Modelling policies towards pesticide-free agricultural production systems

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Modelling policies towards pesticide-free agricultural production systems

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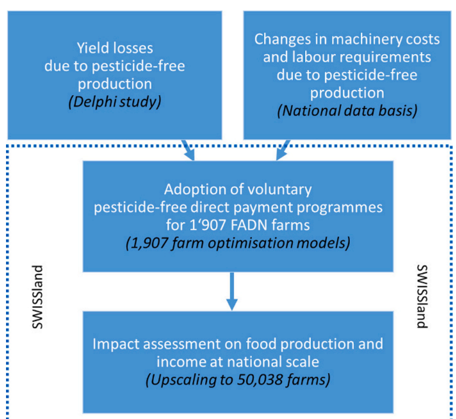
HIGHLIGHTS

- We model the transition to pesticide-free production using a mixed.method approach.
- Especially yield losses determine whether pesticide-free cropping systems are adopted.
- Widespread voluntary adoption of pesticide-free systems is possible only if farmers are compensated for yield losses
- Flexible, voluntary pesticide-free policy and incentive programmes reduce trade-offs in food production.
- Swiss policy programs will likely trigger large-scale adoption of pesticide-free but non-organic production systems

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: The use of pesticides implies negative effects on human health and the environment. Thus, the reduction in pesticide risks without harming food security and farmers' income is a key policy goal.
OBJECTIVE: The aim is to investigate the implications of policies that explicitly foster the large-scale adoption of pesticide-free, non-organic production systems at the national scale using Swiss crop production as an illustrative example.
METHODS: We develop a bio-economic modelling approach that combines agent-based modelling, a Delphi study to assess yield implications and a detailed representation of labour and machinery implications of pesticide-free, non-organic production. Using an agent-based modelling framework allows the consideration of heterogeneous farm-specific adaptation responses to voluntary direct payments for crop-specific conversion to pesticide-free but non-organic production systems. The modelling framework is used to assess the effects of changing pesticide policies on farm and sector levels and its implications for (crop-specific) food production in terms of area, volume, value and income. Our approach is illustrated using Switzerland as an example, where voluntary direct payments for a crop-specific conversion to pesticide-free but non-organic production systems will be implemented.

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RESULTS AND CONCLUSIONS: The results show that the extent of crop-specific yield losses has an especially significant effect on the adoption rate of pesticide-free cropping systems. The impacts of introducing voluntary direct payments for pesticide-free production at the national scale imply reduced food (volume) and calorie production but only minimal reductions in the production value, especially due to expected higher prices for pesticide-free products. The 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 labour and machinery due to non-use of pesticides. 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 the crop rotation but not necessarily entire crop rotations.

SIGNIFICANCE: This is the first national-scale study on the implications of adopting a pesticide-free, non-organic crop production system by using Swiss crop production as an illustrative example.

1. Introduction

Pest management is key to ensuring the provision of affordable and safe food (Cooper and Dobson, 2007; Möhring et al., 2019; Savary et al., 2019). However, the use of pesticides implies negative effects on human health and the environment (Malaj et al., 2014; De Souza et al., 2020; Meena et al., 2020; Gill et al., 2012; Rani et al., 2021; Tang et al., 2021). Thus, the reduction in pesticide risks without harming food security and farmers' income is a key policy goal. For example, the 'Farm-To-Fork Strategy' of the European Union aims for a 50% reduction in pesticide use and risks by 2030 (European commission, 2020; Schebesta and Candel, 2020). Switzerland aims to reduce pesticide risks by 50% until 2027 compared to the average of the years 2012–2015 (BLW (Bundesamt für Landwirtschaft), 2021). There are also ongoing debates on banning ubiquitous pesticides, such as glyphosate, in Europe (Kudsk and Mathiassen, 2020). Recent research and policy debates go even further. For example, in 2021, the people of Switzerland voted on a popular initiative that intended to ban all chemical synthetic pesticides (Huber and Finger, 2019; Schmidt et al., 2019). The initiative was rejected, but the political and societal debate led to significant changes in governmental and industry policies (Finger, 2021). Jacquet et al. (2022) argued that agricultural research must adopt a pesticide-free (but non-organic) paradigm to considerably reduce pesticide use and related risks. However, we currently lack methodological approaches and empirical examples to quantify the trade-offs, especially on food production of large-scale transitions into pesticide-free production systems. In the context of more frequent global food shortages, policy measures towards pesticide-free production are increasingly under political debate because they can lead to a reduction in the national food self-sufficiency rate.

This is the first national-scale study on the implications of policies that explicitly foster the large-scale adoption of pesticide-free, non-organic production systems, using Swiss crop production as an illustrative example. We develop a bio-economic modelling approach that combines agent-based modelling, a Delphi study to assess yield implications and a detailed representation of labour and machinery implications of pesticide-free, non-organic production. Using an agent-based modelling framework allows the consideration of heterogeneous farm-specific adaptation responses to voluntary direct payments for crop-specific conversion to pesticide-free but non-organic production systems. This modelling framework is used to assess the effects of changing pesticide policies on farm and sector levels and its implications for (crop-specific) food production in terms of area, volume, value and income.

We build upon a rich literature on the effects of reduced pesticide use on crop yield, farm income and other outcomes. Most previous research has focused on the effects of partial reductions in pesticide use. For example, a study in France showed that 30% reduction in pesticide use could be achieved without reducing farmers' income (Jacquet et al., 2011). Lechenet et al. (2017) estimated that, in France, the total pesticide use could be reduced by 42% without any negative effects on both productivity and profitability in 59% of the farms. Hossard et al. (2014) estimated that yield losses in France resulting from a 50% reduction in pesticide use ranged from 5% to 13% of the yield obtained with the current pesticide use. Other studies have focused on the implications of not using a specific pesticide. For example, the effect of a glyphosate or neonicotinoid ban has been extensively investigated (e.g. Böcker et al., 2019; Böcker et al., 2020; Jacquet et al., 2021; Scott and Bilsborrow, 2019). Similarly, the effects of adopting organic production methods have been widely documented (e.g. Seufert and Ramankutty, 2017; Meemken and Qaim, 2018; Muller et al., 2017). Even though the first partly pesticide-free but non-organic production systems are emerging in Europe (Möhring and Finger, 2022), the implications of large-scale transitions into pesticide-free (but non-organic) production systems are not yet documented (Jacquet et al., 2022). Pesticide-free production methods differ from organic production methods because there are fewer field- and farm-level constraints. For example, artificial fertilizers can still be used. In addition, partially pesticide-free production systems are possible; that is, only some parts of crop rotations can be voluntarily transitioned to pesticide-free production. Moreover, implications for production, production risks and labelling, marketing channels and price markups are still highly uncertain. In contrast to other production systems (e.g. organic) there are no real-world data and experiences so far for the impacts of pesticide-free production systems. Thus, pesticide-free production systems are expected to have diverse agronomic and economic implications. Along these lines, methods to assess the effects of potential policies supporting pesticide-free production are not yet available.

This paper contributes to filling this literature gap by providing the first national-scale study on the implications of adopting a pesticide-free, non-organic crop production system by using Swiss crop production as an illustrative example. We focus on voluntary pesticide-free production of seven major crops (i.e. wheat, barley, rapeseed, sunflower, protein crops, potatoes and sugar-beets). To address the key issues arising from pesticide-free production, we apply a multi-method approach that combines various data sources. First, we estimate the yield effects of pesticide-free but non-organic production by conducting a Delphi study among nationally recognised experts from advisory services, research and administration. Second, based on national data repositories, we build a database on crop-specific changes in labour and machinery use resulting from the adoption of pesticide-free production systems. Third, we integrate this knowledge with a bio-economic agent-based modelling approach. This approach allows us to disentangle farmers' expected adjustments to policies that incentivise the adoption of pesticide-free production systems in two dimensions: i) at the intensive margin (e.g. input use adjustments within a specific crop) and ii) extensive margin (e.g. changes in crop choices and land use) (see Möhring et al., 2020). In particular, we consider the introduction of direct payment schemes, where farmers can voluntarily adopt crop-specific pesticide-free production practices. Combining all these approaches allows us to quantify implications for crop production areas, volumes, values and incomes. Using an agent-based bio-economic modelling approach that is representative of Swiss agriculture at large allows us to document the total effects on agricultural supply and income at the sectoral level, whereas market responses due to changes in supply were not considered. Furthermore, it helps demonstrate the crop- and farm-specific heterogeneity of a voluntary pesticide-free production programme depending on farm endowments and structures as well as capturing feedback effects.

Bio-economic farm models, in combination with an agent-based approach, are a powerful tool for an ex-ante assessment of policy changes. We use the agent-based agricultural sector model SWISSland which has been widely applied to analyse the impact of policy changes on the adoption decisions of voluntary direct payment programmes, such as the grassland-based milk and meat programme (Mack and Huber, 2017) or farmers' responses to changes in cross-compliance standards (Schmidt et al., 2019).

The remainder of this paper is structured as follows. Section 2 presents the currently existing cropping systems and direct payment programmes of Switzerland. Section 3 provides information on the data and methods used, including a description of the Delphi study, the agent-based model, the generation of the machinery and labour cost database and the scenarios considered in the agent-based bio-economic modelling approach. Section 4 presents crop-specific results and income effects at the farm and national level. Section 5 provides a discussion on the results and section 6 concludes this study.

2. Policy background: Public support for different arable cropping systems in Switzerland

Currently, three main cropping systems exist on arable land in Switzerland which are supported by direct payments: 1) intensive (OLN), 2) extenso (insecticide- and fungicide-free) and 3) organic. These three systems are detailed as follows.

Intensive (OLN) cropping systems have to meet the Swiss cross-compliance standards (Proof of Ecological Performance = OLN), which are mandatory for farmers to receive any direct payments. These standards include biodiversity measures, wide crop rotations and buffer strips. Moreover, farmers have to restrict pesticide use to products released in the Swiss Plant Protection Products ordinance and must adopt integrated pest management practices. However, all types of pesticides (e.g. herbicides, fungicides and insecticides) are allowed to be used.

Extenso cropping systems meet not only cross-compliance standards but also the requirements of the voluntary extenso programme (Finger and El Benni, 2013). This agri-environmental programme does not allow the application of insecticides, fungicides and growth regulators. However, the use of herbicides is permitted. The eligible crops are cereals (e.g. wheat and barley), oilseeds (e.g. rapeseed and sunflower) and protein crops (e.g. field peas and horse beans). Farmers adopting the extenso programme currently receive a direct payment of 400 CHF/ha. The share of extenso cropping systems ranges between 25% of the total rapeseed area and 77% of the sunflower area. Farmers are eligible to the extenso payments also if only parts of the arable area are cultivated under extenso.

Organic cropping systems meet much stricter standards of organic production, including a ban on all synthetic pesticides and mineral fertilizers; that is, organic production uses only non-synthetic pesticides and organic fertilizers. Therefore, the federal government provides a direct payment of 1200 CHF/ha for arable crops. For farmers to receive direct payments under the Swiss Organic Farming Ordinance, the entire farm must be managed organically; that is, the regulations for organic farming apply to the entire farm and not just to specific crops. The share of organic arable cropping systems is relatively low and ranges between 2% of the total rapeseed area and 35% of the protein crops in Switzerland.

Despite the manifold governmental support to restrict pesticides in the past, the environmental goals regarding biodiversity, water, air and soil quality set by the Swiss government in 2008 were not achieved: 36% of animal, plant and fungi species are still endangered, and pesticide

Table 1
Proposed direct payments (CHF/ha) for pesticide-free cropping systems on arable land from 2023 onward.

