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Modeling the implications of policy reforms on pesticide risk for Switzerland

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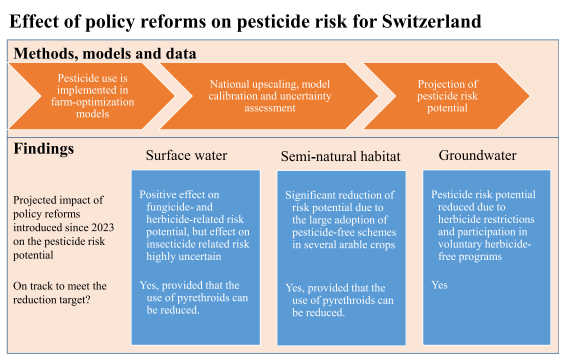
HIGHLIGHTS

- We developed a method for including pesticide risk into bio-economic farm models.
- The models project the effects of 2023 policy reforms on reducing pesticide risks.
- Ex-ante analysis of groundwater shows a noteworthy decrease in pesticide risk.
- Pyrethroid restriction is essential to reduce pesticide risk in surface water.
- Switzerland needs comprehensive datasets on pesticide use to reduce uncertainties.

GRAPHICAL ABSTRACT



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ABSTRACT

Growing public awareness of the negative effects of pesticides on the environment, ecosystems, and human health has led governments to set targets for reducing pesticide risk. Switzerland introduced in 2023 two new policy measures to reduce pesticide risk by 50 % by 2027: (1) voluntary direct payment programs supporting pesticide-reduced and pesticide-free but non-organic cropping systems for most crops on arable land, and (2) restrictions of harmful pesticides for farmers managing under Swiss cross-compliance standards. This study aims to (1) develop a method to assess pesticide risk on a national scale and (2) carry out an ex-ante impact assessment to predict whether these policies can effectively reduce pesticide risks in Switzerland. Therefore, we introduced crop-specific pesticide quantities and pesticide risk scores into a sample of 1907 bio-economic farm optimization models. The models were used to predict farmers' adoption decisions regarding voluntary direct payment programs from 2019 to 2030. By combining the bio-economic farm optimization models with an agent-based modeling approach, we assessed the evolution of pesticide-related risks at the national level. Simulations for pesticide risk from 2019 to 2022 reflected the observed pesticide risk monitored by the Swiss government. In surface waters and semi-natural habitats, achieving the target depends on reducing pyrethroids, a class of insecticides with high-risk potential. Further, we highlight significant uncertainty in projecting the risk potential for surface waters and semi-natural habitats due to uncertainty about the amounts of pyrethroid used for different crops. The results underline the need for comprehensive datasets on pesticide use in Switzerland.

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1. Introduction

The use of pesticides[1] in agriculture has certainly contributed to the reduction of yield losses, and to food security, but it is also at the root of their widespread presence in the aquatic and terrestrial environments, with negative effects on non-target organisms and biodiversity (Malaj et al., 2014; Meena et al., 2020; Rani et al., 2021; Sharma et al., 2020). Pesticides represent not only a risk for the environment but also for humans, who are exposed through the food chain, air, and water. Studies suggest that pesticide exposure is linked to adverse birth outcomes, and an increased risk of developing several diseases (Jones, 2020; Kim et al., 2017; Larsen et al., 2017).

In recent years, growing public awareness of the environmental persistence of pesticides and their negative effects on ecosystems and human health has led governments to set targets for reducing pesticide use (Mohring et al., 2020). One of the objectives of the European Union's "Farm to Fork" strategy is to reduce chemical pesticides by 50 % by 2030 (European Commission, 2020; Schebesta and Candel, 2020). In Switzerland, two recent popular federal initiatives targeted at reducing pesticide uses in agriculture: The Drinking Water Initiative aimed to restrict direct payments to pesticide-free production (Federal Chancellery, 2018; Schmidt et al., 2019), while the Pesticide Initiative proposed a complete prohibition of the use of synthetic pesticides (Federal Council, 2021). Both initiatives were rejected by the Swiss population, but they prompted Switzerland to set the goal of reducing the risks associated with pesticides. (Finger, 2021; Finger and Möhring, 2022). The 'Reduction paths for pesticide' strategy was implemented in the Agriculture Law (LwG Art 6 b[2]) in 2021, with the objective of reducing pesticide risks by 50 % until 2027 compared to the reference period 2012/2015 (BLW, 2021). To reach these targets, Switzerland introduced in 2023 two new policy measures: (1) a national-scale voluntary direct payment program for pesticide-free or pesticide-reduced cropping systems on arable land, and (2) restriction of harmful pesticides within the Swiss cross-compliance standards.

This is the first national-scale study to forecast the effectiveness of these pesticide-related policy reforms on pesticide risk. Therefore, we develop a bio-economic modeling approach that allows the (a) forecasting of pesticide-use quantities and pesticide risk for a representative sample of up to 3077 FADN-farms, and (b) upscaling of pesticide use quantities and pesticide risk at the national scale. This modeling framework is used to assess the evolution of pesticide-related risk until 2030 for three compartments: groundwater, surface water, and semi-natural habitats (terrestrial habitats with little human influence that support biodiversity and ecosystem services). This enables us to determine whether Switzerland is on track to meet the target of reducing pesticide-related risks.

Bio-economic farm models, in combination with an agent-based approach, are a powerful tool for an ex-ante assessment of policy changes (Mack et al., 2023). We use the agent-based agricultural sector model SWISSland, which has been widely applied to analyze the impact of policy changes on land-use decisions and the adoption decisions of voluntary direct payment programs, such as the grassland-based milk and meat program (Mack and Huber, 2017) or farmers' responses to changes in cross-compliance standards (Schmidt et al., 2019). In 2023, the SWISSland model was used to predict the adoption potential of direct payment programs for pesticide-free, but not organic, cropping systems and their implications for food production and agricultural income at the national scale (Mack et al., 2023). Pesticide-free production shares with organic production the principal of non-use of chemical synthetic pesticides, but does not impose other requirements such as the restriction on mineral fertilizer (Finger, 2024). In this study, we extend this modeling framework to assess the implications of pesticide-related policy reforms on pesticide risk.

Several pesticide risk indicators have been developed to assess the environmental impact of crop protection products and the efficiency of policies (Möhring et al., 2019; Pierlot et al., 2017; Reus et al., 2002). The Swiss government uses the pesticide risk indicator developed by Korkaric et al. (2023) for monitoring pesticide risk in Switzerland (Ordinance on the Evaluation of Sustainability in Agriculture, Art. 10c). To ensure that our modeling results for pesticide risk from 2018 to 2030 are consistent with the monitoring results for Switzerland, we develop a bio-economic modeling framework based on pesticide risk scores from Korkaric et al. (2023).

The remainder of this paper is structured as follows. Section 2 summarizes the pesticide policy in Switzerland and gives an overview of the SWISSland model. Section 3 presents the bioeconomic modeling framework for assessing pesticide risk on a national scale and describes the modeling scenarios. Section 4 compares the simulated pesticide use at national scale with sales from national statistics and presents pesticide-related risks for the three compartments (groundwater, surface water, and semi-natural habitats) at the crop and national levels. Section 5 provides a discussion of the results, and Section 6 concludes this study.

2. Background

2.1. Pesticide policy in Switzerland

Three different policy instruments steer pesticide use in Swiss agriculture: (1) plant protection product authorization; (2) cross-compliance standards; and (3) voluntary direct payment programs for pesticide-reduced or pesticide-free cropping systems.

