Plant protection product losses via tile drainage: A conceptual model and mitigation measures

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Drainage pipe discharging into a watercourse. (Photo: Volker Prasuhn, Agroscope)

Summary

Drains can be installed to reduce saturated soil conditions and improve crop growth. This article evaluates the extent to which these systems may cause losses of plant protection products (PPP). To that end, we estimated the drained fraction of Swiss arable land using both existing drainage maps and machine learning. Our drainage map suggests that 25% of Swiss agricultural land has a moderate to high potential of being drained. We further evaluated the risk for PPP losses via drainage and the potential of selected mitigation measures based on a conceptual model summarising the relevant scientific literature. Although drainage losses are highly variable, they are strongly influenced by the extent of preferential flow (PF) in soils and are an important transport pathway to surface waters. Most agricultural soils in Switzerland are prone to PF, given their loamy texture, suggesting that PPP losses via tile drains are an important phenomenon in Switzerland's drained arable fields. The most common mitigation measures for drainage are those recommended for runoff, erosion and leaching. However, given the uncertainty of the local PPP losses and driving factors, no site- or PPP-specific measures can currently be proposed to reduce PPP drainage losses. This study also examines the effectiveness of the regulatory model EXPOSIT in predicting total PPP losses and peak concentrations in watercourses. When compared with experimental data from Agroscope at Zurich-Affoltern, our findings suggest that EXPOSIT does not yield the worst-case estimates for Swiss conditions.

Key words: drainage, plant protection products, macropore flow, mitigation measures, EXPOSIT.

Introduction

Currently, around 2,000 tons of plant protection products (PPP) are used in Swiss agriculture every year (FOAG 2019). Measurements from small and medium watercourses, including those taken by the *NAWA-SPEZ programme*, which investigate pesticide contamination in surface waters, have shown that numerous streams are contaminated with PPP, particularly after intense rain events (Knauer 2016; Spycher *et al.* 2019), and that PPP loss rates can vary by over an order of magnitude (Doppler *et al.* 2012). According to Kladivko *et al.* (2001), although losses via runoff and erosion tend to be the highest of all pathways, PPP losses of up to 3% of the applied PPP can occur from drainage and are, on average, higher than those occurring via leaching, though smaller than those occurring via runoff and erosion.

In response, the Swiss 'National Action Plan for Risk Reduction and Sustainable Use of PPPs' aims to significantly reduce the environmental risks of PPP use (The Federal Council 2017). In particular, runoff and erosion were identified as important loss pathways transporting PPP from agriculture into surface waters; possible mitigation measures were also proposed and evaluated (Prasuhn *et al.* 2018). However, the relevance of subsurface drainage on PPP losses is less known, in part because the spatial extent of drained agricultural land is not well documented (Gramlich *et al.* 2018).

Therefore, the national action plan calls for an investigation of the importance of PPP losses via drainage and an assessment of potential mitigation measures. This article addresses this need by first describing a newly developed spatial map of potentially drained areas in Switzerland. Second, a conceptual model is presented that summarises the knowledge about PPP transport through drainage. Using the conceptual model, we then evaluate the potential of several mitigation measures to reduce losses via drainage under Swiss conditions. Finally, the total PPP load and peak concentration in watercourses are important to be estimated robustly, allowing for an objective risk evaluation of PPP use in Swiss agriculture. Using data from a drainage field experiment in Switzerland, we also evaluate the potential of the regulatory tool EXPOSIT to predict realistic worst-case losses.

Methods

Koch and Prasuhn (2020) generated a map of drained areas in Switzerland based on the available geodata for melioration and drainage supplied by 10 cantonal authorities (AG, BL, BS, BE, FR, GE, NE, SH, SG, ZH). The potential for drained land in the remaining 16 cantons was calculated by a machine learning algorithm (Gradient Boosting Machine [GBM]) using 12 topographical and pedological characteristics.