	(1) Fungicide- & insecticide- & growth regulator-free cropping systems (extenso)	(2) Herbicide-free cropping systems	Pesticide-free cropping systems (as combination of (1) and (2))
Crop type			
Cereals (wheat, barley)	400	250	650
Rapeseed	800	600	1400
Sunflower	400	250	650
Protein crops	400	250	650
Sugar-beets	800	600	1400
Potatoes	800	600	1400

Source: BLW (2021).

concentrations are above the established limits, especially in small water bodies (Munz et al., 2012; BAFU and BLW, 2016; Doppler et al., 2017; Spycher et al., 2018). This led to a growing number of plebiscites requesting a stricter pesticide policy (Huber and Finger, 2019). In 2018, two popular federal initiatives were launched to limit pesticide use in Swiss agriculture (Drinking Water Initiative, Federal Chancellery, 2018) or to ban it completely (Pesticide Initiative, Federal Council, 2021). Although the Swiss population rejected both initiatives, they gave a new impetus to the Swiss government to reduce pesticide risks (Finger, 2021). For example, in 2022, the 'Reduction paths for pesticide' was introduced by the Swiss government, which aims at reducing pesticide risks by 50% until 2027 compared to 2012/2015 (BLW, 2021).

Pesticide-free but non-organic cropping systems are to be introduced nationwide in the future to reduce pesticide risks. The Federal Council decided to redesign, as of 2023, the direct payment system to enhance pesticide reduction measures on arable land and permanent crops (BLW, 2021). On arable land, the current extenso programme for insecticide-, fungicide- and growth-regulator-free cropping systems will be expanded (not only cereals, oilseeds and protein crops but also root crops (i.e. potatoes and sugar-beets) will be eligible) and payments will be partly increased from 400 to 800 CHF/ha (Table 1). Moreover, from 2023 onward, the direct payment programme for herbicide-free cropping systems on arable land will be further developed, and payments for rapeseed, potatoes and sugar-beet cropping systems will be substantially increased (Table 1).[1]

This means that, from 2023 onward, in addition to the three main cropping systems (intensive, extenso and organic), a fourth option, 'pesticide-free but non-organic', will be supported for all major arable crops (cereals, oilseeds, protein crops and root crops). To produce 'pesticide-free' crops, farmers have to meet the requirements of fungicide- and insecticide-free cropping as well as herbicide-free direct payment programmes (Table 2). These payment schemes are voluntary and crop-specific; thus, farmers have the opportunity but no obligation to adopt these practices for one or for all crops of the crop rotation. Here, we investigate the potential transition from intensive (OLN) and extenso

[1] Note that no-herbicide direct payments were already introduced as a temporary measure from 2019 to 2022 for herbicide-free arable crops. This is now expanded and made a continuous payment scheme. However, the baseline of our analysis does not include this measure; thus, we investigate the possible transition of intensive (OLN) and extenso production systems to pesticide-free production.

Table 2
Requirements for receiving direct payments for pesticide-free cropping systems as a combination of (1) and (2).

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

Only weed-suppressing plants that cover the soil or mechanical weed control measures with harrows and hoes are permitted.
Source: BLW (2021).

cropping systems to pesticide-free but not-organic production.[2] Note that the requirements for pesticide-free potatoes and sugar-beets are less strict than those for other crops (Table 2).

3. Databases and methods

We applied a multi-method approach for assessing farmers' adoption of the voluntary direct payment programmes supporting pesticide-free but non-organic cropping systems in Switzerland. Based on this approach, we further conducted an ex-ante impact assessment at the national scale. Thereby, we investigated impacts on crop-specific food production (pesticide-free area, volume and value) and income.

Our approach combines qualitative and quantitative methods and links databases from different sources (Fig. 1):

1. Based on an expert survey (Delphi study), we built a table on expected yield losses when farmers switch from currently intensive resp. extenso cropping systems to pesticide-free (but non-organic) systems.
2. Based on national data repositories, a database on changes in crop-specific machinery costs and labour requirements resulting from the adoption of pesticide-free cropping systems was built for typical Swiss cropping systems.
3. Farmers' decisions to adopt voluntary pesticide-free direct payment programmes were determined using 1907 bio-economic single-farm optimisation models. These models were developed based on 1907 real farms (with arable land) that provided data to the Swiss Farm Accountancy Data Network (FADN) for the years 2016–2018. Data records on expected yield losses and changes in machinery costs, as well as labour requirements, were implemented in the 1907 farm optimisation models. All optimisation models were part of the agent-based agricultural sector model SWISSland (Möhring et al., 2016a). Further, this allowed us to carry out an impact assessment on food production and income at the national scale. Therefore, the model results of the 1907 FADN farms were upscaled to the total Swiss farm population (50,038 farms).

Section 3.1 describes the methodological approach of the Delphi study. Section 3.2 describes the databases used for calculating machinery costs and labour requirements for chemical and non-chemical pest treatments. Section 3.3 provides an overview of the agent-based agricultural sector model SWISSland. Furthermore, it describes the underlying assumptions of the policy scenarios simulated with SWISSland and the modelling of the adoption decisions.

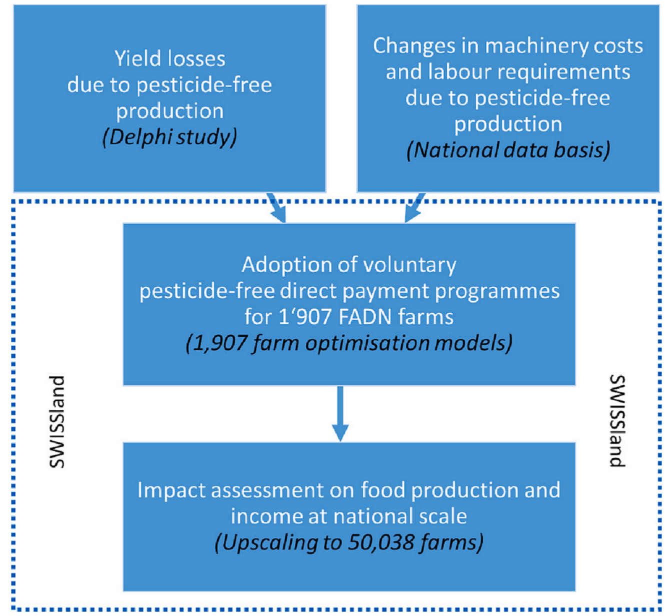

Fig. 1. Modelling a transition to pesticide-free (but non-organic) food production systems at the national scale: Overview of the applied multi-method approach (high-lighted in red) and the combined databases for assessing farmers' adoption decisions of the voluntary pesticide-free direct payment programmes and their impacts on food production and income at the national scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1. *Delphi study for estimating yield losses caused by pesticide-free cropping systems*

To assess the yield losses incurred when farmers switch from currently intensive resp. extenso (insecticide- and fungicide-free) cropping systems to pesticide-free (but non-organic) cropping systems, we used the Delphi method. This is an established tool for scientific forecasting with the aim of obtaining high-quality responses from a selected panel of experts (Devaney and Henchion, 2018).

The questionnaire described the specific requirements for pesticide-free cropping systems for each crop (Table 2). The experts estimated the yield losses (in percentages) for currently intensive and extenso cropping systems of seven crops (wheat, barley, rapeseed, sunflower, protein crops, potatoes and sugar-beets). For each crop, the experts received a set of reference yields (in dt/ha), which they were expected to consider for the estimates. The reference yields used for the questionnaire are listed in Table A1 and are based on Swiss FADN data (Agroscope, 2020) and national data repositories for typical Swiss farms (Agridea, 2020). Experts had to estimate yield losses for three reference levels (average, above-average and below-average yields, see Table A1 in the appendix). With that, site-specific properties such as climate, soil, altitude or differences in cultivation techniques, which influence the yield were considered. The experts were asked to answer the following question:

"On average over a period of 5 years with different disease and pest pressures due to weather changes: How do you estimate the yield loss if no pesticides are applied and if no additional management measures are implemented? This means that no pest-resistant varieties are used, the use of fertilizers remains unchanged and no strips of beneficial insects

[2] In addition to these pesticide-free direct payments for the main arable crops, other adjustments are also planned from 2023 onward. For example, the Swiss government intends to expand and increase financial support for partially or totally pesticide-free vegetable and permanent crops (BLW, 2021). However, their impacts are beyond the scope of this paper.

are implemented. Only mechanical weed control measures such as weeders and hoes are used".

Crop protection consultants from cantonal and federal organisations and researchers with the expertise necessary for this study were identified and contacted beforehand to check whether they were willing to participate. We aimed for a heterogeneous sample to ensure that various fields of work, including research, advisory and administration, were covered and that the participants had expertise in crop protection. Furthermore, we chose experts to obtain geographic heterogeneity as well as institutional heterogeneity (Table 3). In total, 30 experts were contacted, of whom 18 were willing to participate. All experts remained anonymous throughout the Delphi study. With this, we ensured that all experts were free to express their opinions without having single individuals dominating the consensus process.

The study was conducted in November and December 2020 (Möhring et al., 2021). The questionnaire consisted of two Delphi rounds, which were completed online using the survey platform Unipark (Questback GmbH). The first Delphi round contained closed questions regarding natural yield losses for pesticide-free production schemes. For each question, the experts could use commentary fields in case they wanted to provide additional information. The time estimate for the completion of the questionnaire was one hour. A reminder was sent three days ahead of the deadline to the experts who had not yet provided their estimates. The data collection for the first round took eight days.

For the second Delphi round, the experts received feedback on the results of the first round in the form of average yield losses. The experts were asked to re-evaluate the questions from the first Delphi round, now considering the feedback from the first round. Based on this feedback, questions in the second round were organised as open questions because some of the experts criticised the given categories in the first round as insufficient. In the second round, the experts could also skip questions on which the experts agreed in the first round (criterion: at least 50% of the experts agreed) by agreeing with the majority. If necessary, they also had the opportunity to make changes. Questions in which no agreement was obtained after the first Delphi round were compulsory to answer. Again, the completion of the second Delphi round took approximately one hour. Data collection lasted 11 days.

3.2. Databases for calculating changes in machinery costs and labour requirements due to pesticide-free cropping systems

We calculated changes in machinery costs and labour requirements when farmers switched from typical intensive (OLN) or extenso (insecticide- and fungicide-free) cropping systems to pesticide-free (but non-organic) systems. Therefore, it was assumed that farmers adopting herbicide-free cropping systems mainly apply mechanical weeding. The focus was on this practice because it represents the most preferred non-chemical pest treatment, according to a recent survey conducted among a network of Swiss pilot farmers (Zorn et al., 2022). It was further assumed that additional fixed costs arise for weeders because, as indicated by Möhring and Finger (2022), acquisition costs have a significant negative impact on farmers' decision to adopt herbicide-free cropping systems. Fixed annual machinery costs were calculated assuming an average utilisation of weeders per year, based on Gazzarin (2021).

A national data repository, developed by Agroscope (Gazzarin, 2021), on machinery costs for various weeders, sprayers and tractors was used to calculate the cost changes. Crop management data published by national extension services for typical intensive (OLN) and extenso (fungicide- and insecticide-free) cropping systems (Agridea, 2020) were used to define the number of chemical and non-chemical pest treatments per year. Machines typically used for chemical and non-chemical pest treatments in Switzerland were considered using a database from Agridea (2020). Changes in fixed costs when farmers switched from typical intensive (OLN) or extenso (insecticide- and fungicide-free) to pesticide-free (but non-organic) cropping systems were considered to determine the adoption of the systems based on profit maximization.

Table 3
Expert panel and response rates for the two Delphi rounds.

Organization	Invited	Participated
Cantonal offices	12	7
Training, advisory and associations	8	5
Research	10	6
Total	30	18

Note: The response rate was 60%. All participants from Round 1 also participated in Round 2.