1) The **Plant Protection Products authorization** regulates the approval of plant protection products. Approvals are based on the precautionary principle, intended to ensure that products placed on the market are not harmful to human and animal health and the environment, if correctly used (Art. 1 paragraph 4 of the Plant Protection Products Ordinance). Switzerland adopted most parts of the Plant Protection Products Ordinance of the European Union in 1992, including the revisions that have taken place since then. The most relevant pesticide authorization withdrawals for Swiss farmers from 2018 until 2023 are shown in Table 1. Farmers must either replace them with other substances or alternative methods, if available.

2) Since 1999, the Swiss government has introduced environmental **cross-compliance standards (proof of ecological performance, PEP)**, which are mandatory for farmers receiving direct payments (Article 11 of the direct payment regulations[3]). These standards include requirements regarding the selection and application of pesticides, which are stricter than those in the Plant Protection Products Ordinance (Article 18 of the direct payment regulations[4]). In principle, active ingredients with an increased pesticide risk potential for the environment may not be used by farmers cropping under cross-compliance standards. Under the Swiss policy reform introduced since 2023, the use of several pesticides has been restricted (see Annex 1 of the direct payment regulations, Section 6.1.1). This includes five widely used herbicides: S-metolachlor, terbuthylazine, nicosulfuron, metazachlor, and dimethachlor (Table 2). These products must be replaced with less harmful ones, or

[1] In this study, the term pesticide is used as a synonym of plant protection products.

[2] https://www.fedlex.admin.ch/eli/cc/1998/3033_3033_3033/de.

[3] Source: Regulation on direct payments for agriculture from 23rd October 2013 (as of 14th March 2023). https://www.fedlex.admin.ch/eli/cc/2013/765/de#art_11.

[4] Source: Regulation on direct payments for agriculture from 23rd October 2013 (as of 14th March 2023). https://www.fedlex.admin.ch/eli/cc/2013/65/de#art_18.

Table 1
Examples of active substances whose authorization has been withdrawn or suspended[1] in the Plant Protection Products Ordinance in recent years (2018–2023).

	Active substance	Authorization withdrawal or suspension
Fungicide	Chlorothalonil	01.01.2020
	Epoxiconazole	01.11.2021
	Mancozeb	01.01.2022
Herbicide	Chloridazon	01.01.2022
	Desmedipham	01.07.2022
	Haloxyfop	01.07.2022
	Diquat	01.07.2022
	Glufosinate	01.01.2022
Insecticide	Chlorpyrifos	01.07.2020
	Chlorpyrifos-methyl	01.07.2020
	Bifenthrin	01.07.2022
	Zeta-cypermethrin	01.06.2022
	Alpha-cypermethrin	01.07.2023

[1] Authorization for chlorothalonil has been suspended, while authorizations for the other active substances have been withdrawn.
Source: https://www.blv.admin.ch/blv/de/home/zulassung-pflanzenschutzmittel/anwendung-und-vollzug/zurueckgezogene-pflanzenschutzmittel.html.

herbicide-free cropping systems must be adopted. They may still be used if there is no substitute (e.g., S-metolachlor against yellow nutsedge). Furthermore, the use of four pyrethroids has been restricted under policy reform since 2023 (cypermethrin, deltamethrin, etofenprox, and lambda-cyhalothrin). The use of these pyrethroids is approved if special authorization is obtained before treatment. Special authorizations are issued by local authorities in epidemic cases or if there is a mass propagation of pests. They are granted per plot, culture, and pest for the entire duration of the culture in the given year. As far as vegetable production is concerned, the law permits the use of pyrethroids to fight a range of pests without special authorization (Schweizer, 2023).

3) In addition to the pesticide restrictions in the cross-compliance standards, the Swiss government introduced various **voluntary direct payment programs** in the past that compensate farmers for the adoption of partially or totally pesticide-free arable cropping systems. Until 2022, farmers could adopt the so-called Extenso program, which did not allow the application of insecticides, fungicides, and growth regulators, whereas the use of herbicides was permitted (Finger and El Benni, 2013). The eligible crops were cereals, oilseeds, and protein crops. Farmers adopting the Extenso program received a direct payment of 400 CHF/ha. The share of Extenso cropping systems ranged between 25 % of the total rapeseed area and 77 % of the sunflower area (Mack et al., 2023). In 2023, the Federal Council redesigned the direct payment system to enhance pesticide reduction measures on arable land and permanent crops (BLW, 2021). Since 2023, the Extenso program for insecticide-, fungicide-, and growth-regulator-free cropping systems has been expanded to root crops, and payments have partly increased from 400 to 800 CHF/ha (Table A1 in the Appendix). Moreover, the direct payment program for herbicide-free cropping systems on arable land has been further developed, and payments for rapeseed, potatoes, and sugar-beet cropping systems have substantially increased (Mack et al., 2023). Table 3 shows the requirements for receiving direct payments.

2.2. Overview of the SWISSland model

SWISSland allows for both the modeling of heterogeneous farm responses to policy changes and the assessment of the sectoral impacts resulting from these responses. Therefore, the SWISSland model consists of two modules: (1) a single farm module, which consists of approximately 3000 bio-economic farm optimization models, and (2) an upscaling module (Fig. 1). SWISSland predicts economic and structural indicators for the Swiss agricultural sector based on 3077 bio-economic farm optimization models. Individual models are built on economic and structural data from the Swiss Farm Accountancy Data Network (FADN) (see Möhring et al., 2019). The agent population of SWISSland represents the FADN farm sample for Switzerland. This sample covers all farm types, regions (plain, hill, and mountain), and farm size categories of the Swiss farm population (Renner et al., 2019). In total, 1907 farms of the agent population include arable crops. Furthermore, policy scenarios for the upcoming years, which are defined by policymakers from the Swiss Federal Office for Agriculture, are implemented in the bio-economic farm optimization models. SWISSland estimates land use and livestock decisions for each farm using positive mathematical programming (PMP) over a period of 10–15 years (Mack et al., 2019).

Furthermore, SWISSland models the adoption decisions of voluntary direct payment programs, such as programs to reduce pesticides (Mack et al., 2023). It captures the economic dimension of farming activities, assuming a fully informed and profit-maximizing decision maker. Farm records from the FADN database (three-year averages of the years 2016–2019) are used to define the input costs (e.g., seed costs, pesticide costs, fertilizer costs, cleaning and drying costs, hail insurance costs, and other costs), output coefficients (yields and product prices), and production capacities (e.g., land, and labor) of the farm-level optimization models. In particular, crop-specific FADN data for intensive (no restriction of pesticides), Extenso (fungicide- and insecticide-free), and organic cropping systems are used to build the databases of the models. Tables A2 and A3 in the Appendix provide a summary of yields and costs for the intensive and Extenso cropping systems of the 1907 farms. For national-scale predictions, the results of the 3077 single-farm models (all crops) are upscaled to the Swiss agricultural sector consisting of 50,038 farms. A previous study by Mack et al. (2023) described in detail the data basis and the method to model the adoption of voluntary pesticide-free cropping systems with SWISSland and showed the structural and economic impacts of voluntary direct payments for pesticide-free cropping systems at a national scale for Switzerland. In this study, we extend this framework to integrate the assessment of pesticide risk.

Table 2
Active substances restricted for farmers cropping under Swiss cross-compliance standards since 2023.

	Active substance	Restriction
Herbicide	S-Metolachlor Terbuthylazine Nicolsulfuron Metazachlor Dimethachlor	Not allowed, must be replaced with less harmful substance
Insecticide	Cypermethrin Deltamethrin Etofenprox Lambda-cyhalothrin	Allowed only with special authorization[1]

Source: 910.13 Direct payment regulations, Annex 1 (https://www.fedlex.admin.ch/eli/cc/2013/765/de).
[1] There are exceptions for vegetable crops.