After an extensive literature review, we developed a conceptual model of PPP losses via drainage, including data from Swiss experiments. The model depicts qualitative relationships between many different soils, PPP and farm management parameters. Based on the model, literature and expert knowledge, we subsequently evaluated the mitigation measures suggested by the TOPPS (Train Operators to Promote best management Practices and Sustainability) working group (TOPPS 2018) and discussed other options that may become important in the future.

Existing regulatory tools use process-based models (e.g. the MACRO model for FOCUS drainage scenarios) or qualitative rules of thumb, such as those used by the German tool EXPOSIT (UBA 2008). EXPOSIT provides a rough approximation of PPP losses by subsurface drainage based on data from Germany, where substances are grouped into two mobility classes (less mobile vs. more mobile) and application times are grouped into two seasons (spring/summer vs. autumn/winter). Each combination (out of the four total combinations) has a predefined percentage of how much of the applied substance contributes to the peak loss or to the total loss by tile drains.

We based this work on Kobierska *et al.* (2020), whose study provided an exhaustive report on the conceptual model, mitigation measures and EXPOSIT.

Results

Map of drained areas in Switzerland

The most recent survey (Béguin and Smola 2010) estimated that the drained areas in Switzerland covered about 192,000 ha (18% of the utilised agricultural area). We supplemented this assessment with a map of potentially drained agricultural areas in Switzerland (Fig. 1), on which 240,000 ha (27% of the modelled agricultural land) have a low potential to be drained, 120,000 ha (13%) have a moderate potential and 110,000 ha (12%) have a high potential (for details see Koch and Prasuhn 2020). Overall, the areas with a moderate and high potential to be drained constituted 25% of the utilised agricultural areas in Switzerland, in agreement with the survey by Béguin and Smola (2010). This finding confirms that drainage is an important factor in many agricultural soils and should not be neglected. Thus, it is important to understand how drainage systems may affect PPP transport.