3.3. Modelling adoption decisions of farmers and impacts at the national scale

3.3.1. Overview of the agent-based agricultural sector model SWISSland

SWISSland allows both the modelling of the three current cropping systems (intensive, extenso and organic) and the transition to pesticide-free direct payment schemes. Furthermore, it allows for the assessment of national effects on production and income resulting from the adoption of pesticide-free direct payment programmes. The following are the key characteristics of SWISSland with respect to the analysis presented here:

(1) At the farm scale, SWISSland models a sample of 3077 FADN farms. Thereof, 1907 farms have open arable land. The Swiss FADN farm sample is based on a stratified random sampling procedure and covers all farm types, regions (plain, hill and mountain), and farm size categories of the Swiss farm population (Renner et al., 2019). Thus, the FADN farm sample includes farms from different regions with different yield levels. The model results at the farm scale reflect the heterogeneous responses to policy changes in Switzerland.
(2) SWISSland estimates land-use and livestock decisions for each farm using recursive-dynamic, PMP-based farm-level optimisation models over a period of 10–15 years (Mack et al., 2019a). The model captures the economic dimension of farming activities assuming a fully informed and profit-maximising decision maker. Farm records from the FADN database (three-year averages of the years 2016–2019) were used to define the technical coefficients of the optimisation models. In particular, crop-specific FADN data for intensive, extenso (fungicide- and insecticide-free) and organic cropping systems were used to build the databases of the models. Table A2 and Table A3 in the Appendix provide an overview of yields and costs for intensive and extenso cropping systems. The initial yields of the heterogeneous FADN farm sample consider the regional differences in Switzerland. Model assumptions on the development of the variables until 2027 are documented in Mack and Möhring (2021).
(3) SWISSland models the adoption of various voluntary agri-environmental schemes for each of the 3077 farm agents using farm-optimisation models. The models consider the observed adoption rate reported in the FADN data of the base year (Möhring et al., 2016a). Adoption decisions are forecasted under the assumption that farmers maximise their income. This means that farmers will adopt voluntary direct payment schemes when their compliance costs are lower than direct payments. Though, we do not model a switch to organic farming systems.
(4) SWISSland aggregates the model results of 3077 farm agents to the national scale using upscaling factors (Zimmermann et al., 2015). In addition to adoption decisions and food production, the model returns the Economic Accounts for Agriculture.

The agent-based sector model SWISSland considers not only a heterogenous agent population but also interactions among agents. Interactions are modelled on the land market between exiting and the remaining neighbouring farms. It is assumed that exiting farms have no farm successor to whom they can hand over their farm, or whose potential successor decides against taking over the farm. A detailed model description is available in Möhring et al. (2016a).

3.3.2. Description of the reference and pesticide-free (but non-organic) policy scenarios

The ex-ante impacts of the pesticide-free direct payment programme were assessed by comparing the simulation results for a current policy scenario (reference) with different pesticide-free scenarios in 2027. The time horizon for scenario definition was 2018–2027. Our reference scenario was built on the direct payment scheme defined by the Swiss agricultural policy AP 2018–2021 (Möhring et al., 2016b). Up to 2027, no policy changes were assumed for the reference scenario. This means that in the reference scenario, farmers can either stick to their main cropping systems observed in the base year (intensive or extenso), or farmers with intensive systems can switch to extenso for cereals, oilseeds and protein crops (direct payment: 400 CHF/ha).

The 'pesticide-free (but non-organic)' scenarios were built on the assumption that pesticide-free direct payment programmes would be introduced from 2023 to 2027 for all main groups (according to Section 2). This means that farmers with currently intensive or extenso cropping systems can switch to pesticide-free (but non-organic) systems. We further assumed a price bonus of 10% when farmers switch from extenso (fungicide- and insecticide-free) to pesticide-free systems and a bonus of 20% when they switch from intensive to pesticide-free systems. These assumptions are based on the price premium paid by the private farmer association IP-Suisse for pesticide-free cereal production (Möhring and Finger, 2022). Farmer switching from extenso to pesticide-free receive a lower price bonus (+10%) than intensive farmers (+20%) because they have received already a price bonus for switching from intensive to extenso. A switch to organic systems is modelled neither in the reference nor in the pesticide-free (but non-organic) scenarios. Thus, we assume that the share of organic production depends on the number of FADN farms with organic production.

We examined three scenarios that assume different crop yield reductions due to the switch to pesticide-free cropping systems: (1) a high-yield-loss scenario, based on the 10% highest experts' ratings from the Delphi survey; (2) an average-yield-loss scenario, assuming averages over all experts' ratings and (3) a low-yield-loss scenario, based on the 10% lowest ratings. This allows us to assess how expected yield losses influence the adoption of pesticide-free cropping systems.

Increasing and expanding payment schemes for pesticide-free production have budgetary implications at the national scale. Due to a fixed national budget for direct payments (2.8 bn CHF per year), the government plans to decrease other payments if the national expenditures will increase due to the pesticide-free programmes in the future. This especially concerns transitional payments that are not linked to any environmental standard. A percentage reduction in transitional payments was assumed when the pesticide-free scenarios exceeded the sectoral budget. Therefore, we iteratively reduced the transitional payments for each FADN farm as long as the total sectoral direct payment budget reached 2.8 billion CHF (Schmidt et al., 2019, p. 4).

The main assumptions of the reference and pesticide-free scenarios are summarised in Table 4.

Table 4
Scenario definition: Modelling assumptions for the reference scenario and pesticide-free (but non-organic) scenarios.

	Reference scenario	Pesticide-free (but non-organic) scenarios		
Name of the scenario	Reference	High loss	Medium loss	Low loss
Expert rating of yield losses from the Delphi study		10% highest ratings	Average of all ratings	10% lowest ratings
Price premium for pesticide-free production		From extenso to pesticide-free: 10% From intensive to pesticide-free: 20%		
Swiss direct payment policy	AP 18–21	Pesticide-free direct payment programmes & AP 18–21		
National direct payment budget	2.8 bn CHF	2.8 bn CHF Reduction in transitional payments if the budget is exceeded due to the pesticide-free payments		

Note: AP 18–21: Swiss agricultural policy 18–21 (Möhring et al., 2016b).
Extenso: Fungicide- and insecticide-free cropping systems.
Intensive: Cropping systems in which all types of pesticides are applied.

3.3.3. Determining the adoption decisions of pesticide-free cropping systems for individual farms

The adoption decisions of pesticide-free cropping systems were determined considering the effects on yield losses, price and revenue changes, input cost changes (pesticide, hail insurance and cleaning & drying costs), labour requirements, and changes in variable and fixed machinery costs. These various effects were assessed for the 1907 FADN farms with arable land implemented in SWISSland. Therefore, their databases from the FADN were combined with the results of the Delphi study and machinery cost calculations. Profit changes due to the switch to pesticide-free systems were implemented in the objective functions of the farm optimisation model. Changes in profits arise from those in yields, prices and costs. Yield implications of the adoption of pesticide-free production were implemented using percentage yield changes resulting from the Delphi study for the three reference yield levels (average, above-average and below-average yields) and were assigned to all FADN farms based on their initial yield levels. Moreover, we assumed that pesticide-free crops would receive a price premium (Möhring and Finger, 2022). Cost changes include savings of pesticide costs, reduction in hail insurance and cleaning and drying costs. A description of how FADN data for hail insurance and cleaning & drying costs were reduced is provided in Appendix B. Additional annual fixed costs for weeders and changes in variable costs for weeders, tractor and sprayers were also included in the profit change function. Changes in labour requirements were implemented in the labour constraints of the farm optimisation models. When family labour resources of farms were exceeded due to the adoption of pesticide-free cropping systems, the hiring of non-family labour was considered in the farm optimisation models.

Eq. 1 shows the profit change function implemented in the farm optimisation models when FADN farms with intensive (all types of pesticides) or extenso (insecticide- and fungicide-free) cropping systems switch to pesticide-free systems:

$$\Delta PR_{c,i,f} = \left[Y_{c,i,f}{*}\,\Delta Y_{c,i}{*}\,P_{c,I,f}\right] - \left[\left[Y_{c,i,f} - Y_{c,i,f}{*}\,\Delta Y_{c,i}\right]{*}\,P_{c,i,f}{*}\,\Delta P_{c,i}\right] - \Delta PC_{c,i,f} - \Delta HC_{c,i,f} - \Delta DC_{c,i,f} + \Delta FC_{c} + \Delta VC_{c,i} + \Delta DP_{c,i} \quad (1)$$

ΔPR = Profit changes due to the adoption of pesticide-free cropping systems.

c = Crop (wheat, barley, rapeseed, sunflower, protein crops, potatoes, sugar-beets).

i = Intensity (intensive or extenso).

f = FADN farm (f = 1.0.1907).

Y = Initial crop yield from FADN data.

ΔY = Percentage yield changes due to pesticide-free production from the Delphi study.

P = Initial product price from FADN data.

ΔP = Percentage price premium for pesticide-free crops.

ΔPC = Reduction in pesticide costs due to pesticide-free production.

ΔHC = Reduction in hail insurance costs due to pesticide-free production (due to lower yields).

ΔDC = Reduction in cleaning & drying costs due to pesticide-free production (due to lower yields).

ΔFC = Additional fixed machinery costs due to pesticide-free production.

ΔVC = Additional variable machinery costs due to pesticide-free production.

ΔDP = Additional direct payments due to pesticide-free production.

4. Results

We first provide the results of the Delphi study on the expected yield losses for the relevant seven main crops when farmers switch from intensive or extenso (fungicide- and insecticide-free) to pesticide-free systems. Then, we show how machinery costs and labour requirements would change due to the transition to pesticide-free systems. Finally, we provide modelling results on the adoption of pesticide-free systems by farmers and an ex-ante assessment of the impacts of food production (on pesticide-free arable land, volume and value) and income (on income distribution and sectoral income according to the Economic Accounts for Agriculture) at the national scale.

4.1. Delphi Study: Expected yield losses due to pesticide-free production

Experts rated the yield losses when farmers switched from intensive to pesticide-free cropping systems to be 2–3 times higher (in percentage) than that from extenso to pesticide-free system (Table 5). For intensive cropping systems, the lowest yield loss was expected for sunflower (10%–30%), whereas the highest loss was expected for sugar-beet (40%–60%) (Table 5). Differences between the high-loss scenario (10% highest ratings) and low-loss scenario (10% lowest ratings) ranged between 10% and 40% for intensive and 10% and 20% for extenso cropping systems. For extenso rapeseed and sunflower, some experts even expected no yield losses when farmers switched to pesticide-free cropping systems. Yield loss related to average yield levels observed in Switzerland was quite similar compared to the ratings for above-average yield levels. Experts rated substantially lower losses for crops with below-average yield levels.

4.2. Changes in machinery costs due to pesticide-free production

To enable pesticide-free production, investments in tined weeders and hoeing equipment are required, which cause additional annual fixed costs of 30–72 CHF/ha for typical Swiss cropping systems (Fig. 2). The highest costs arise for potatoes and sugar-beets because typical Swiss mechanical weeding systems require both tined weeders and hoeing equipment. Table A3 provides an overview of chemical and non-chemical pest treatments and variable machinery costs for typical intensive, extenso and pesticide-free cropping systems in Switzerland. The results show that when farms with typical intensive cropping systems (cereals, protein crops and rapeseeds) would switch to pesticide-free systems, their variable machinery costs would even decrease (Fig. 3). This can be explained by the fact that savings of spraying costs are higher than additional mechanical weeding costs. In contrast, if farms with typical extenso cropping systems would switch to pesticide-free systems, their variable machinery costs would increase (Fig. 3) The highest additional variable machinery costs resulted for sunflower (extenso) because a typical Swiss pesticide-free system requires not only a weed treatment with a tined weeder but also two treatments with a hoe (Table A4). Percentage changes in labour requirements are provided in Table A7.

4.3. Modelling results

4.3.1. Adoption of pesticide-free direct payment schemes in arable production at the national scale

Adoption results at the national scale are displayed by the variable 'pesticide-free crop area', which results from the number of farms switching to pesticide-free systems and their cultivated area—both extrapolated to the national scale (Fig. 4).

The reference scenario shows the area for the three main cropping systems (organic, intensive and extenso) in 2027 when the agricultural policy would remain unchanged (Fig. 4a). The results for 2027 differ only slightly from the observed base-year levels in 2016/2018 because prices and costs are assumed to be relatively stable during this period (Fig. A1).

Modelling results for the three pesticide-free scenarios show that adoption depends highly on the associated yield losses (Fig. 4a). As expected, the lower the losses, the higher is the pesticide-free area. In the high-yield loss scenario, the pesticide-free (but non-organic) area makes up 41% of the total arable land, whereas in the low-yield scenario, it increases to 79% of the total arable land. Furthermore, under the proposed direct payments (Table 1), it would be profitable for existing extenso and intensive cropping systems to switch to pesticide-free systems. The share of intensive production systems on total open arable land would decrease substantially from 45% (reference) to 8% (low-loss scenario), and that of extenso would decrease from 47% (reference) to

Table 5
Results of the Delphi study: Expected yield losses (in %) when farmers switch from intensive (all types of pesticides are allowed) to pesticide-free cropping systems. Percentages for extenso (fungicide- & insecticide-free) cropping systems are shown in brackets.