3. Methods and data

We developed a method to integrate pesticide use and pesticide-related risk into the SWISSland model. This requires three consecutive steps (Fig. 2):

Table 3
Requirements for receiving direct payments for partially pesticide-free cropping systems.

	(1) Fungicide-, insecticide-, and growth regulator-free cropping systems (Extenso)	(2) Herbicide-free cropping systems
Cereals (wheat, barley)	Insecticide and fungicide applications and growth regulators are not allowed	Herbicide applications are not allowed[1]
Rapeseed		
Sunflower		
Protein crops		
Sugar beets		Only herbicide applications until the 4-leaf stage are allowed
Potatoes	Fungicides are allowed	Herbicide applications are not allowed[1]

[1] Only weed-suppressing plants that cover the soil or mechanical weed control measures with harrows and hoes are permitted. The treatment of individual plants is allowed.
Source: Mack et al. (2023).

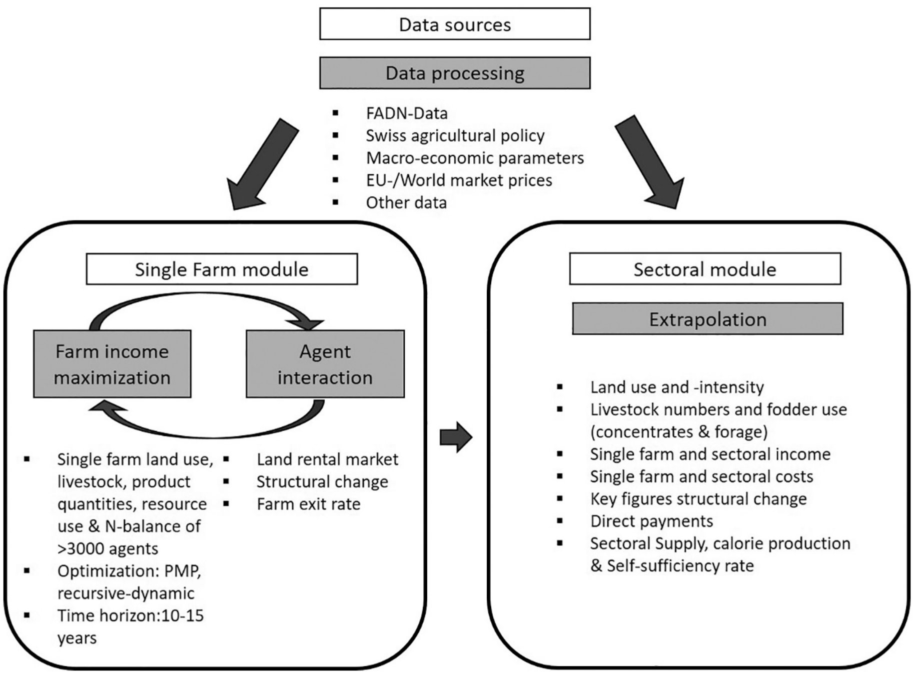


Fig. 1. Overview of the agent-based sector model SWISSland.

1) **Introduction of pesticide-use data in bio-economic farm optimization models**: Therefore, we merged FADN data from 3077 farms with pesticide-use data from approximately 300 farms of the Swiss agro-environmental data network (SAEDN)[5] (Gilgen et al., 2023).
2) **National upscaling of pesticide use, calibration, and uncertainty assessment:** The quantity of active substances applied by the SWISSland total agent population (3077 farms) must be upscaled to the national scale (50,038 farms). To ensure that our forecasts of pesticide quantities were consistent with monitoring data in Switzerland, we calibrated the results of our model on national pesticide sale quantities for 2018. Furthermore, we account for uncertainties surrounding the attribution of pesticide sales from national statistics to the agricultural sector.
3) **Implementation of risk scores**: To project the pesticide risks, we adapted the risk scores from Korkaric et al. (2023) so that they could be used with a simulated pesticide application. Based on these scores, we calculated the pesticide risks for the three compartments: groundwater, surface water, and semi-natural habitats.

[5] The data of the SAEDN is used for agri-environmental monitoring by the Federal Office for Agriculture to support agricultural policy.

3.1. Introduction of pesticide use data in bio-economic farm optimization models

To implement crop-specific pesticide applications for all FADN farms represented in the SWISSland model, we merged the FADN dataset used for the parametrization of individual farms (agents) with the SAEDN dataset, which contains detailed information on crop-specific pesticide use. Therefore, we defined a common key, namely crop-specific pesticide costs per management type. More precisely, in both datasets (FADN and SAEDN), crops are grouped into three different management types: Extenso (without fungicides or insecticides), organic (no chemical pesticides at all), and intensive crops (no restriction on pesticides) (see Mack et al., 2023). Information on crop-specific pesticide costs was taken from the FADN dataset (see summary for FADN data in Table A2 for intensive and Table A3 for Extenso cropping systems in the Appendix) and calculated for the SAEDN dataset by combining pesticide use with pesticide price. A list of pesticide prices was compiled by combining different sources of information, such as a report on farm costs (Schoch and Gascard, 2018) and store price lists available on the internet (www.landi.ch, www.agroline.ch, data from August 2022). The SAEDN data were then classified by management type and crop. To merge the SAEDN with the FADN dataset, we first ordered the SAEDN datasets based on their crop- and management-specific pesticide costs (CHF/ha) into a sequence from the smallest to the biggest value. We

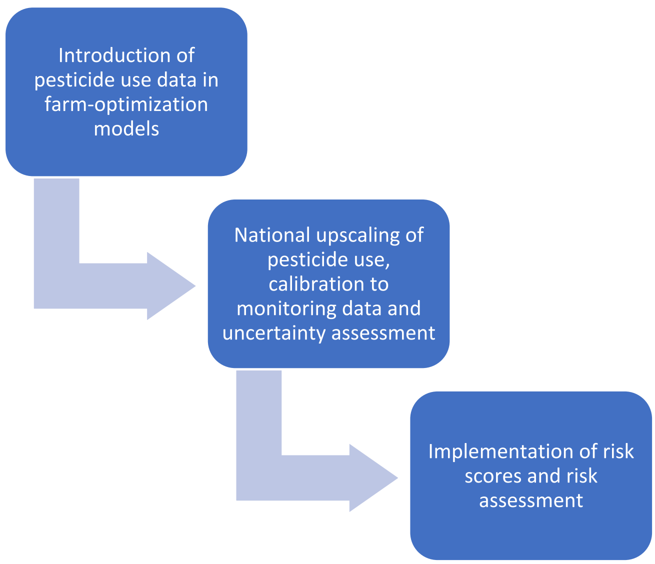


Fig. 2. Schematic view of the method for the projection of pesticide risk based on SWISSland.

then used 33 % and 66 % quantiles to split the costs into three groups: low, intermediate, and high costs (Fig. 3). Further, we applied the same limits to split the FADN farms into 3 groups. This allowed us to assign the pesticide use data of the SAEDN sample to the FADN farm sample using the crop, management type, and cost class criteria as keys. For each FADN farm cultivating a specific crop with a specific management type, we assigned a pesticide application randomly chosen from the corresponding subset in the SAEDN data.