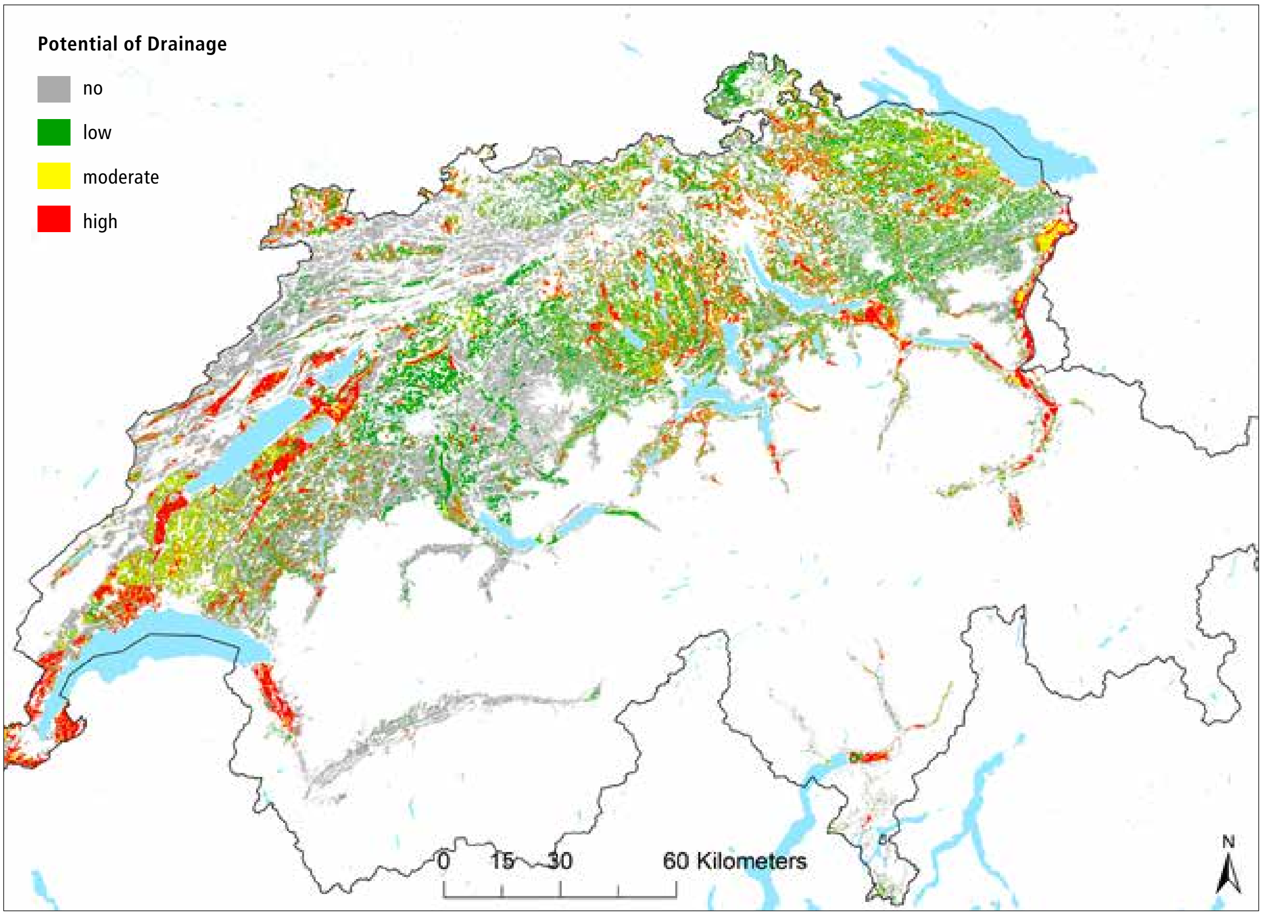

Fig. 1 | Map of potentially drained agricultural areas in Switzerland (from Koch and Prasuhn 2020).

Conceptual model of PPP losses via drainage

To better understand the relevance of drainage on PPP transport, a conceptual model was developed based on the existing literature. This evaluation revealed that individual processes affecting PPP losses are reasonably well understood. However, their various interactions under specific local conditions (e.g. soils, weather, topography, drainage setup, crops, tillage practices and PPP use) make it difficult to identify and generalise the relevance of each parameter.

Preferential flow (PF) is a key factor affecting PPP transport to subsurface drains. It is well established that PF generally occurs in many soils (Flury *et al.* 1994; Weiler 2017) and can be very fast, bypassing (larger) parts of the bulk soil when compared to matrix flow, which is a relatively slow process. This characteristic leads to short residence times in the soil compartment, so that even adsorbing chemicals such as PPP can reach the groundwater (GW) by a single rainfall event (Kördel *et al.* 2008). Often, PF follows macropore structures in the soils, which are generally abundant in loamy and clayey soils and can be biopores (e.g. earthworm burrows and decayed roots) or shrinkage cracks. Compared to cracks, biopores are temporally more stable, as they do not retract upon rewetting. A key question in studying PPP transport is how well the PF structures connect the soil surface to the GW table. Even with structurally persistent macropores, PF only occurs if these structures receive sufficient water. In general, this happens during high intensity precipitation or snowmelt events when the infiltration capacity of the soil matrix is exceeded. Therefore, PF is an event-driven process that can induce the GW table to rise quickly. Drain depth and spacing also affect how effectively GW will discharge into the drainage system. The drain response can be particularly quick if a confining layer immediately below the drain causes the rapid rise of a perched GW table. This hydrological context has a strong impact on PPP losses at the plot scale, and influences the partition between leaching losses and drainage losses, as well as surface runoff and erosion losses.

The existing literature (i.e. Brown and van Beinum 2009; Kladivko *et al.* 2001) has revealed that many factors influence the extent of PPP losses from PF to subsurface drains. In Table 1, we list the key parameters influencing drainage losses and assess their impact and uncertainty. The parameters are grouped into the following categories: drainage design, climate, soil, catchment properties, PPP properties, crop types and farming practices. Furthermore, the relationships between the most important parameters are illustrated as a flow diagram in Figure 2. Many relationships are multi-parameter and non-linear, and some parameters had uncertain impacts on drainage losses. The literature shows that quantitative predictions regarding PPP losses via drainage are uncertain due to the strong influence of local conditions. To deal with this complexity, several decision trees have been suggested to quantify the extent of macropore flow through soils in broad categories (Jarvis *et al.* 2012). However, the decision trees do not allow for quantitative flux estimates. Swiss soils, which are mainly loamy, often fell into the medium risk category within these decision trees.