	Wheat	Barley	Rapeseed	Sunflower	Protein crops	Sugar-beet*	Potatoes*
Initial yield levels are on average							
High-loss scenario	−50% (−20%)	−40% (−20%)	−50% (−30%)	−30% (−10%)	−30% (−20%)	−60%	−60%
Medium-loss scenario	−30% (−10)	−30% (−10%)	−40% (−10%)	−15% (−10%)	−20% (−15%)	−50%	−35%
Low-loss scenario	−20% (−10%)	−25% (−10%)	−30% (−0%)	−10% (−0%)	−10% (−10%)	−40%	−20%
Initial yield levels are above average							
High-loss scenario	−30% (−10%)	−35% (−20%)	−50% (−25%)	−20% (−10%)	−30% (−20%)	−55%	−60%
Medium-loss scenario	−30% (−7.5%)	−30% (−10%)	−40% (−17%)	−15% (0%)	−25% (−10%)	−50%	−40%
Low-loss scenario	−20% (0%)	−20% (0%)	−30% (0%)	−10% (0%)	−20% (−5%)	−40%	−15%
Initial yield levels are below average							
High-loss scenario	−20% (−10%)	−25% (−10%)	−50% (−25%)	−10% (−10%)	−20% (−15%)	−50%	−50%
Medium-loss scenario	−20% (0%)	−20% (0%)	−25% (−10%)	−10% (−5%)	−15% (−10%)	−40%	−30%
Low-loss scenario	−20% (0%)	−20% (−0%)	−20% (0%)	0% (0%)	−10% (0%)	−30%	−15%

Note: * For sugar-beets and potatoes, the direct payment programme for pesticide-free crop systems allows specific herbicide and fungicide treatments. The extenso programme does not apply to sugar-beets and potatoes. Reference yield levels for the three categories average, above-average and below-average yields are shown in Table A1 in the appendix. Experts rated percentage losses for above-average yield levels similar or a bit lower than under the average yield levels. However, absolute yield losses for average and above-average yield levels were similar.
High-loss scenario: 10% highest.
Medium-loss scenario: Average yield loss ratings by experts due to pesticide-free were assumed.
Low-loss scenario: 10% lowest.

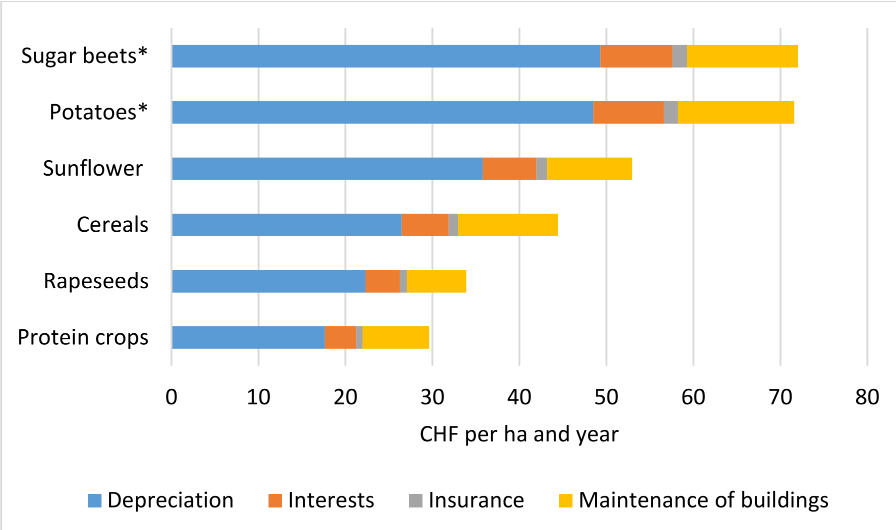

Fig. 2. Additional annual fixed machinery costs (CHF/ha) when farmers switch from typical intensive (all types of pesticides) or extenso (insecticide- & fungicide-free) cropping systems to pesticide-free system.
Note: * For sugar-beets and potatoes, the direct payment programme for pesticide-free crop systems allows specific herbicide and fungicide treatments. Additional fixed machinery costs stem from investments in tined weeders and hoeing equipment. Additional fixed costs increase when tined weeders and hoeing equipment are necessary.

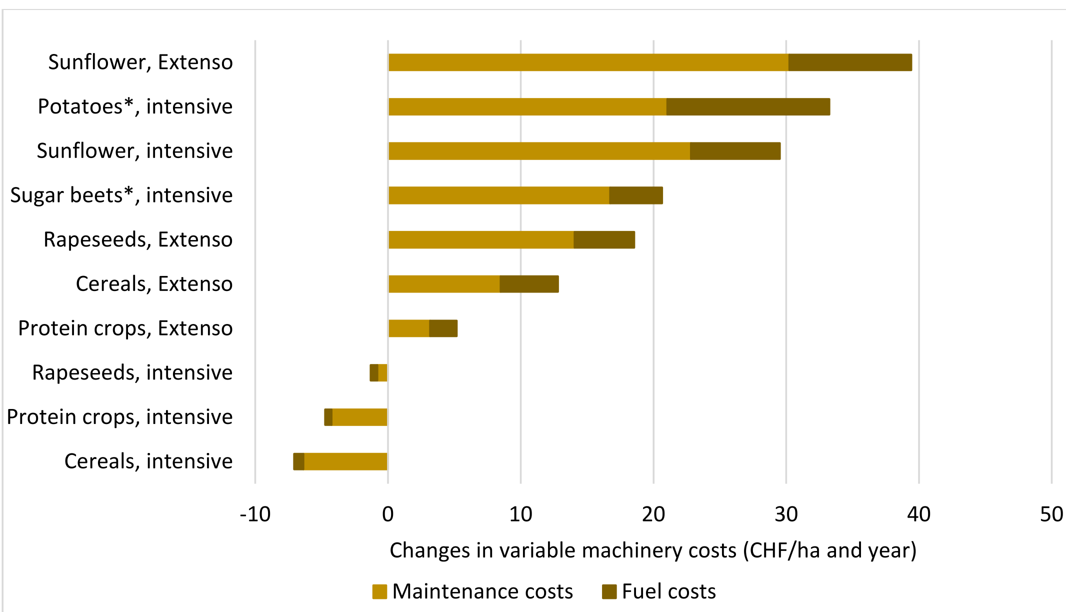

Fig. 3. Changes in variable machinery costs (CHF/ha) when farmers switch from typical intensive (all types of pesticides) or extenso (insecticide- & fungicide-free) to pesticide-free cropping systems.
Note:* For sugar-beets and potatoes, the direct payment programme for pesticide-free cropping systems allows specific herbicide and fungicide treatments. Variable machinery costs increase when machinery costs for mechanical weeding are higher than those for spraying herbicides. Variable machinery costs for some crops even decrease because cost savings for spraying are higher than additional variable costs for mechanical weeding.

5% (low-loss scenario) (Fig. 4a). Most of the pesticide-free area would be cereals and oilseeds, while the pesticide-free area cultivated by root and protein crops would be relatively low (Fig. 4b).

When looking at adoption rates for single crops, this overall picture can be explained in more detail (Fig. 5). For intensively and extensively wheat producing farmers, a transition to pesticide-free cropping systems would be highly attractive (Fig. 5). Even for many farmers with intensive wheat systems, it would be profitable to switch to pesticide-free systems because significantly lower variable machinery costs, savings in pesticide costs, a 20% price premium and direct payment of CHF 650/ha would compensate for the revenue losses (medium and high loss scenarios). The pesticide-free wheat area would rise, depending on yield losses, up to 35% (high-loss scenario) or even 82% (low-loss scenario). Similar results are obtained for barley cropping systems. A transition to pesticide-free systems would not only be attractive for those already participating in the extenso programme but also for intensively barley producing farmers.

While rapeseed production in Switzerland is currently intensive with respect to pesticide application, with only 25% participating in the extenso programme and organic production being negligible at 2% (Fig. 5), between 70% and 95% of the rapeseed area would be converted to pesticide-free cropping systems, and the extenso programme would be no longer attractive for farmers. Even though the transition to pesticide-free rapeseed production implies high-yield losses between 30% and 50%, the price premium and reduced variable machinery costs, especially the high direct payment of 1400 CHF/ha, over-compensate for these yield losses. Overall, the agricultural area under rapeseed would expand by 4%.

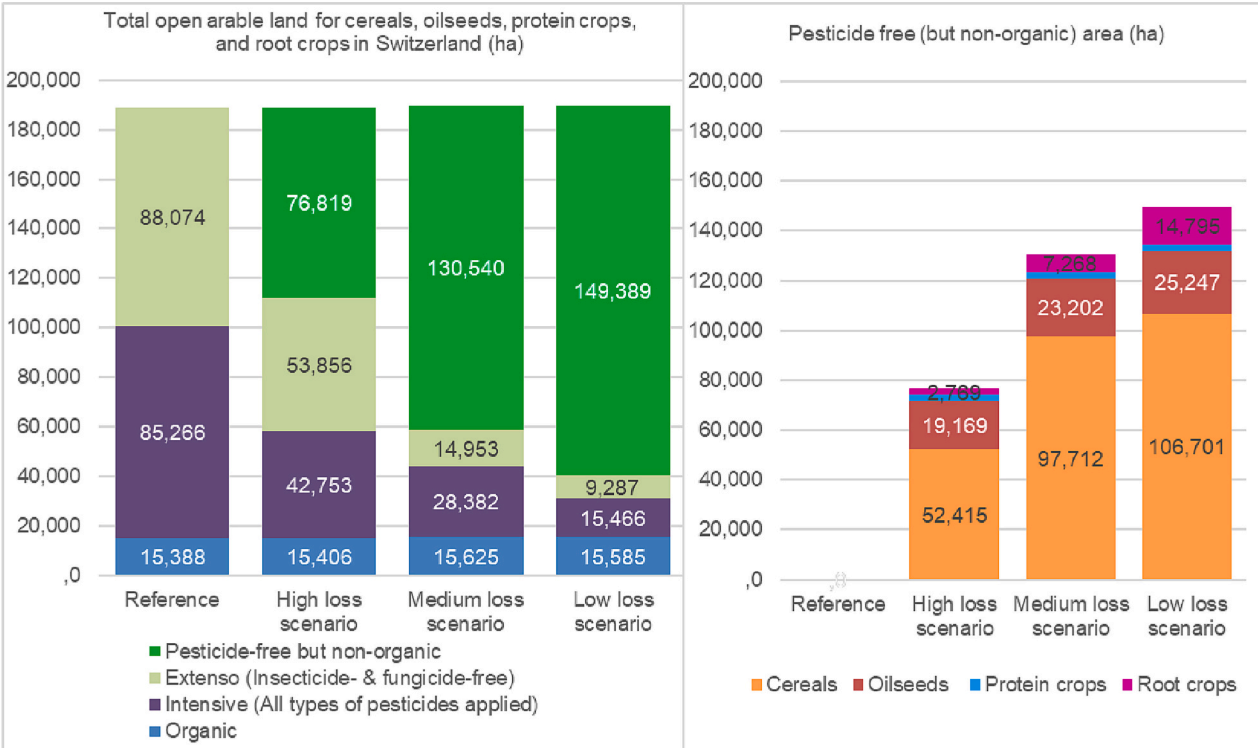

Fig. 4. Share of organic, intensive (all types of pesticides are allowed), extenso (fungicide- & insecticide-free) and pesticide-free (but non-organic) areas on total arable land (Fig. 4a, left); total pesticide-free (but non-organic) area for cereals, oilseeds, protein crops and root crops (year 2027) (Fig. 4b, right).
Note:
High-loss scenario: 10% highest.
Medium-loss scenario: Average yield losses due to pesticide-free were assumed based on the Delphi study.
Low-loss scenario: 10% lowest.