3.2. National upscaling, uncertainties, and simulations of pesticide use in 2018–2022

Crop-specific upscaling factors were used to extrapolate the pesticide use of the 3077 FADN farms simulated in SWISSland to the national scale (Zimmermann et al., 2015). To ensure that our simulations of pesticide quantities were consistent with the monitoring results for Switzerland, we compared the simulated quantities of active substances for 2018 with the annual pesticide sales for Switzerland (BLW, 2023). The difference between simulated and sold quantities can be attributed to two factors. First, pesticide sales include pesticides used outside of the agricultural sector that are not covered by SWISSland, such as in forestry, private gardens, urban infrastructures (e.g., parks, sport facilities, and railway tracks) and ornamental plant nurseries. However, how much of the national pesticide use can be attributed to these uses remains unclear (Lutz et al., 2023). If we assume that the difference is due to the non-agricultural use of pesticides, no correction of the simulated pesticide quantities would be necessary.

The second factor is the representativeness of the SAEDN data for some crops and management. SAEDN data well represent the dominant arable crops in Switzerland, but for certain crops (viticulture and vegetable crops), the representation is marginal (Gilgen et al., 2023). Pesticide use for under-represented crops introduces a bias that can lead to under- or overestimation of certain pesticides. A correction factor allows for adjusting the simulated pesticide use to the quantity sold and correcting this bias.

The relative importance of these two factors (contribution of non-agricultural sector and marginal representativeness of SAEDN data for some crops) depends on the active substance, but the available data do not allow for quantification. Therefore, we run two scenarios that characterize the uncertainty: (1) an uncalibrated scenario in which the difference is fully attributed to the non-agricultural sector (and therefore not corrected), and (2) a calibrated scenario in which we used correction factors to redistribute the whole difference of sold and simulated active substances to crops (see Table 4). The range between these two simulations represented uncertainty.

The correction factor was applied to the seven most widely used active substances in terms of quantity (sulfur, paraffin oil, glyphosate, folpet, metamitron, copper, and mancozeb) and to the nine active substances with the highest environmental risk (lambda-cyhalothrin, cypermethrin, deltamethrin, bifenthrin, chlorpyrifos, chlorpyrifos-methyl, chlorothalonil, and S-metolachlor, terbuthylazine). The correction factor was calculated as the ratio between the sale quantity and the simulated quantity for a given substance in the basis year (2018) and was applied to adjust the upscaled pesticide use for all crops until 2030.

For the simulation of pesticide use between 2019 and 2022, we assumed that crop-specific pesticide use of the farms continued as in the base year (2018) if cultivation and management type (Extenso, organic, intensive) remained the same. Pesticides containing active substances whose authorization was withdrawn or suspended before 2023 (Table 1) were removed from the simulation in the year in which withdrawal or suspension occurred.

3.3. Adaptation of risk scores and projections of pesticide risk with SWISSland

To forecast the development of pesticide risk with SWISSland, we adapted the risk scores of the National Pesticide Risk Indicator (Korkaric et al., 2022; Korkaric et al., 2023) for integration into SWISSland. This indicator was developed to support the Swiss Federal Office of Agriculture (FOAG) in monitoring potential pesticide risks and is based on annual pesticide sale quantities. The risk scores depend on the substance properties (absorption and degradation), which affect their transport and concentration in the environment. Risk scores were developed for three environmental compartments: surface water, semi-natural habitats, and groundwater. For surface waters and semi-natural habitats, the

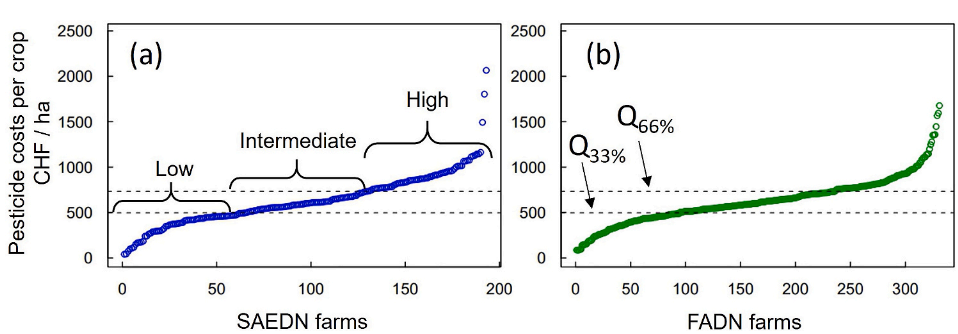
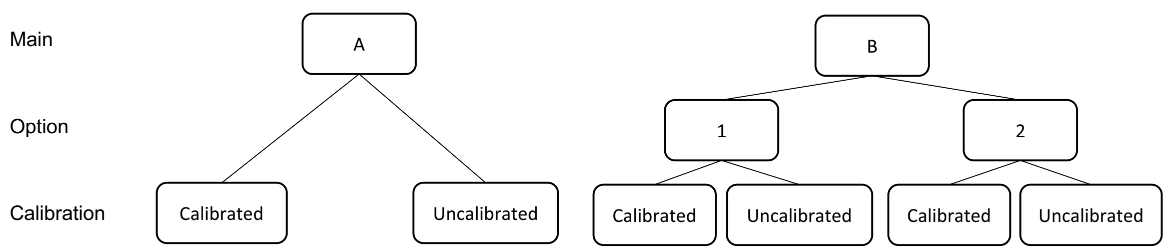


Fig. 3. Illustration of the methodological approach for merging (a) SAEDN farms and (b) FADN farms by crop and management type. Farms in both data sets were sorted in ascendant order of pesticide costs per hectare, and classified in low, intermediate, and high cost classes, using the $Q_{33\%}$ and $Q_{66\%}$ quantiles.

Table 4
Description of the scenarios.

SCENARIOS

Diagram



Description

Main	A	Reference scenario without pesticide-related policy reforms from 2023 onwards
	B	With pesticide-related policy reforms from 2023 onwards
Option	1	No pyrethroid restriction
	2	100% pyrethroid restriction
Calibration	Calibrated	Simulated pesticide use is calibrated on observed sales
	Uncalibrated	Difference between simulated pesticide use and observed sales is attributed to the non-agricultural sector

risk scores account for the toxicity to organisms living in these environments, while in groundwater, risk scores represent potential exposure to pesticide metabolites, and their toxicity was not taken into account. The value of the individual risk scores cannot be compared between compartments.

The original risk scores of the National Pesticide Risk Indicator represent the risk of a single standardized use of an active substance, corresponding to the average application rate in the agricultural sector. In SWISSland, we modeled the risk associated with simulated pesticide applications by crop and farm. Therefore, we divided the risk score from Korkaric et al. (2023) by the standardized application rate and then multiplied by the simulated application rate. Further, an exposure factor was used according to Korkaric et al. (2023). The exposure factor represents the effect of risk mitigation measures, such as product-specific measures to prevent drift and runoff, or more general requirements in the context of cross-compliance standards (e.g., buffer strips, renovation of washing areas). It includes the effectiveness of a measure as well as the extent of its implementation in agriculture. An exposure factor of 1 means that risk mitigation measures have not been implemented or are ineffective. At present, the exposure factor has only been assessed for surface water and takes into account several routes of pesticide entry: point sources, runoff, shortcuts, drainage, and drift. For surface water, the exposure factor was available from 2018 to 2021, and from 2022 onward, we assumed a constant value until the end of the simulation.

In SWISSland, the pesticide risk is calculated by multiplying the (adapted) risk score by the simulated crop area and, for surface water, by the exposure factor (Eq. 1). The product is summed across all active substances and all simulated applications i to obtain the projected pesticide risk (Eq. 1).

$$\textit{Projected Pesticide Risk} = \sum_i \textit{Simulated crop area}_i \times \textit{Risk Score}_i \times \textit{Exposure factor}_i \qquad (1)$$

Risk scores, average application rate, and exposure factors are available here: https://www.blw.admin.ch/blw/de/home/nachhaltige-produktion/pflanzenschutz/risikoindikatoren_pflanzenschutzmittel.html.