Drainage design

With deeper tile drains and a less dense drainage network, macropores originating from the surface will be less likely to remain connected to the GW table. On the other hand, more water can be drained with a deeper GW table, enhancing the dilution of PF. Thus, these modifications will lead to lower peak losses, but likely increase leaching losses. In addition, if the drain is on a slope, a wider area could contribute to lateral flow paths.

Climate

The greater the autumn and winter precipitation, the more active the drains will be between approximately October and April, potentially increasing the losses of

Tab. 1 | Influence of key parameters on PPP losses via drainage (focus on peak concentration).

Category	Parameter (analyzed as increasing in value)	– – –	– –	–	0	+	++	+++	Uncertainty
Drainage design	Depth of subsurface drain	×	×						×
Drainage design	Drain spacing		×	×					×
Drainage design	Improved drainage (permeable filter, i.e. gravel)					×	×		×××
Climate	Total winter precipitation				×	×	×		××
Soil properties	Clay content						×	×	×
Soil properties	Silt content			×	×	×	×		×
Soil properties	SOC content	×	×						×
Soil properties	Water holding capacity		×	×					×
Catchment properties	Slope		×	×	×				××
Catchment properties	Runoff from nearby slopes			×	×	×	×		×
Catchment properties	Ratio of critical source areas for infiltration/runoff					×	×	×	×
PPP properties	Half-life DT_{50}						×	×	×
PPP properties	Sorption coefficient K_{oc}		×	×	×				××
PPP properties	Volatility		×	×					×
Crops	Temporary grassland	×							×
Crops	Winter rapeseed and winter cereals		×	×					×××
Crops	Sugar beet, maize					×	×		×××
Crops	Vegetable and potatoes						×	×	×××
Crops	Soil cover		×	×					×
Agricultural practice	Tillage intensity: no-till				×	×	×		×××
Agricultural practice	Time between application and first intense rain event	×	×						×
Agricultural practice	Intensity of first rain event after application						×	×	×
Agricultural practice	Soil wetness at application date			×	×	×	×	×	××

'Zero' means that an increasing value of the parameter will have little or no effect on peak PPP losses. '+++' means that an increasing value of the parameter will strongly contribute to higher peak PPP losses (vice versa for '– – –'). The uncertainty denotes the confidence with which the effect of each parameter is assessed based on the literature. Dark green highlights the extremes, green the moderate, and yellow the small or neutral effects. Parameters highlighted in blue are environmental parameters that cannot be affected in the short term by mitigation measures. The parameters that are more readily affected by mitigation measures are presented in pink.

(persistent) PPPs applied in late autumn for winter cereals. In spring, soils are likely to be saturated, leading to losses mainly via runoff, though drainage is also an important contributor. In addition, drains can become active in exceptionally wet summer periods or if high intensity precipitation occurs on soils prone to macropore flow.

Soil properties

Clay content is a key driver in the development of macropores. In clayey soils, cracks form upon drying and close upon rewetting, while very high clay content is not favourable to earthworms. Earthworms prefer loamy soils where it is easier to create stable burrows. In contrast to clayey soils, silty soils exhibit a high water-holding capacity, leading to lower PPP losses. On the other hand, higher silt contents are conducive to higher earthworm activity and the development of biopores, which lead to potentially higher peak PPP losses via drainage.
Soil organic carbon (SOC) content provides adsorption sites for PPPs and also helps form stable soil aggregates, which tend to limit PF (Jarvis 2007), thereby decreasing peak PPP losses via drainage. However, Kördel *et al.* (2008) stress that more SOC leads to higher macroporosity and greater stability for the macropores, promoting PPP losses via macropore flow to the drainage systems.