As for extensively produced cereals and oilseeds, the extenso programme loses much of its importance in sunflower production. Already today, the sunflower area is extensive, with a share of 77%. A transition to pesticide-free sunflower cropping system would be highly profitable despite the relatively high yield losses of up to 30%, even though direct payment is 650 CHF/ha, which is lower than that for rapeseed production. With medium-and low-yield losses, almost the entire sunflower area (92%–93%) would be pesticide-free, and the total sunflower area would expand by 1%–2%.

Protein cropping systems are already extensive today, with 34% of the area under organic and 61% under the extenso programme (Fig. A1). With the introduction of the pesticide-free production programme, it is attractive for most farms with intensive and extenso cropping systems to switch to pesticide-free production, even though this means an increase in machinery costs and yield losses of between 10% and 20%. Direct payments and higher prices compensate for these losses, and even a slight expansion of the total protein area can be expected.

In contrast, for sugar-beet producers, the pesticide-free production programme is hardly attractive because of high-yield losses of between 30% and 60% and higher machinery costs (e.g. due to switching to mechanical weed control). Sugar-beet is currently grown intensively in Switzerland (Fig. A1), and even with only minor yield losses, less than a third of the sugar-beet area is converted to pesticide-free production. The direct payment and the 20% higher prices do not compensate for the losses. The situation is different for potato production; the direct payment of 1400 CHF/ha and the 20% higher prices provide an incentive for large-scale adoption of the pesticide-free production programme, even though machinery costs increase. If yield losses do not exceed 20%, all farms would switch to pesticide-free production.

4.3.2. Impact of pesticide-free systems on production volume and value at the national scale

The modelling results indicate that the national production volume of wheat would decrease by 7%–10% depending on the assumed yield losses and adoption rates. Similar volume losses (−10% to −11%) can be expected for barley (Fig. 6a). However, because of the price premium of 10% or 20% compensating for the volume decline, the production value for wheat and barley declined only by −3% to −5% (Fig. 6b). The highest decline in production volume is expected for oilseeds (−20% to −12%) because of the relatively high adoption rate of pesticide-free cropping systems and the relatively high yield losses. Although the national rapeseed area has increased by up to 4% (low loss scenario, Fig. 6), production volume declined by −12% in the low-loss scenario. Again, because of the considered price premium, the value of rapeseed production would decline to a much lower extent (−13% to −3%).

In the case of sugar-beet, the model results indicate a maximum production volume decline of −9% due to the limited transition to pesticide-free sugar-beet cropping systems and a production value decline of only −2% to −4%. When the total potato area would be pesticide-free (low yield loss scenario with maximum yield loss of 20%), we expect a decline of −12% in the national potato production volume, while the production value would increase by 2%. In this case, the price premium can fully compensate for the yield losses.

In total, across all crops considered, calorie production of Swiss agriculture would decline by −7 to −10% with higher reductions in the low-yield-loss scenarios (Fig. A2).

In summary, the transition to pesticide-free cropping systems reduces the volume and calorie produced at the national scale, but due to higher prices for pesticide-free products, the value of total production decreases only minimal, with the exception of oilseeds.

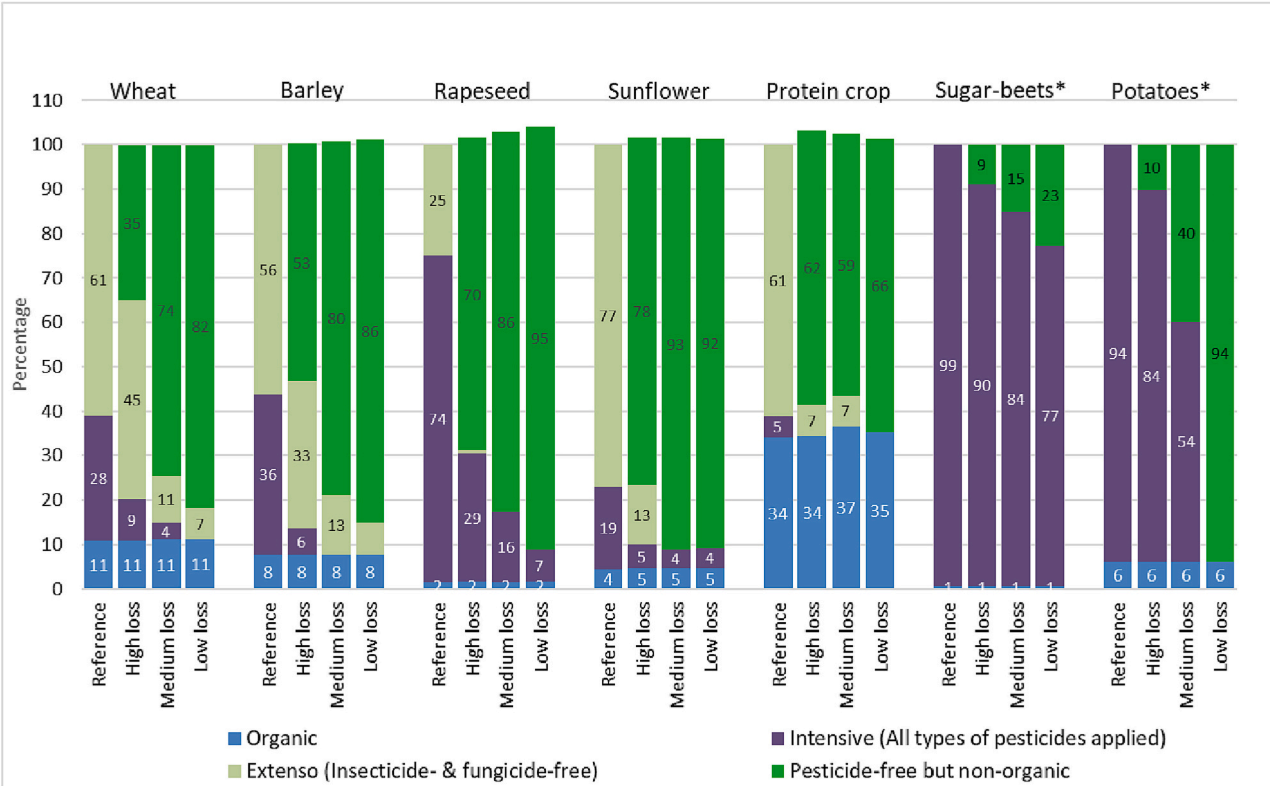

Fig. 5. Adoption of pesticide-free direct payment programmes for single crops: Percentage of pesticide-free (but non-organic) area in Switzerland under the different scenarios (year 2027).
Note: * For sugar-beets and potatoes, the direct payment programme for pesticide-free crop systems allows specific herbicide and fungicide treatments.
High-loss scenario: 10% highest.
Medium-loss scenario: Average yield losses due to pesticide-free were assumed based on the Delphi study.
Low-loss scenario: 10% lowest.

4.3.3. *Impact of pesticide-free production systems on income*

Fig. 7 shows changes in average farm income for different farm types compared to the reference scenario. We find that the average farm income would slightly increase for specialised and combined arable crop farms. These results can be explained by the fact that we consider voluntary adoption of a pesticide-free production programme targeting plant production but not animal production and, thus, reallocating direct payments within Swiss agriculture. Adopting arable farms, mainly those with cereal production, benefit from pesticide-free direct payment programmes because their on-farm compliance costs are lower than the received direct payments. The average income of arable crop farms would increase by up to 2–16%. The high average income increase, particularly in the low-loss scenario, shows that the direct payment programme would be highly profitable for farmers with low yield losses. However, the average income of farms without arable crops would decrease slightly, because their transitional direct payments would decrease slightly. These results show that arable farms would benefit economically at the expense of farms without arable farming.

Table 6 shows how the sectoral key figures of the Economic Accounts for Agriculture for Switzerland would change. We find that pesticide-free direct payment programmes for the main arable crops lead to only small changes in crop output in total. The decline ranges from −0.3% to −0.8%. Intermediate consumption also declines because expenses for pesticide products decline. However, given that pesticide-free but non-organic programmes are adopted on a large scale, the decline in expenses for pesticide products is rather low (only −8.8% to −19.5%). In addition, the pesticide-free direct payment programme likely leads to very small sectoral income changes (−0.3% to +0.3%). In the case of low yield losses and price premiums of 10% and 20%, the direct payment programme even leads to a small increase in the operating surplus.

5. Discussion

5.1. *Delphi study*

In the Delphi-study, we asked experts for average yield losses over 5 years with different pests and diseases due to weather changes. Additional measures such as pest-resistant cultivars and protective stripes for beneficial insects are not considered in the expert estimations of yield losses although such measures could reduce yield losses of pesticide-free cultivation practices (Möhring et al., 2021). Therefore, the experts' average ratings might overestimate expected yield losses in the future. On the other hand, yield losses of pesticide-free crops might also depend on the adoption rate of pesticide free crops. Thus, there are potential spill-overs within landscapes if farmers start producing pesticide free (see e.g. Bianchi et al., 2013; Larsen and Noack, 2021). When some or all neighbouring farms in a region adopt pesticide free cropping systems, this may also affect pest and disease spread and spill-over to other farms, both that use and not use pesticides. In this case, the experts' ratings might under- or overestimate yield losses. This also implies that spatial coordination can improve the efficiency of policy efforts. This shall be addressed in future research. Furthermore, we did not ask experts for potential changes in crop quality due to pesticide reduction measures.

To address uncertainties in model assumptions regarding yield losses, we defined three different yield loss scenarios: (1) a high-yield-loss scenario, based on the 10% highest experts' ratings from the Delphi survey; (2) an average-yield-loss scenario, assuming averages over all experts' ratings and (3) a low-yield-loss scenario, based on the 10% lowest ratings. The scenario with low yield loss ratings might include that more pest-resistant cultivars will be available in future and that the stimulation of natural enemies will become more popular. On the other

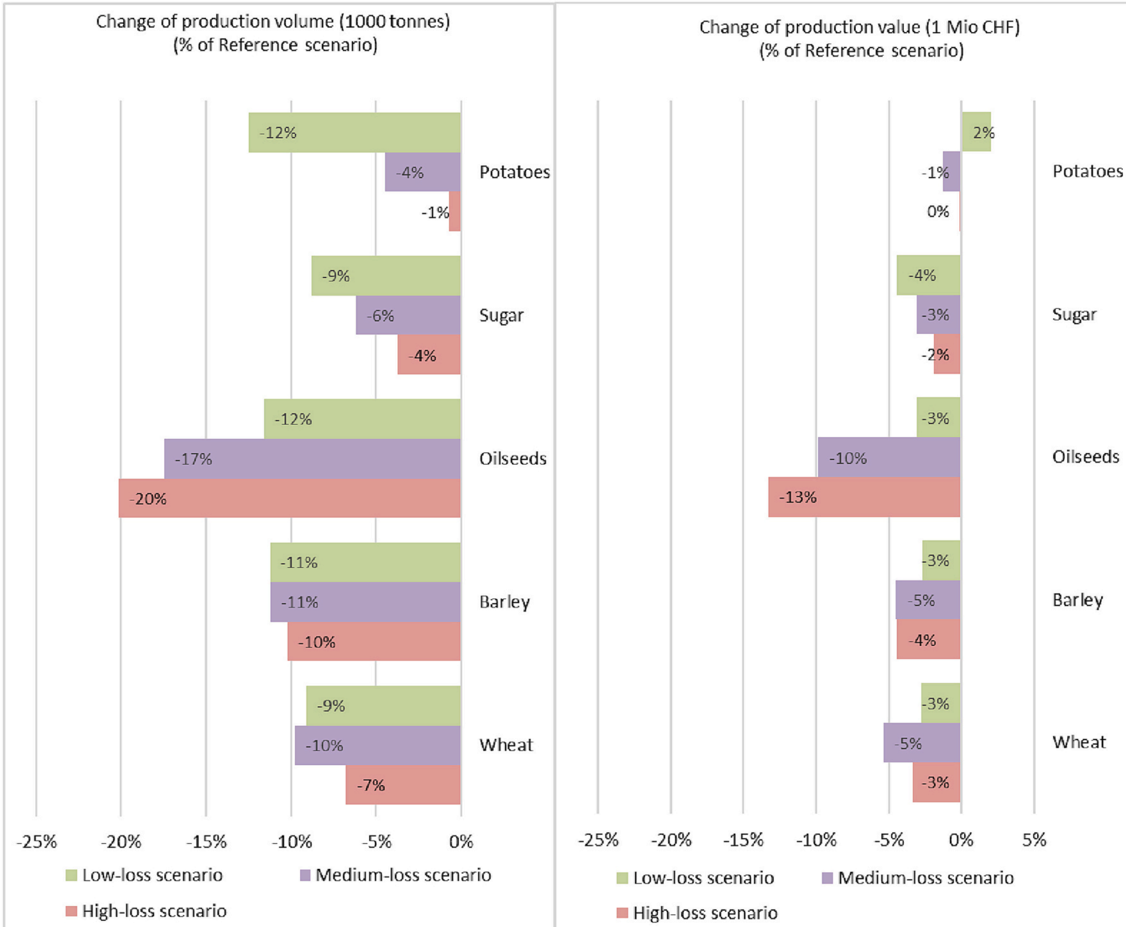

Fig. 6. Impact on production at the national scale (2027): Percentage changes in production volume (Fig. 6a, left) and production value (Fig. 6b, right) of pesticide-free scenarios (compared to the reference scenario) at the national scale.
Note:
High-loss scenario: 10% highest.
Medium-loss scenario: Average yield losses due to pesticide-free were assumed based on the Delphi study.
Low-loss scenario: 10% lowest.

hand, the scenario with high yield losses might cover a situation with high pest- and disease pressure due to easier spreading of pest and diseases.