3.4. Policy scenarios and uncertainty

We further carried out an impact assessment to analyze whether policy reforms focusing on pesticides since 2023 can reduce the national pesticide risk until 2030 in Switzerland. Previous results showed that to establish large-scale production systems between conventional and organic cropping systems and, thereby, reduce trade-offs resulting from both extremes, policy schemes need to be flexible, allowing the adoption of a pesticide-free paradigm for some parts of crop rotation but not necessarily entire crop rotations (Mack et al., 2023). The reduction in food (volume) and calorie production following the adoption of pesticide-free cropping systems has been assessed by experts for several arable crops (wheat, barley, rapeseed, sunflower, protein crops, potatoes and sugar beets), but the impact on production value is minimal, especially due to expected higher prices for pesticide-free products (Mack et al., 2023). Effects on farmers' income are small, as participation in pesticide-free production is compensated with direct payments and higher prices and often implies cost reduction in labor and machinery due to non-use of pesticides (Mack et al., 2023).

To assess the impact of policy reforms on pesticide risks, we defined two main scenarios (Table 4). Reference scenario A represents the counterfactual scenario when no pesticide-related policy reforms (neither changes in cross-compliance standards nor changes in the direct payment program) would have been introduced in 2023. Scenario B considers pesticide restrictions under cross-compliance and the redesign of the direct payment program for reducing pesticides since 2023. In scenario B, all non-authorized herbicides are replaced by less harmful products (assumptions on the replaced herbicides are shown in Appendix Table A4). For pyrethroids, by contrast, we considered two options: (B1) there is no restriction on pyrethroids because special authorizations for pyrethoids are granted and pyrethroid consumption does not fall, and (B2) 100 % pyrethroid restrictions from 2023 onwards.

For each scenario, we considered the range of uncertainty derived from (a) the lack of information regarding the contribution of the non-agricultural sector and (b) the marginal representativeness of SAEDN data for some crops (see Section Section 3.2). These two uncertainty factors correspond to (a) the uncalibrated simulation and (b) the calibrated simulation, in which correction factors are used to adjust the simulated pesticide quantities with regard to sale quantities.

The projections of pesticide use by the agents of the SWISSland model (the FADN-farm population) for different policy scenarios until 2030 consider land use changes and the adoption of voluntary pesticide reduction schemes simulated by SWISSland (Fig. A1 in the Appendix shows the adoption results).

In the scenarios, we assumed that crop-specific pesticide use of the farm models continued as in the base year (2018) if cultivation and management type (Extenso, organic, intensive) remained the same. However, if the farm changed to a new management type in the forecasting period, such as pesticide-free but not organic or herbicide-free, we adapted the pesticide use to the new management type. For example, if, for a given crop, the farm switches to pesticide-free management, pesticide use is reduced to zero for that farm and crop.

If the farm switches to a crop and management that does not exist in the SAEDN data because it is a new program (e.g., herbicide-free management for bread cereals, fodder cereals, sugar beet, or rapeseed), we adjust the pesticide application by removing the appropriate pesticide category (e.g., herbicides for herbicide-free management).

4. Results

4.1. Comparison between simulated pesticide quantities and sale quantities for 2018

We compared the simulated quantities of active substances upscaled to the Swiss agricultural sector for 2018 with the annual pesticide sales for Switzerland in the same year (BLW, 2023). In 2018, pesticide sales were just over 2050 metric tons of active substances, whereas the SWISSland model simulated pesticide use of 1650 metric tons (Fig. 4). The results show that sulfur use is largely underestimated by the model. Sulfur is used as an insecticide and fungicide on several crops, in both conventional and organic farming, and has a low risk score for surface water and a medium risk score in semi-natural habitats.

The difference between simulated and sold quantities can be attributed to two uncertainty factors: (1) the amount of pesticide sales that are used outside of the agricultural sector and (2) the limited representativeness of the SAEDN data for some crops and management. To explicitly represent the effect of this uncertainty on risk projections, we run two simulations for each scenario, one in which simulated pesticides in 2018 are calibrated to observed sales, and an uncalibrated one in which the difference is attributed to the non-agricultural sector (see Table 4).

4.2. SWISSland projection of total pesticide risk

To determine whether policy reforms are effectively reducing pesticide risks, and whether the risk reduction target can be achieved by 2030, we project total pesticide risk between 2018 and 2030 (Fig. 5) compared to the 50 % reduction target. In the uncalibrated simulation (blue line in Fig. 5), the difference between simulated pesticide use and observed pesticide sales in 2018 is attributed to the non-agricultural sector. Therefore, to project the total risk, we included the contribution of the non-agricultural sector. The pesticide risk of the non-agricultural sector was calculated as the difference between pesticide sales and simulated pesticide use in 2018, and it was added as a constant value in subsequent years.

For surface waters, between 2018 and 2022, the projections of the pesticide risk for the calibrated simulation showed an 18 % reduction, while the decrease in the uncalibrated simulation was barely 4 %. However, when we considered only the agricultural sector, we obtained a very similar risk reduction in both simulations (18 %). In both cases, risk mitigation measures played an important role in reducing the risk potential. When mitigation measures were neglected (exposure factor was set at 1), the risk potential hardly changed between 2018 and 2022 (Fig. A2).

In surface waters, pesticide risk potential was stable or slightly increasing in reference scenario A and overall stable in scenario B1 with policy reform and no pyrethroid restriction. The effect of herbicide restrictions was small because in surface water, the major contribution to the pesticide risk comes from pyrethroids (Korkaric et al., 2023). In scenario B2 with 100 % pyrethroid restriction, the pesticide risk potential for surface water showed a high degree of uncertainty. This was due to the lack of fully representative data on the use of pyrethroids in agriculture. Indeed, the simulation of pesticide use is based on SAEDN data, which have limited representativeness for some crops and management (see Section 3.2), and therefore introduce uncertainty into the model. For pyrethroids, which have high risk scores, particularly in surface waters, this leads to a high degree of uncertainty in the risk potential. To reduce the uncertainty, we would need more data on pyrethroid use. In the uncalibrated simulation, scenario B2 led to a small reduction in pesticide risk, as a significant proportion of pyrethroids is attributed to the non-agricultural sector, which is not affected by the new agricultural policy programs. However, in the calibrated simulation, scenario B2 was likely to overestimate the effect of the pyrethroid restriction on the projected pesticide risk.

In semi-natural habitats, between 2018 and 2022, the model projected a decrease in risk potential between 15 % (calibrated) and 12 % (uncalibrated). The decrease occurred mainly in 2021 and was due to