With regard to PPP losses via drainage, organic soils pose a lower risk, since their high water-holding capacity enables more infiltrating water to be stored and more PPP to be held back (Gramlich *et al.* 2018). Microbial activity tends to persist at deeper depths in organic soils than in mineral soils, leading to a quicker degradation of the PPPs trapped in the soil matrix.

Catchment properties

An increasing slope will decrease the losses via drainage since runoff becomes more dominant in inclined areas and transports PPP away from the plot (Gramlich *et al.* 2018). This interrelation is important for a hilly country like Switzerland. Koch and Prasuhn (2020), for instance, estimate that 72% of the drained land in the 10 cantons mentioned above may have a slope higher than 2%, offering a relevant threshold for the occurrence of runoff events. However, this high fraction of sloping drained land may not necessarily be dominated by PPP losses via runoff, since draining a plot lowers the ratio between infiltration and runoff. In addition, runoff from surrounding slopes can accumulate into depressions and lead to a higher amount of infiltrated water than would be expected by looking at each field individually (Doppler *et al.* 2012). Ultimately, this action could lead to higher peak losses via drainage in specific areas.

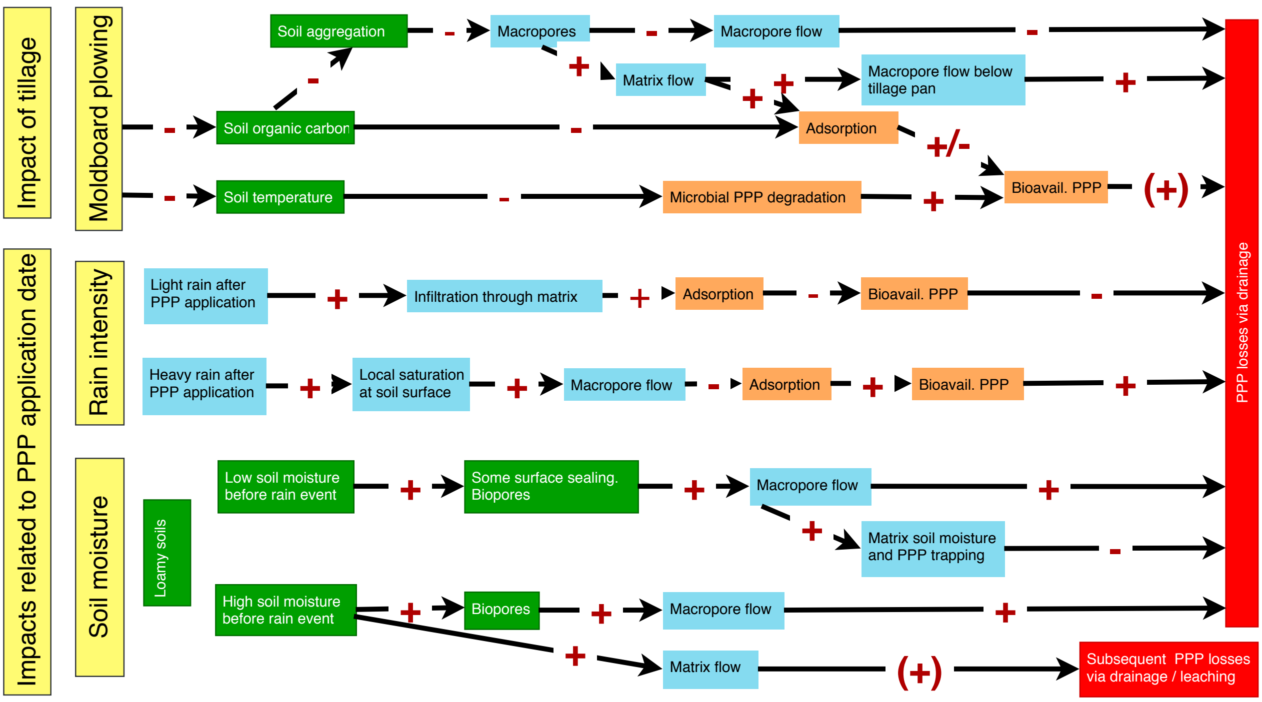

Fig. 2 | **Conceptual model of PPP losses via drainage. Different management scenarios are considered. The boxes represent parameters and processes related to soil (green), hydrology (blue) and PPPs (orange). The consequences in terms of PPP losses are shown in red. '+' means an increase of the destination box, '–' means a decrease and '+/–' means conflicting effects. (+) means that the increase is weak.**