5.2. Modelling results

Under our scenario assumptions, for cereals, oilseeds and protein crops, a large-scale transition to pesticide-free systems would be highly profitable for intensive and extenso cropping systems. In addition, for potatoes, direct payments and higher prices are the main drivers for switching to large-scale pesticide-free production (low loss scenario). However, these modelling results are based on the assumption that farmers are purely profit maximizers and adopt pesticide-free cropping systems when associated costs are lower than revenues. Although, a study by Dessart et al. (2019) suggests that farmers' decisions to adopt pesticide reduction measures are not entirely following profit maximization. In addition, aspects like resistance to change, risk tolerance, environmental concerns, and behaviours of fellow farmers influence farmers' decision to adopt more sustainable farming practices (Dessart et al., 2019). Thus, our evaluation of pesticide free cropping systems does not consider behavioural factors which might lead to a low individual openness towards such systems (Finger and Möhring, 2022; Knapp et al., 2021; Möhring et al., 2020). From this viewpoint, modelling results based on profit maximization might overestimate adoption rather than underestimating it. On the other hand, we do not consider behavioural factors such as environmental attitudes and social networks, which might influence the adoption rate positively rather than negatively (e.g. Finger and Möhring, 2022). Moreover, we do not consider the administrative burden associated with the adoption of agri-environmental schemes. However, in a recent study conducted in Switzerland, the administrative burden did not influence the adoption of agri-environmental programmes (Mack et al., 2021). In addition, the extenso programme caused a relatively low administrative burden compared to other agri-environmental programmes in Switzerland (Mack et al., 2019b).

Furthermore, prices for pesticide-free crops are based on exogenous assumptions. Prices for pesticide-free products can decrease because of quality deficits. But they could also increase because consumers are willing to pay more for these environmental-friendly products. This is currently the case in Switzerland, as the producers` organization IP-Suisse pays farmers (who receive agri-environmental payments as well) a price premium when they produce pesticide free but not organic (see Möhring and Finger (2022). We assumed price differentials between conventional and pesticide-free products accordingly in our study. Moreover, the reduction in production volume might also lead to changes in market prices, which are not considered in the calculations. Likewise, effects from possibly changing imports and exports on market prices were not considered.

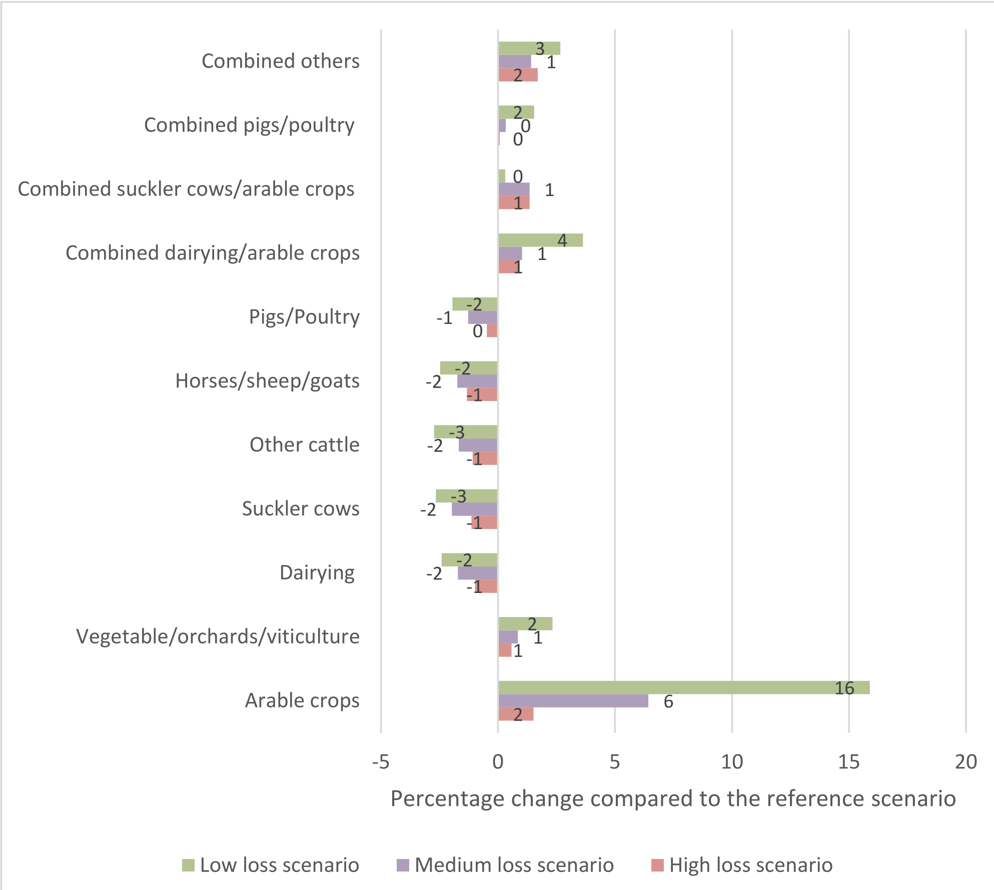

Fig. 7. Impact on average farm income for different farm types: Percentage change compared to the reference scenario.
Note:
High-loss scenario: 10% highest.
Medium-loss scenario: Average yield losses due to pesticide-free were assumed based on the Delphi study.
Low-loss scenario: 10% lowest.

Our results show that under the assumed scenarios it is profitable for both already extensively (fungicide- and insecticide-free) and intensively (all types of pesticides are applied) producing cropping systems to switch to pesticide-free production. However, for crops with high potential yield losses pesticide-free production is less attractive for farmers. Furthermore, the extensive margin effects of direct payments for pesticide-free production are especially important for aggregated outcomes, while intensive margin effects of the programme are rather low. The aggregated effect of introducing voluntary direct payment programmes for pesticide-free production implies reduced sectoral production volumes and produced calories, but only minimal reductions in the production value, especially due to higher prices for pesticide-free products. In addition, the effects on farmers' income are small because the adoption of pesticide-free production is compensated with direct payments and higher prices, and often implies cost reduction in labour and machinery.

6. Conclusion

We investigated the implications of adopting policies that explicitly foster the large-scale adoption of pesticide-free, non-organic production systems, using Swiss crop production as an illustrative example. We combined agent-based modelling, a Delphi study to assess yield implications and detailed representation of labour and machinery implications of pesticide-free production. We found that the expected impacts of switching to pesticide-free production on yields, as well as production costs and labour demand, are highly heterogeneous. The proposed policy changes in Switzerland towards direct payment schemes for pesticide-free but non-organic production will lead to a widespread adoption of this cropping system. In particular, the extensive margin effects (e.g. land use effects) of direct payments for pesticide-free production matter for aggregated outcomes, while intensive margin effects (changes in input use) of the programme are rather low. Introducing direct payments for pesticide-free production implies reduced sectoral production volumes and a reduction of produced calories, but only minimal reductions in the production value. In addition, the effects on farmers' incomes are small, as participation in pesticide-free production in the considered systems is compensated with direct payments and higher prices, but often implies reductions in machinery and labour costs due to non-use of pesticides.

Our findings have clear industry and policy implications. Introducing pesticide-free but non-organic production systems (Möhring and Finger, 2022) is feasible, for example, with specific direct payment schemes. This allows the establishment of large-scale production systems between conventional and organic, thereby reducing trade-offs resulting from both extremes. We find that switching to pesticide-free production is currently easier for some crops, such as cereals, as compared to others, such as potatoes. This highlights the necessity of flexible policy schemes; that is, these policies allow some parts of crop rotations and not necessarily entire crop rotations are pesticide-free. Moreover, this highlights the need to support the development of pesticide-free production schemes for other crops, for example, by supporting efforts in plant breeding and improving production systems. For upstream actors, our findings underline the need to provide farmers with new inputs. For example, new, robust varieties, new technologies, and new forms of extension service will be required if switching to pesticide-free production. For downstream actors, the widespread switch to pesticide-free production implies new challenges in meeting desired production volumes and production qualities, as well as new marketing opportunities. For example, labelling pesticide-free products will become a viable option.

Our analysis has implications for future research. We show that

Table 6
Impact of pesticide-free cropping on Economic Accounts for Agriculture in Switzerland (2027).

	Reference scenario	Pesticide-free scenarios (% change compared to the reference scenario)		
	Million CHF	High-loss scenario	Medium-loss scenario	Low-loss scenario
Output of the agricultural industry	11264	−0.3%	−0.4%	−0.3%
Crop output	4567	−0.6%	−0.8%	−0.3%
Animal output	6697	−0.1%	−0.1%	−0.2%
Total intermediate consumption	6725	−0.3%	−0.4%	−0.5%
Plant protection products and pesticides	125	−8.8%	−14.1%	−19.5%
Maintenance of materials	520	0.0%	0.0%	0.0%
Maintenance of buildings	252	0.0%	0.0%	0.1%
Gross value added at basic prices	4539	−0.4%	−0.4%	0.1%
Fixed capital consumption	2021	0.0%	0.1%	0.1%
Net value added at basic prices	2518	−0.7%	−0.8%	0.0%
Other subsidies on production	2910	0.0%	0.0%	0.0%
Operating surplus / Mixed income	3374	−0.3%	−0.3%	0.3%

High-loss scenario: 10% highest.
Medium-loss scenario: Average yield losses due to pesticide-free were assumed based on the Delphi study.
Low-loss scenario: 10% lowest.

integrated mixed-method approaches are needed to address such a transition into new pesticide-free production systems. Future research should integrate continuous experiences within the process (i.e. combine ex-ante and ex-post assessments). For example, incorporating farmer behaviour beyond the profit maximization considered here will be required. Along these lines, future research should coherently integrate aspects of changes in production risks caused by pesticide-free production and consider farmers` risk as well as environmental preferences. Developing spatially explicit modelling approaches that account for spill-over effects of pesticide-free production (e.g. pests, knowledge, machinery use) can further guide policy decisions.

Declaration of Competing Interest

The authors declare that there are now financial interests/personal relationships which may be considered as potential competing interests.

Data availability

The data that has been used is confidential.

Appendix A

Table A1
Assumptions on yield levels for currently intensive (all pesticides) and extenso (insecticide- & fungicide-free) cropping systems [dt/ha].