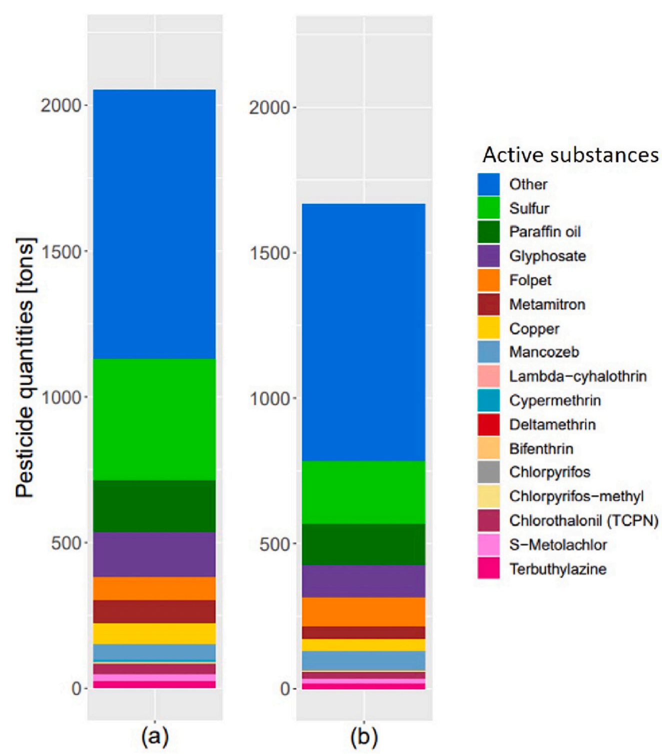


Fig. 4. (a) Sale quantities and (b) with SWISSland simulated quantities of active substances for 2018. The color scale highlights the seven most widely used active substances in terms of quantity (sulfur, paraffin oil, glyphosate, folpet, metamitron, copper, and mancozeb) and the nine active substances with the highest environmental risk (lambda-cyhalothrin, cypermethrin, deltamethrin, bifenthrin, chlorpyrifos, chlorpyrifos-methyl, chlorothalonil, and S-metolachlor, terbuthylazine).

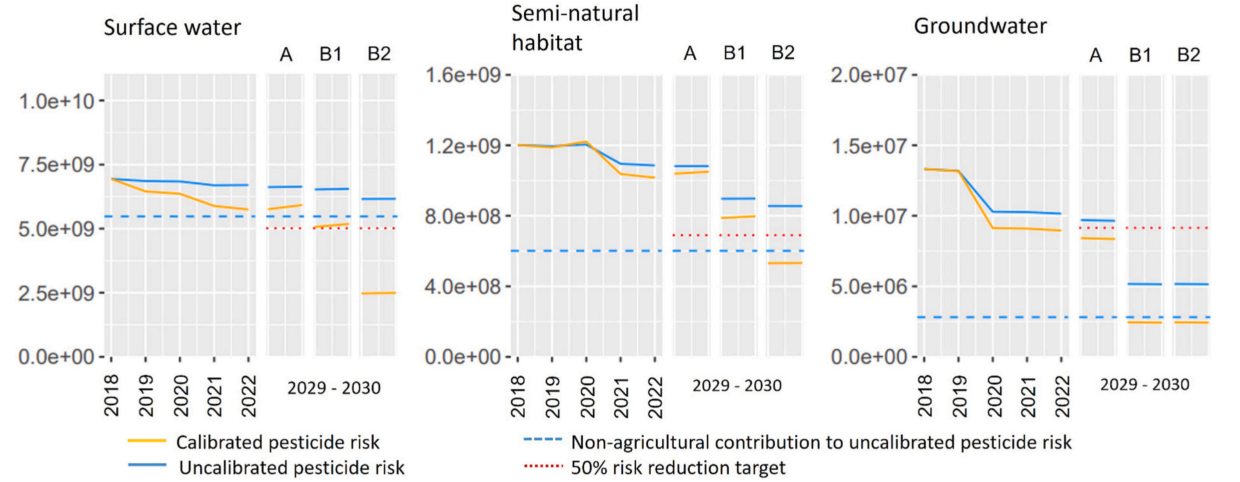


Fig. 5. SWISSland projections of pesticide risk potential in surface water, semi-natural habitats and groundwater for the years 2018–2022 and 2029–2030, considering the reference scenario A without policy reforms, scenario B1 with policy reform and no pyrethroid restrictions and scenario B2 with policy reform and 100 % pyrethroid restrictions. The orange and blue lines represent the development of the risk for the calibrated and uncalibrated simulations, respectively. The dashed blue line shows the non-agricultural contribution of the uncalibrated simulation. The red dotted line represents the 50 % risk reduction target that should be achieved in 2027, based on sale data (from Korkaric et al., 2023).

the authorization withdrawal of chlorpyrifos and chlorpyrifos-methyl in the Plant Protection Products Ordinance. Compared to reference scenario A, the policy reforms for pesticide reduction had a significant effect on risk potential. In scenario B1, the decrease was mainly due to the large adoption of pesticide-free schemes in bread cereals, fodder cereals, rapeseed, sunflower, and pulses. Similar to surface water, pyrethroid restriction played an important role in the development of the projected pesticide risk, especially for the calibrated simulation.

The simulated pesticide risk in groundwater showed a significant decrease between 2018 and 2022, due to the suspension of the chlorothalonil authorization in 2020 in the Plant Protection Products Ordinance. After 2023, we observed an important decline in risk, partly due to the herbicide restrictions (Table 3) under cross-compliance, which mandates substituting with herbicides with lower risk scores, and partly due to participation in voluntary programs for pesticide- or herbicide-free management (bread cereals, fodder cereals, rapeseed, sunflower, and pulses). Since groundwater risk is not affected by pyrethroids, scenarios B1 and B2 are equivalent.

4.3. SWISSland projection of pesticide risk for different pesticide classes

We analyzed how the different classes of pesticides (insecticides, fungicides, and herbicides) contribute to the projected risk potential in the three environmental compartments, and how the policy reforms affected risk reduction (Fig. 6). In contrast to the previous section, here, we focused only on the agricultural sector.

Insecticides were the main contributors to risk potential in surface waters and were an important contributor in semi-natural habitats. In these compartments, insecticide-related risk potentials also showed a large difference between the calibrated and uncalibrated simulations. This highlights the considerable uncertainty in risk assessment for this pesticide class. Furthermore, in surface water and semi-natural habitats, scenarios B1 and B2 led to very different projections, showing the importance of pyrethroid restriction. Groundwater shows a lower level of uncertainty regarding insecticide-related risk, and we observed a significant difference between the scenarios that included a policy program to reduce pesticides (B1 and B2) and the reference scenario without policy reforms (A).

Fungicides were important contributors to pesticide risk potential in groundwater. Between 2018 and 2022, several fungicides, such as chlorotalonil (2020), epoxinazole (2021), and mancozeb (2022), were withdrawn (or suspended) by the Plant Protection Ordinance. In groundwater, the suspension of chlorothalonil authorization led to a major reduction of the simulated fungicide risk in 2020. In surface water, the simulation showed a significant decrease in the projected fungicides-related risk until 2022.

Herbicides were the main contributors to the risks in groundwater and important contributors in semi-natural habitats. The restrictions on herbicides in the cross-compliance standards from 2023 were very effective in reducing risk. The scenarios that included the policy reforms (B1 and B2) had a significantly lower pesticide risk than the reference scenario A: groundwater showed the most pronounced decrease in pesticide risk, while surface water showed the least reduction.

4.4. SWISSland projection of pesticide risk for arable crops

To assess and compare the effectiveness of different policy instruments (pesticide withdrawal under the Plant Protection Ordinance, restriction under environmental cross-compliance standards, and voluntary agri-environmental programs) in reducing pesticide risk, we analyzed in greater detail the evolution of the projected risk in various arable crops (Fig. 7). The analysis focused on bread cereals, fodder cereals, sugar beet, rapeseed, and potato.

Bread and fodder cereals showed similar patterns. For these crops, the suspension of chlorothalonil authorization in 2020 caused a significant decline in the potential pesticide risk in the surface water and groundwater. For semi-natural habitats, pesticide withdrawal before 2023 did not affect the simulated risk, but high participation in voluntary pesticide-free programs from 2023 (scenarios B1 and B2) had a major effect on risk reduction.