Physicochemical PPP properties

The PPPs on the market can have considerably different physicochemical properties and formulations. Here, we refer to a PPP as the active ingredient of a pesticide product. The adsorption properties can also vary between substances and depend on parameters such as soil organic matter, clay content and/or pH (Wauchope *et al.* 2002). The fraction of PPP mobilised depends on complex sorption processes. A high sorption coefficient K_{oc} will reduce losses much less when the macropore flow is dominant due to low adsorption in the macropores and the particle-facilitated transport of PPPs (Jarvis 2007).

The degradation of PPPs can be biotic or abiotic. Biotic degradation is generally more important. The half-life of DT_{50} may differ strongly between PPPs and is additionally influenced by soil texture, organic matter, pH, bacterial communities, water content and temperature. DT_{50} is a key parameter because it controls how much PPP is available for mobilisation in the soil during the first rain events after application. However, DT_{50} loses relevance for values exceeding the average return period of significant rainfall events (in the order of 10 days).

Crops and agricultural practice

Our assessment of the drainage risks for different crops were based on the intensity and frequency of PPP spraying in combination with the soil cover of each crop. Vegetables and potatoes are thought to have the largest risk because of their relatively low soil coverage and the high spraying intensity they require.

Alletto *et al.* (2010) provide a comprehensive review of the impact of various types of tilling practices. No-till will lead to more PF, but also potentially less surface runoff. Kördel *et al.* (2008) concluded that there was no significant difference between no-tillage and mouldboard plowing with regard to PPP losses via drainage. In addition, reduced tillage is listed as less risky than no-till with regard to PPP losses, because tillage can help to break up permanent macropores. On the other hand, reduced tillage tends to temporarily increase the hydraulic conductivity of the tilled layer. In this regard, shallow tillage could be a good compromise.

The time between PPP application and the first intense rain event is listed in Table 1 as 'management-related' because the farmer can influence the application date based on the weather forecast. In combination with DT_{50}, this practice is one of the most important parameters controlling the peak concentrations in the surface waters and the total leaching amounts of the PPPs. Reichenberger *et al.* (2007) discuss the impact that the choice of application date has on PPP losses in relation to both the soil moisture at application and the time before the next heavy rainfall.

Low rainfall intensities will lead to matrix flow rather than PF, giving more time for adsorption and degradation, in addition to possibly providing immobile storage to the PPPs (Kördel *et al.* 2008). As a result, the PPPs can later be mobilised as more soluble metabolites or transported via desorption exchanges to macropores. The higher the rainfall intensity, the more likely PF occurs (Jarvis 2007). The impact of soil wetness depends on soil texture. However, wetter soils tend to generate more macropore flow than dryer soils, as there are less lateral losses into the soil matrix (Jarvis 2007). On the other hand, clayey and silty soils can become water-repellent or more cracked when dry, leading to high peak losses.

EXPOSIT registration model

EXPOSIT was used to provide worst-case estimates for both the total losses to a ditch and the initial concentration in a ditch due to drainage flow from a storm event. The latter was used in the ecotoxicological risk assessment. The model predictions can be verified by designed field experiments. As evidence, we showed as much using the study by Wettstein *et al.* (2016), which monitored the concentration of the insecticides thiamethoxam and imidacloprid (seed dressing), the pre-emergence herbicide S-metolachlor, and the fungicides epoxyconazole and kresoxim-methyl (and its acid metabolite) in subsurface tile drain water during the sugar beet growing season at an experimental site in Zurich-Affoltern. Both the total loss and peak concentration in the drainage water were within the same order of magnitude in the model and in the experiment. Of note, the spring storm event, which triggered the peak concentrations of the insecticides and herbicide in the tile drains, occurred around 40 days after application, leaving far more time for degradation than the model did (three days).