	Average yield level		Yield levels below average		Yield levels above average	
	Intensive	Extenso	Intensive	Extenso	Intensive	Extenso
Wheat	69.2	59.2	60.3	50.2	77.7	66
Barley	84.4	64.1	68	49.2	92.8	79
Rapeseed	31.7	28.1	23.8	21.4	36	32.4
Sunflower	30.9	29.3	28.8	27.3	36	34.1
Protein crops	40	37.8	35	33.1	42	39.7
Sugar-beets	840		695		978	
Potatoes	343		296		438	

Source: Agroscope, 2020 and Agridea, 2020.

Table A2
SWISSland data basis: Yields, prices and costs for currently intensive (all types of pesticides applied) cropping systems (median; SD = standard deviation) (base year 2016/2019).

	Unit	Wheat Intensive		Barley Intensive		Rapeseed Intensive		Sunflower Intensive		Protein crop Intensive		Potatoes		Sugar-beet	
		Median	SD	Median	SD	Median	SD	Median	SD	Median	SD	Median	SD	Median	SD
No. of farms		352		553		175		25		59		201		124	
Yields	dt/ha	67.3	12.3	75.4	19.5	36.7	9.1	31.8	7.6	40.0	10.4	357.6	123.2	808.6	164.1
Product price	CHF/dt	48.9	7.7	35.2	13.5	76.5	8.3	80.0	8.9	37.9	14.7	44.8	22.6	5.6	1.2
Seed costs	CHF/ha	238.2	102.1	186.1	128.8	140.5	131.8	181.0	142.3	348.5	143.2	2731.4	1221.7	322.5	102.0
Fertilizer costs	CHF/ha	214.0	202.7	168.2	156.6	296.9	258.7	256.6	212.9	0.0	154.7	671.3	382.4	271.4	236.2

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Table A2 (*continued*)

	Unit	Wheat Intensive		Barley Intensive		Rapeseed Intensive		Sunflower Intensive		Protein crop Intensive		Potatoes		Sugar-beet	
		Median	SD	Median	SD	Median	SD	Median	SD	Median	SD	Median	SD	Median	SD
Pesticide costs	CHF/ha	280.6	167.9	212.2	164.4	353.5	197.3	187.0	125.6	130.2	87.1	729.6	332.8	625.7	260.4
Cleaning/Drying costs	CHF/ha	140.2	186.7	131.2	170.9	121.5	143.2	166.1	155.6	103.7	113.0	0.0	689.6	0.0	0.0
Hail insurance costs	CHF/ha	79.0	81.7	59.2	53.3	106.9	99.3	86.9	56.3	77.2	59.5	125.7	95.8	93.3	57.6
Other costs	CHF/ha	0.0	137.0	0.0	57.8	0.0	38.8	0.0	16.1	0.0	47.0	238.8	727.6	0.0	62.9

Source: FADN.

Table A3
SWISSland data basis: Yields, prices and costs for currently extenso (insecticide- & fungicide-free) cropping systems (median; SD = standard deviation) (base year 2016/2019).

	Unit	Wheat Extenso		Barley Extenso		Rapeseed Extenso		Sunflower Extenso		Protein crop Extenso	
		Median	SD	Median	SD	Median	SD	Median	SD	Median	SD
No. of farms		746		627		322		99		150	
Yields	dt/ha	59.1	10.5	66.9	19.6	35.0	8.1	31.6	7.1	39.1	10.8
Product price	CHF/dt	50.3	7.5	35.2	14.9	79.1	9.1	84.2	9.6	37.0	12.1
Seed costs	CHF/ha	239.0	95.1	183.0	110.8	126.3	106.2	197.9	114.3	348.5	109.3
Fertilizer costs	CHF/ha	187.4	143.8	167.9	170.8	285.0	256.5	188.4	194.3	0.0	142.1
Pesticide costs	CHF/ha	114.7	116.7	158.6	168.5	309.5	249.9	180.8	107.4	115.7	95.3
Cleaning/Drying costs	CHF/ha	92.9	156.1	114.5	210.3	146.6	153.9	199.2	160.0	119.4	116.1
Hail insurance costs	CHF/ha	55.0	61.3	52.6	54.4	98.2	96.6	80.6	52.7	77.9	52.1
Other costs	CHF/ha	0.0	131.2	0.0	108.5	0.0	49.5	0.0	32.6	0.0	43.3

Source: FADN.

Table A4
Machinery use, variable machinery costs, and labour requirements for chemical and/or non-chemical pest treatments for typical intensive (all types of pesticides applied), extenso (fungicide- & insecticide free), and pesticide-free cropping systems.

		Reference: Intensive crop system				Reference: Extenso crop system				Pesticide-free crop system			
		Treatment [No/ha]	Maintenance costs [CHF/ha]	Fuel costs [CHF/ha]	Working time requirement [h/ha]	Treatment [No/ha]	Maintenance costs [CHF/ha]	Fuel costs [CHF/ha]	Working time requirement [h/ha]	Treatment [No/ha]	Maintenance costs [CHF/ha]	Fuel costs [CHF/ha]	Working time requirement [h/ha]
Cereals	Sprayer (15 m) & tractor	3	22.27	7.54	1.20	1	7.42	2.51	0.40	–	–	–	–
	Tined weeder & tractor	–	–	–	–	–	–	–	–	3	15.90	6.84	1.08
Rape-seed	Sprayer (15 m) & tractor [1)]	4	29.70	10.06	1.60	2	14.85	5.03	0.80	1	7.42	2.51	0.40
	Tined weeder & tractor	–	–	–	–	–	–	–	–	1	5.30	2.28	0.36
	Sugar beet hoe & tractor	–	–	–	–	–	–	–	–	1	16.18	4.74	1.50
Sunflower	Sprayer (15 m) & tractor	2	14.86	5.04	0.80	1	7.43	2.52	0.40	–	–	–	–
	Tined weeder & tractor	–	–	–	–	–	–	–	–	1	5.30	2.28	0.36
	Sugar beet hoe & tractor	–	–	–	–	–	–	–	–	2	32.37	9.47	3.01

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Table A4 (*continued*)

		Reference: Intensive crop system				Reference: Extenso crop system				Pesticide-free crop system			
		Treatment [No/ha]	Maintenance costs [CHF/ha]	Fuel costs [CHF/ha]	Working time requirement [h/ha]	Treatment [No/ha]	Maintenance costs [CHF/ha]	Fuel costs [CHF/ha]	Working time requirement [h/ha]	Treatment [No/ha]	Maintenance costs [CHF/ha]	Fuel costs [CHF/ha]	Working time requirement [h/ha]
Protein crops	Sprayer (15 m) & tractor	2	14.86	5.04	0.80	1	7.43	2.52	0.40	–	–	–	–
	Tined weeder & tractor	–	–	–	–	–	–	–	–	2	10.60	4.56	0.72
Sugar beets	Sprayer (15 m) & tractor	7	51.97	17.60	2.79	–	–	–	–	2	14.85	5.03	0.80
	Tined weeder & tractor	–	–	–	–	–	–	–	–	1	5.30	2.28	0.36
	Sugar beet hoe & tractor	–	–	–	–	–	–	–	–	3	48.55	14.21	4.51
Potatoes	Sprayer (15 m) & tractor	9	66.82	22.63	3.59	–	–	–	–	4	29.70	10.06	1.60
	Tined weeder & tractor	–	–	–	–	–	–	–	–	1	5.30	2.28	0.36
	Potato hoe & tractor	–	–	–	–	–	–	–	–	2	52.87	22.50	3.57

Note: * In sugar-beet production, herbicide applications until the 4 leaf-stage are allowed in the pesticide-free cropping system. We assumed that one treatment is applied before the sprouting of the weeds and one treatment between the sprouting and the 4th leaf stadium. Mechanical weeding is carried out between and in the rows. In potato production, fungicides and BT preparations are allowed in the pesticide-free cropping system. For rapeseed, 95% Kaolin (Surround) against pollen beetle for insecticide-free rapeseed production is allowed.
Sprayer 15 m; 800 l tank; tined weeder, 6 m; sugar beet hoe 6-row, foldable; potatoe hoe & ridging hiller, 4-row;
Sources: Own calculations based on Agridea (2020) and Gazzarin (2021).

Table A5
Changes in revenues and costs per ha (CHF/ha) due to a transition to pesticide-free cropping systems for intensive crops (Medium loss scenario).

	Unit	Wheat Intensive		Barley Intensive		Rapeseed Intensive		Sunflower Intensive		Protein crops Intensive		Potatoes		Sugar-beet	
		Median	SD	Median	SD	Median	SD	Median	SD	Median	SD	Median	SD	Median	SD
No. of farms		352		553		175		25		59		201		124	
Revenue changes	CHF/ha	−482	256	−116	230	−845	295	+221	46	+30	15	−2881	1330	−1618	548
Costs reduction	CHF/ha	+292	184	+217	180	+246	124	+118	122	+123	86	+235	260	+374	182
Direct payment changes	CHF/ha	+650		+650		+1400		+650		+650		+1400		+1400	
Total changes	CHF/ha	+553	257	+611	224	+829	275	+995	135	+802	92	−1271	1317	+147	561

Table A6
Changes in revenues and costs per ha (CHF/ha) due to a transition to pesticide-free cropping systems for Extenso crops (Medium loss scenario).

	Unit	Wheat Extenso		Barley Extenso		Rapeseed Extenso		Sunflower Extenso		Protein crops Extenso	
		Median	SD	Median	SD	Median	SD	Median	SD	Median	SD
Number of farms	No										
Revenue changes	CHF/ha	−322	242	−276	254	−229	130	120	28	−16	7
Cost reductions	CHF/ha	+99	125	+139	184	+147	138	+99	109	+99	96
Direct payment changes	CHF/ha	250		250		600		250		250	
Total changes	CHF/ha	11	241	57	230	589	170	466	110	331	96

Table A7
Change in labour requirements when farmers with currently intensive (all pesticides) resp. extenso (insecticide- & fungicide-free) cropping systems switch to pesticide-free systems (% change of labour requirements compared to the reference scenario).

	Intensive	Extenso
Wheat	−1%	+3%
Barley	−1%	+3%
Rapeseed	+3%	+6%
Sunflower	+10%	+12%
Protein crops	+0%	+1%
Sugar-beet*	+5%	
Potato*	+1%	

Note: * In sugar-beet production, herbicide applications until the 4 leaf-stage are allowed in pesticide-free cropping systems. We assumed that one treatment is applied before the sprouting of the weeds and one treatment between the sprouting and the 4th leaf stadium. Mechanical weeding is carried out between and in rows. In potato production, fungicides and BT preparations are allowed in pesticide-free cropping systems.

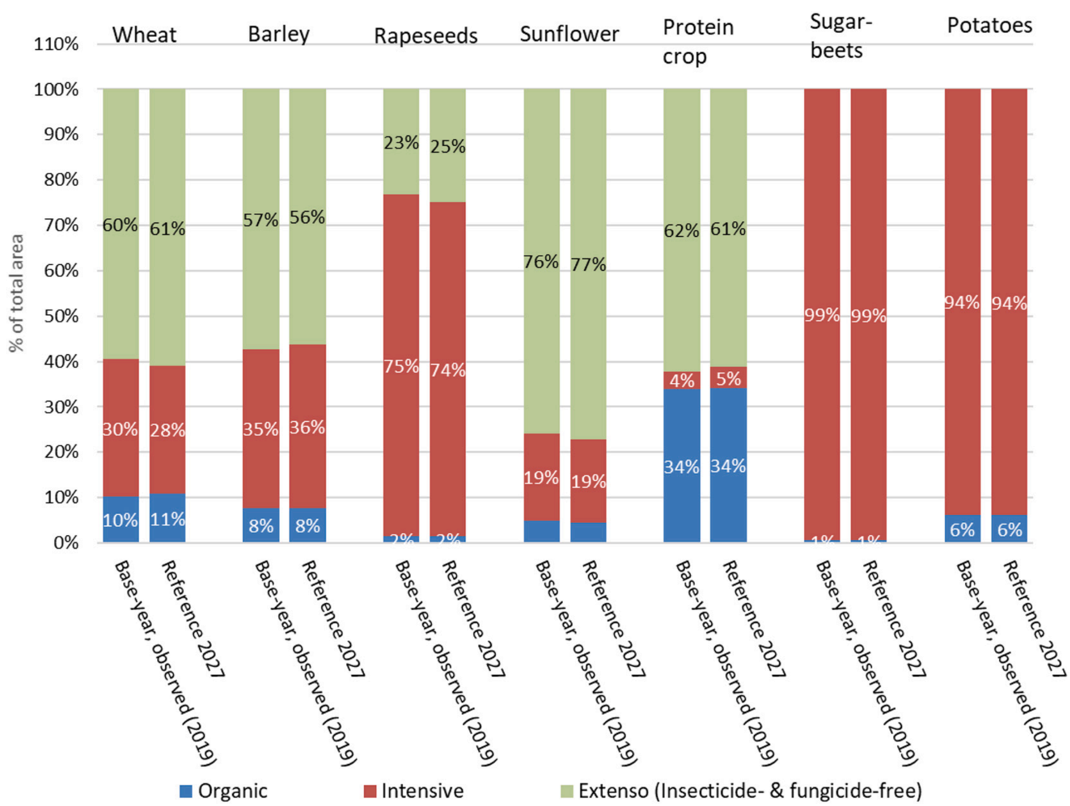

Fig. A1. Crop-specific share of organic, intensive (all pesticides) and extenso (insecticide- & fungicide-free) areas at the national scale: Comparison of observed base-year levels in 2019 with forecasting results (year 2027) in the reference scenario.