The cultivation of sugar beet and rapeseed was characterized by the extensive use of pyrethroids, which, as we observed, introduced considerable uncertainty in model simulations. Therefore, we observed a large uncertainty in the projection of pesticide risk in surface water and semi-natural habitats of these crops, as well as a significant difference between scenarios B1 and B2 in those compartments. Despite uncertainty, sugar beet and rapeseed also showed the highest contribution to the simulated risk in surface water and semi-natural habitats, among arable crops. By contrast, the risk in groundwater showed a lower uncertainty and a major impact of the policy reforms on risk reduction. In fact, according to SWISSland's simulations, a significant number of rapeseed growers participated in pesticide- or herbicide-free programs

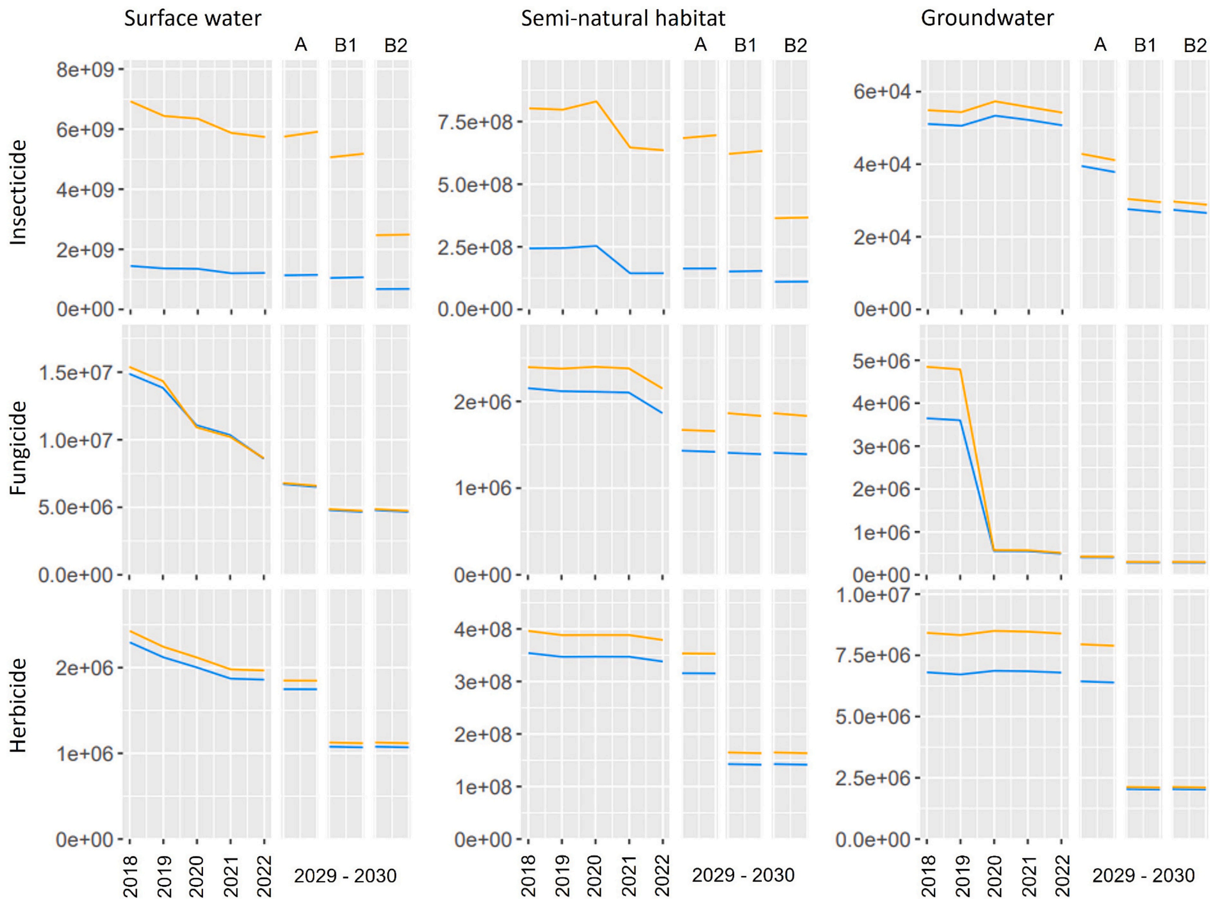


Fig. 6. SWISSland projection of pesticide risk evolution of insecticide/acaricide, fungicide and herbicide in surface water, semi-natural habitat, and groundwater, for the years 2018–2022 and 2029–2030, considering the reference scenario A without policy reforms, scenario B1 with policy reform but no pyrethroid restriction, and scenario B2 with policy reform and 100 % pyrethroid restriction. The orange and blue lines represent the development of the risk potential for the calibrated and uncalibrated simulations, respectively, considering only the agricultural sector.

(Fig. A1).

For sugar beet, the risk reduction in groundwater was linked to the herbicide restrictions (particularly S-metolachlor) under the PEP from 2023 and the replacement with herbicides with lower risk scores. For potatoes, the projected pesticide risk showed a major decline in 2021 in surface water and semi-natural habitats due to chlorpyrifos withdrawal. Groundwater also showed an important risk decrease in 2020, due to suspension of the chlorothalonil authorization.

5. Discussion

According to SWISSland projections, the new agro-environmental policy has an overall positive effect on reducing pesticide-related risks. In semi-natural habitats, a significant reduction in risk is projected after 2023 due to the large adoption of pesticide-free schemes in bread cereals, fodder cereals, rapeseeds, sunflowers, and pulses. Similarly, for groundwater, the herbicide restrictions and participation in voluntary herbicide-free programs from 2023 onward have a very marked effect on reducing pesticide-related risks. In surface water, the model projects a positive effect on the fungicide- and herbicide-related risk potential, but the effect on insecticide-related risk has high uncertainty. The projections for 2030 show that the target of a 50 % reduction compared with the average risk in the reference period (2012–2015) is reached in groundwater, while in surface waters and semi-natural habitats, achievement of the target depends on the reduction of the use of pyrethroids. In all compartments, the pesticides withdrawn prior to the policy reforms of 2023 contribute to at least half of the reduction in the risk potential and are the main drivers of pesticide risk reduction.

Certain model assumptions may lead to an overestimation of the positive effects of the agro-environmental policies. For example, risk projections are based on SWISSland modeling results (Mack et al., 2023), which forecast a large adoption of the pesticide reduction program, based on the assumption that farmers are purely profit maximizers. However, SWISSland simulation might overestimate adoption, since behavioral factors that are not included in the model might slow down the decision to adopt more sustainable farming practices (Dessart et al., 2019). Moreover, SWISSland's projections of risk react very quickly to a change in pesticide use, but measurements in the groundwater will only show the effect of reduced inputs much later, because groundwater generally has a long renewal time.