Mitigation measures for Switzerland

TOPPS (2018) suggest various mitigation measures to reduce losses via drainage and leaching. An assessment of the potential of each mitigation measure for Switzerland is presented in Table 2. This evaluation entails the level of available knowledge, the practical feasibility, the effectiveness per treated field and the expected overall effect considering the total area where the measure can be implemented.

The level of knowledge for most measures is considered to be good (i.e. scientific publications on the effectiveness and efficiency exist). However, many measures are difficult to implement because of additional labour and cost. Moreover, some measures (e.g. paludiculture and rice production) are hardly suitable for Swiss agriculture due to the country's climatic or topographic characteristics. In addition, many measures have a very good or good impact on reducing PPP losses, but because many of them can only be implemented in a few areas, their impact on reducing PPP transport via drainage to surface waters is only moderate.

Furthermore, most mitigation measures are already part of the Proof of Ecological Performance (PEP) in Switzerland and, therefore, are already widely implemented. This context limits the potential for substantial reductions of PPP losses via drainage. Measures against leaching losses will reduce the total, but not necessarily the peak drainage losses. In addition, many measures against runoff and erosion will decrease losses via drainage. However, some measures against runoff and erosion, such as no-till, can have negative impacts on PPP losses via drainage (Brown and van Beinum 2009; Alletto *et al.* 2010). On land prone to runoff and erosion, the reduction in losses via those pathways tends to outweigh the potential risk of increased drainage losses.

Some crops, such as rice or reed for bioenergy, are either niche productions or difficult to carry out at a profitable scale in Switzerland. Technical mitigation measures are

Tab. 2 | List of mitigation measures adapted from TOPPS (2018), their specificities and their applicability in Switzerland. The overall potential reduction is assessed for the whole of Switzerland. Ratings range from weak (–, orange) to average (0, yellow) to very good (++, dark green).

Measure categories	Specific measures	State of knowledge	Applicability, practicability	Potential for reduction of PPP losses via drainage per ha	Overall potential for reduction of PPP losses via drainage
Adapt application timing	Avoid spraying during drainflow season and shortly before heavy rainfall is forecast Consider available treatment alternatives	++	–	++	+
Reduce substance load per field	Reduce overall rate per area Use pesticide mixtures (different active ingredients) Use split applications (strech PPP load) Use pest-monitoring techniques (manual, automatic sensors) and only treat infested areas (spot treatment) Use seed treatment	+	0	++	++
Optimise PPP selection and rotation in catchment	Widen crop rotation to reduce the load of a specific pesticide Rotate pesticide for a specific crop in the catchment Restrict pesticide application in vulnerable fields	0	0	+	++
Optimise crop rotation	Select crop rotation to optimise plant health and – alternate winter and spring corps – consider plants with tap- and fibrous-root systems	+	0	+	+
Adapt tillage practices	If drainflow is a problem: consider using at least shallow tillage to disconnect soil macropores in vulnerable fields	0	+	0	0
Grow cover crops	Select cover crops to fit the rotation of the main crops – pay attention to good cover crop – maintain and manage cover crop – ensure cover crop does not interfere with cash crop	+	+	+	0
Optimise drainage practice	Design drainage professionally (follow guidance) to avoid over-drainage	++	–	0	0
Use water-retention structures	Use retention structures (e. g. ponds, wetlands) to capture drainage water for retention, dilution and dissipiation of high-concentration drainflow pulses in autumn or summer	0	–	+	0
Optimise irrigation practices	Calculate the necessary irrigation volume (balance) Soil moisture monitoring to optimise irrigation scheduling	+	0	+	0
Soil amendment	Biochar	0	–	+	0
Land use change	Paludiculture	+	–	++	0
Land use change	Rice production	–	–	0	0
Land use change	Agroforestry	–	–	++	0

available, such as controlled drainage (temporarily raising the depth of the drainage outlet), artificial wetlands or biomass filters. However, their applicability in Switzerland is limited due to the small scale of the drainage infrastructure, the complex topography and the scarcity of land that can be dedicated to non-productive use. In addition, climate change will surely affect the hydrological behaviour of drains. In the future, warmer and drier summers may require controlled drainage to optimise water usage, which consequently may help mitigate PPP losses via drainage.

