP authorisation therefore has a major impact on the spectrum of active substances that can be used. Consequently, it strongly influences risk, to surface waters as well. Where suitable alternatives are lacking, however, the banning of certain products can also make plant protection more difficult.

The use restrictions imposed in association with PPP authorisation to reduce drift and runoff have also contributed to risk reduction, without limiting the spectrum of usable active substances. These use restrictions have considerably reduced the risk potential posed by herbicides, fungicides and insecticides for surface waters. Even so, neither the calculation of the risk potential itself nor the inclusion of the use restrictions can take every detail into account. For the interpretation of the results, it is important to understand that certain assumptions were made concerning the calculation of the effects of the use restrictions – assumptions, which can lead to over- or underestimation of the effects. For runoff, for example, the fact that the restrictions only concern fields having a slope greater than 2 % and located less than 100 m from a watercourse (FOAG, 2020c) was not taken into account. On the other hand, use restrictions are implemented which do not apply to specific PPPs, but which can also reduce the risk potential of non-restricted PPPs (e.g. 6m vegetation buffer strips). In some cases, individual measures had already been implemented even before the imposition of restrictions associated with authorisation. In general, a better knowledge of the effective implementation of the restrictions and additional risk-reduction measures, e.g. via surveys carried out at farm or cantonal level, or via aerial photo analysis, would help us better assess the effectiveness of risk reduction.

The example of the use of fungicides in winter wheat has shown that 'outlier' farms exist. For these farms, the quantity of active substance used and the risk potential for surface waters was many times higher than the median values of all farms analysed in a year. The reason for the higher quantities of active substances of the outlier farms was their use of active substances with high application volumes per ha (e.g. sulphur). Such active substances are of relatively low toxicity for aquatic organisms, and have only a minor impact on risk potential. Presumably, the higher risk potential of these outlier farms stems from their use of fairly toxic substances. In winter wheat, chlorothalonil, prochloraz and fenpropidin were among the highest-risk active substances, with chlorothalonil since having been withdrawn. We assume that improved support of farms (vocational and continuing education, extension, targeted decision-making tools) in terms of the use of lower-risk active substances could have a significant effect on risk potential. The development of alternative non-chemical plant-protection measures can also make a significant contribution to risk-potential reduction.

Prospects

Detailed analyses of field crops show that it is very important to know exactly which PPPs are used in what crop, and in what quantity. For other types of crops, reliable data on PPP use are still lacking. As part of the PPP Action Plan, various measures are being developed to improve the recording of PPP applications. For example, a distribution key is currently being developed that will allow us to assign the quantity of each active substance sold to different fields of application, and to develop a better idea of the importance of these fields of application (whether part of agriculture or not). Additional data are also being collected for vegetable and organic farms. In future, wider coverage, improved accessibility and increasing digitalisation in agriculture could help ensure the availability of a representative data pool not only for field crops, but also for special crops.

The PPP Action Plan envisages reducing the risk potential for surface waters by 50 % by 2027 compared to the average for 2012–2015. Figure 2 shows both the reference value (black arrow) and the target value (grey arrow). Not only the decrease in quantities used, but above all the increase in use restrictions is an important factor in reducing the risk potential for surface waters. Considering the use restrictions mandated in the PPP authorisation, in 2018 the risk potentials for herbicides, fungicides and insecticides were 28 %, 17 % and 19 % lower, respectively, than the reference value (Fig. 2, right). The analyses of the trends from 2009 to 2018 show that the risk potentials have already decreased.

Compared to considerations of amount alone (sales, use), the risk potentials for surface waters have substantial added value. They help us to better understand the role of risk-reduction measures, the choice of active substances and a reduction in their use. With a greater differentiation of the risk potentials, e.g. a separate depiction of the risk potentials for algae, aquatic plants, crustaceans, insects and fish, or with the inclusion of terrestrial compartments, the impacts of PPPs on the environment can be analysed more specifically. The method not only allows for a better retrospective understanding of risk-potential trends with additional crop- and site-specific knowledge (e.g. the incidence of pests, weather conditions), but also helps us to better understand and assess the effect of the different measures in the overall context for the future, and to evaluate new plant-protection strategies in terms of optimising environmental protection. ■

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