To assess the model performance, we compared the projected pesticide risk obtained with SWISSland for the year 2018 with the results of the National Pesticide Risk Indicators (based on sales volumes) as reported by Korkaric et al. (2023). As the sales quantities for 2018 have been used to calibrate the SWISSland model, sale-based risk indicators are equivalent to the simulated risk for that year. In the following years, modeled risks closely follow the indicator calculated with sale data, although there are deviations due to external conditions (e.g., weather influencing pest emergence) that affect sales but are not represented in the SWISSland model. However, the sales-based National Pesticide Risk Indicator shows a significant decrease in risk related to herbicides in all environmental compartments between 2018 and 2022 (Korkaric et al.,

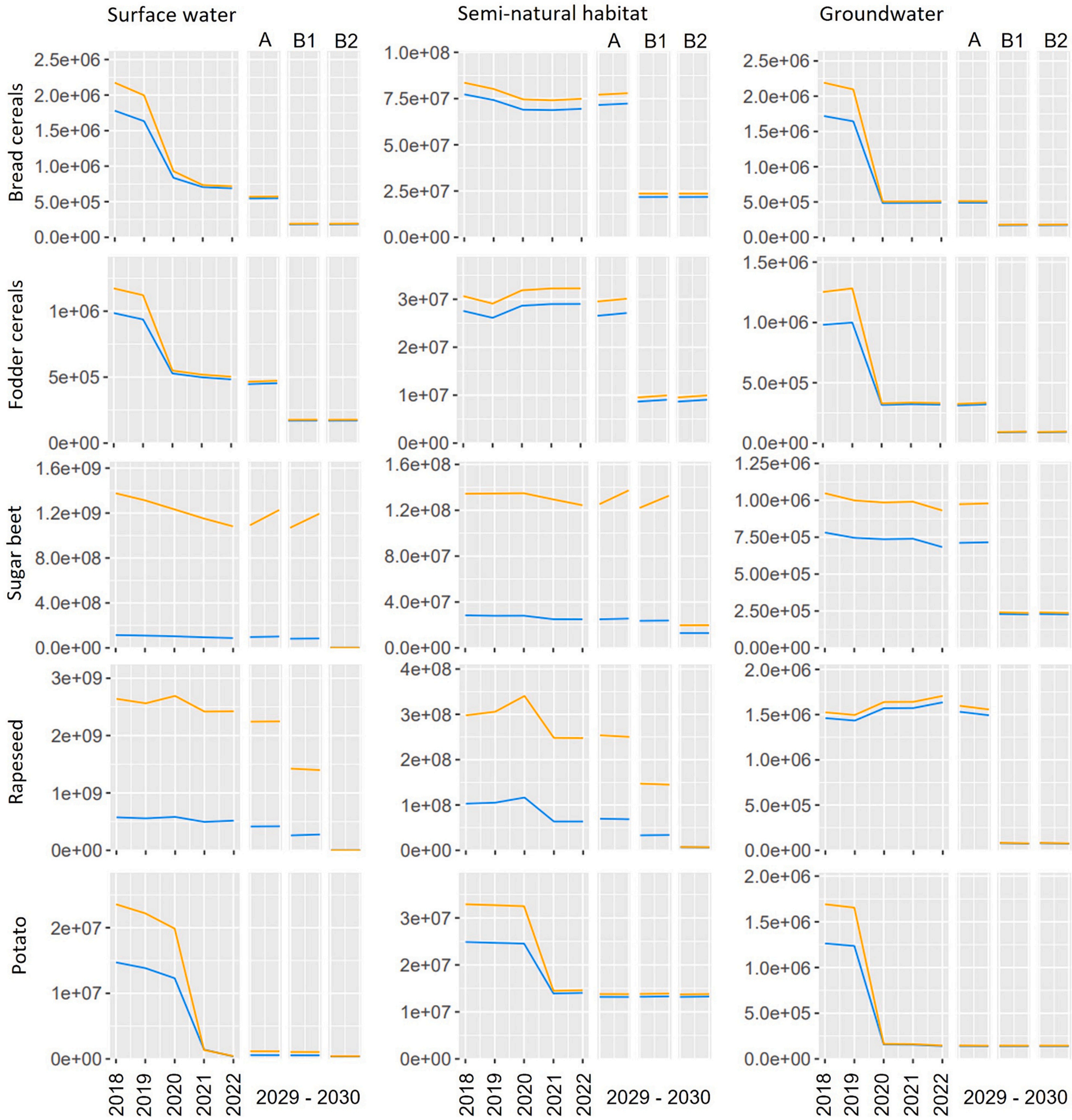


Fig. 7. SWISSland projection of pesticide risk evolution related to arable crop production (bread and fodder cereals, sugar beet, rapeseed, and potato) in the surface water, semi-natural habitat, and groundwater, for the years 2018–2022 and 2029–2030, considering the reference scenario A without policy reforms, scenario B1 with policy reform but no pyrethroid restriction, and scenario B2 with policy reform and 100 % pyrethroid restriction.

2023), while this decrease is not observed in the SWISSland results for semi-natural habitats and groundwater. The decrease in herbicide-related risks could be due to a reduction in herbicide use in favor of alternative weed control methods. In fact, direct payments have been implemented for not using herbicides on vines, fruit, and sugar beet since 2018 and on open arable lands since 2019. However, these measures were not included in the model. Therefore, it is likely that the observed decrease in herbicide-related risk is directly linked to these policy measures.

This study also highlights the importance of the availability and accuracy of data on pesticide use in agriculture to improve the prediction of the impact of agricultural policies targeting the reduction of pesticide use. The lack of data leads to uncertainty in projections, especially if pesticides have high-risk scores, such as pyrethroids. Risk projections for crops on which these pesticides are commonly used (sugar beet, rapeseed, vegetables) show significant uncertainty. In this study, pesticide use was derived from SAEDN data, which is currently the best database for this purpose. These data represent Switzerland's dominant agro-ecosystems well but are marginally representative of small farms and certain crops (viticulture, vegetables) (Gilgen et al., 2023). The FOAG will launch a new agro-environmental monitoring data collection program in 2026 called "digiFlux." All Swiss farms, as well as operators of infrastructure and green spaces, will be required to provide data on their use of plant protection products and fertilizers.

These data will provide an accurate picture of the quantity of pesticides used in agriculture and quantify their use in the non-agricultural sector.

6. Conclusion

The results of this study allow us to highlight the contribution of each of the three pillars of pesticide policies to reducing pesticide-related risks. The first pillar (Plant Protection Products authorization), which regulates the approval of active substances for the market and the withdrawal of the most harmful substances, has an important effect on reducing risk. The results show a major impact of the authorization suspension of chlorothalonil in groundwater and a significant contribution of the withdrawal of chlorpyrifos and chlorpyrifos-methyl to the risk decrease in semi-natural habitats. The second pillar, which restricts the use of certain herbicides and insecticides under the cross-compliance standards since 2023, also has an important effect on reducing pesticide-related risk. Restrictions on herbicide use are effective in reducing environmental risks, especially in groundwater. In addition, the restrictions on pyrethroids could have a significant impact on reducing risks to surface waters and semi-natural habitats, provided there are alternative plant protection measures available for that their use is considerably reduced compared with the current situation. The third pillar, which proposes voluntary agri-environmental schemes that compensate farmers for adopting partially or totally pesticide-free cropping systems, has a considerable effect on reducing the contribution to pesticide risk of some crops (mainly bread cereals, fodder cereals, and rapeseed), for which significant adoption is expected. However, according to the results presented here, these programs contribute relatively little to overall risk reduction, as the use of substances with a high risk potential is already restricted by cross-compliance standards.

In this study, we focused on the risk associated with arable crops, but in the future, research should look at the contribution of other crops, such as vegetables and fruit. These crops use a high level of pesticides, but at this stage, the data availability regarding pesticide use on vegetables and fruit is not sufficiently representative of this production sector; therefore, simulations regarding these crops are characterized by uncertainty and do not allow us to carry out a more detailed analysis.

In conclusion, the findings of this study highlight the need to build comprehensive datasets on pesticide use in Switzerland. This will allow us to better understand how different types of farms apply pesticides, improve the calibration of the model, reduce uncertainty, and clearly distinguish between the contribution of the agricultural and non-agricultural sectors. These efforts can help improve the reliability of models for the evaluation of policies aimed at reducing pesticide risk and improving the efficiency of pesticide policies. The new agri-environmental monitoring data collection program should fill these gaps and improve forecasting capacity.

CRediT authorship contribution statement

Sibylle Dueri: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Gabriele Mack:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.172436.

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