Based on the conceptual model and the existing literature, the measure with the highest mitigation potential, in theory, is optimising the date of application. In practice, however, the potential for farmers is limited because of several constraints, such as limited time windows according to the crop stage, frequent rainfall events, or logistical reasons. Thus, our review does not reveal any widely applicable agronomical mitigation measures specifically targeted against PPP losses via drainage for Switzerland.

Discussion and conclusions

The new map of potentially drained areas in Switzerland is subject to various uncertainties due to the original digital maps used, which were digitized differently and sometimes were no longer up-to-date. Often, it was unclear how accurate and complete these initial maps were. In addition, the absence of high resolution soil maps caused uncertainties in the predictions. Furthermore, the condition and functionality of drains is mostly unknown. Our map confirms the findings of previous surveys (Béguin and Smola 2010) that around 20% of the utilised agricultural area or 30% of the agricultural land best suited to arable crops ('Fruchtfolgeflächen') has been drained, showing that PPP losses via drainage should not be neglected. Thus, this map will help to identify potential problematic areas regarding PPP losses via drainage.

Measurements of PPP concentrations taken from surface water are usually insufficient to quantify the losses via drainage, since runoff, erosion and shortcut losses are often more important and occur at the same time. Our study shows that there is a good general understanding of the processes affecting PPP losses via drainage. However, site-specific conclusions for Switzerland are difficult to draw. More drainage-specific measurements in Swiss agricultural catchments would help researchers better understand their hydrology and the related PPP losses. Given the cost of PPP measurements and the complex dependence of this loss pathway on PPP properties (e.g. sorption), the initial focus of these measurements should be on intensively drained areas based on the current map. One priority is to better assess the hydrological behaviour of drained areas in relation to other loss pathways. Peak losses via drainage are caused by intense rain events, are strongly influenced by the extent of PF, and consequently depend less on PPP properties than losses through matrix flow. In Switzerland, most agricultural soils are loamy soils, which are prone to macropore flow via biopores and, in some cases, shrinkage cracks. In combination with the high rainfall amounts and frequent heavy rainfall events in Switzerland, these soil conditions result in an overall high risk of PPP losses via drainage systems.

This potential to higher losses is rudimentarily reflected in the data from the experimental site in Zurich-Affoltern, although the available data is by far too limited to fully evaluate the EXPOSIT model. Though PF was the main driver for flow and transport towards tile drains at the experimental site and EXPOSIT reflects that assumption in the loss factors, the weather conditions in Switzerland may be different from Germany. The values predicted by EXPOSIT for total and peak losses were in good agreement with the measured values documented in Wettstein *et al.* (2016). However, dry weather conditions in the spring allowed for more PPP degradation than accounted for by EXPOSIT. These experimental results suggest that EXPOSIT did not yield the worst-case estimates for Swiss conditions.

The most common mitigation measures are those recommended for leaching, runoff and erosion (TOPPS 2018). Drainage-specific measures are rare and not applicable on a large scale. There is also much uncertainty in the location of drained areas. Therefore, it is unrealistic to regulate the use of PPPs on drained land with site-specific measures on top of the already enforced regulations for runoff and drift imposed during the PPP registration process (Agridea 2018). However, we would advise farmers working on drained land to avoid applying PPPs if a storm is forecasted in the next few days or if the drains are already active, in addition to following agricultural management best practices. At the farm scale, flat areas that concentrate surface runoff may be drained and act as infiltration 'hotspots' where mitigation measures should be prioritised. As an additional precaution, no-till should be avoided on plots that are flat and prone to tile draining. These considerations should be taken into account in the risk management of PPP losses via runoff in Switzerland. ■

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