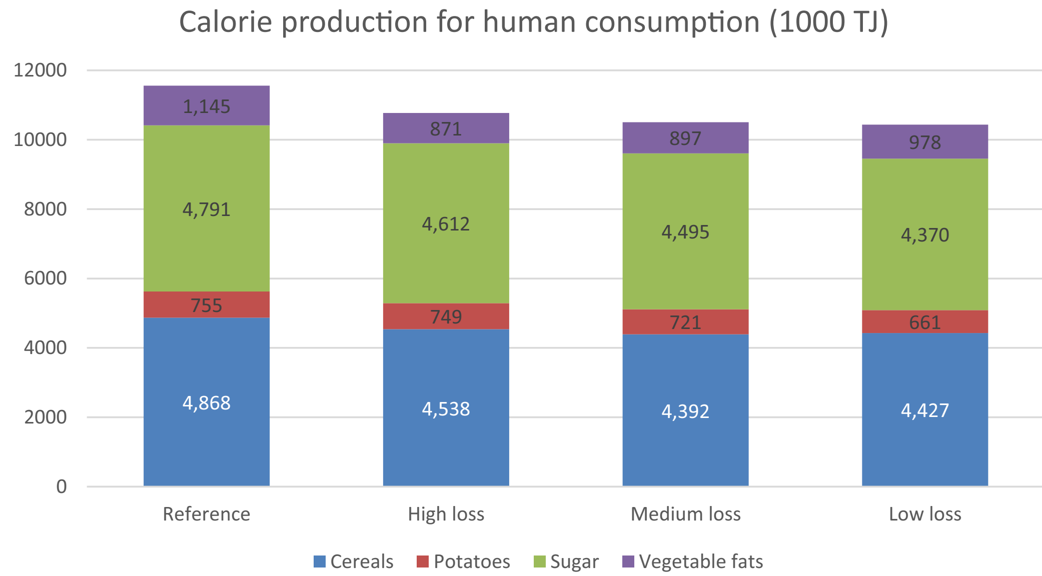

Fig. A2. Impact of pesticide-free production on calorie production for human consumption on the national scale.
Note: High loss: 10% highest. Medium loss: Average yield losses due to pesticide-free were assumed based on the Delphi-study. Low loss: 10% lowest.

Appendix B. Reduction of hail insurance and cleaning & drying costs

When farmers adopt pesticide-free production schemes, they can save costs for hail insurance, grain drying, and purification. Hail insurance costs decrease when crop revenues decline. Cleaning & drying costs depend on crop yield. Cost savings for hail insurance costs were calculated according to eq. B1. Cost savings for cleaning & drying costs were calculated according to eq. B2.

$$\Delta HC_{c,i,f} = HC - \left[HC_{ci,f} / R_{c,i,f} \ast \left[\left[Y_{c,i,f} \ast \Delta Y_{c,i} \ast P_{c,I,f}\right] - \left[\left[Y_{c,i,f} - Y_{c,i,f} \ast \Delta Y_{c,i}\right] \ast P_{c,i,f} \ast \Delta P_{c,i}\right]\right]\right] \quad \text{(B1)}$$

$$\Delta DC_{c,i,f} = DC - \left[DC_{ci,f} / Y_{c,i,f} \ast \left[\left[Y_{c,i,f} \ast \Delta Y_{c,i} \ast P_{c,I,f}\right] - \left[\left[Y_{c,i,f} - Y_{c,i,f} \ast \Delta Y_{c,i}\right] \ast P_{c,i,f} \ast \Delta P_{c,i}\right]\right]\right] \quad \text{(B2)}$$

With.
c = crop (wheat, barley, rapseed, sunflower, proetein crops, potatoes, sugar-beets).
i = intensity (intensive or extenso).
f = farm (*i* = 1.0.1907).
Y = Initial crop yield from FADN data.
ΔY = Percentage yield changes due to pesticide-free production from the Delphi study.
P = Initial product price from FADN data.
ΔP = Percentage price premium for pesticide-free crops.
ΔHC = Reduction of hail insurance costs due to pesticide-free production.
HC = Initial hail insurance costs from the FADN data.
R = Initial revenues from FADN data.
ΔDC = Reduction of cleaning & drying costs due to pesticide-free production.
DC = Initial cleaning & drying costs from FADN.

References

Agridea, 2020. Deckungsbeiträge. Lindau. Juni, p. 2020.
Agroscope, 2020. Zentrale Auswertung von Buchhaltungsdaten. Stichprobe Betriebsführung. Betriebszweigergebnisse 2019. Spezialpublikation, Oktober 2020.
BAFU (Bundesamt für Umwelt) and BLW (Bundesamt für Landwirtschaft), 2016. Umweltziele Landwirtschaft - Statusbericht 2016. In: BAFU. Umwelt- Wissen. Bundesamt für Umwelt, Bern, p. 114.
Bianchi, F.A., Ives, A.R., Schellhorn, N.A., 2013. Interactions between conventional and organic farming for biocontrol services across the landscape. Ecol. Appl. 23 (7), 1531–1543.
BLW (Bundesamt für Landwirtschaft), 2021. Verordnungspaket Parlamentarische Initiative 19.475 «Das Risiko beim Einsatz von Pestiziden reduzieren». Erläuternder Bericht zur Eröffnung des Vernehmlassungsverfahrens. Bern, 28. April 2021. https://www.blw.admin.ch/blw/de/home/politik/agrarpolitik/parlamentarischeinitiative.html.
Böcker, T., Möhring, N., Finger, R., 2019. Herbicide free agriculture? A bio-economic modelling application to Swiss wheat production. Agric. Syst. 173, 378–392.
Böcker, T., Britz, W., Möhring, N., Finger, R., 2020. An economic and environmental assessment of a glyphosate ban for the example of maize production. Eur. Rev. Agric. Econ. 47 (2), 371–402.
Cooper, J., Dobson, H., 2007. The benefits of pesticides to mankind and the environment. Crop Prot. 26 (9), 1337–1348.
De Souza, R.M., Seibert, D., Quesada, H.B., de Jesus Bassetti, F., Fagundes-Klen, M.R., Bergamasco, R., 2020. Occurrence, impacts and general aspects of pesticides in surface water: a review. Process Saf. Environ. Prot. 135, 22–37.
Dessart, F.J., Barreiro-Hurlé, J., van Bavel, R., 2019. Behavioural factors affecting the adoption of sustainable farming practices: a policy-oriented review. Eur. Rev. Agric. Econ. 46 (3), 417–471.
Devaney, L., Henchion, M., 2018. Who is a Delphi 'expert'? Reflections on a bioeconomy expert selection procedure from Ireland. Futures 99, 45–55. https://doi.org/10.1016/j.futures.2018.03.017.
Doppler, T., Mangold, S., Wittmer, I., Spycher, S., Comte, R., Stamm, C., Singer, H., Junghans, M., Kunz, M., 2017. Hohe PSM-Belastung in Schweizer Bächen. NAWA-SPEZ-Kampagne untersucht Bäche in Gebieten intensiver landwirtschaftlicher Nutzung. Aqua & Gas 97 (4), 46–56.
European commission, 2020. A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0381.
Federal Chancellery, 2018. Botschaft zur Volksinitiative «Für sauberes Trinkwasser und gesunde Nahrung – Keine Subventionen für den Pestizid- und den prophylaktischen Antibiotika-Einsatz». In: BLW. Schweizerische Eidgenossenschaft, Bern.

Federal Council, Juni 2021. Erläuterungen des Bundesrates - Volksabstimmung vom 13 (accessed 22 March 2023). https://www.admin.ch/dam/gov/de/Dokumentation/Abstimmungen/juni2021/Abstimmungsbroschuere_13-06-2021_WEB_de.pdf.download.pdf/Abstimmungserl%C3%A4uterungen%20Juni%2021.pdf.
Finger, R., 2021. No pesticide-free Switzerland. Nature Plants 7 (10), 1324–1325.
Finger, R., El Benni, N., 2013. Farmers' adoption of extensive wheat production–determinants and implications. Land Use Policy 30 (1), 206–213.
Finger, R., Möhring, N., 2022. The adoption of pesticide-free wheat production and farmers' perceptions of its environmental and health effects. Ecol. Econ. 198, 107463 https://doi.org/10.1016/j.ecolecon.2022.107463.
Gazzarin, C., 2021. Maschinenkosten, Agroscope Transfer | Nr. 408 / 2021.
Gill, R.J., Ramos-Rodriguez, O., Raine, N.E., 2012. Combined pesticide exposure severely affects individual-and colony-level traits in bees. Nature 491 (7422), 105–108.
Hossard, L., Philibert, A., Bertrand, M., Colnenne-David, C., Debaeke, P., Munier-Jolain, N., Makowski, D., 2014. Effects of halving pesticide use on wheat production. Sci. Rep. 4 (1), 1–7.
Huber, R., Finger, R., 2019. Popular initiatives increasingly stimulate agricultural policy in Switzerland. EuroChoices 18 (2), 38–39.
Jacquet, F., Butault, J.P., Guichard, L., 2011. An economic analysis of the possibility of reducing pesticides in French field crops. Ecol. Econ. 70 (9), 1638–1648.
Jacquet, F., Delame, N., Vita, J.L., Huyghe, C., Reboud, X., 2021. The micro-economic impacts of a ban on glyphosate and its replacement with mechanical weeding in French vineyards. Crop Prot. 150, 105778.
Jacquet, F., Jeuffroy, M.H., Jouan, J., Le Cadre, E., Litrico, I., Malausa, T., Reboud, X., Huyghe, C., 2022. Pesticide-free agriculture as a new paradigm for research. Agron. Sustain. Dev. 42 (1), 1–24.
Knapp, L., Wuepper, D., Finger, R., 2021. Preferences, personality, aspirations, and farmer behavior. Agric. Econ. 52 (6), 901–913.
Kudsk, P., Mathiassen, S.K., 2020. Pesticide regulation in the European Union and the glyphosate controversy. Weed Sci. 68 (3), 214–222.
Larsen, A.E., Noack, F., 2021. Impact of local and landscape complexity on the stability of field-level pest control. Nature Sustainability 4 (2), 120–128.
Lechenet, M., Dessaint, F., Py, G., Makowski, D., Munier-Jolain, N., 2017. Reducing pesticide use while preserving crop productivity and profitability on arable farms. Nature Plants 3 (3), 1–6.
Mack, G., Huber, R., 2017. On-farm compliance costs and N surplus reduction of mixed dairy farms under grassland-based feeding systems. Agric. Syst. 154, 34–44. https://doi.org/10.1016/j.agsy.2017.03.003.
Mack, G., Möhring, A., 2021. SWISSland Modellierung zur PaIv 19.475: «Das Risiko beim Einsatz von Pestiziden reduzieren». 28. April 2021. https://www.agroscope.admin.ch/agroscope/de/home/themen/wirtschaft-technik/oekonomische-modellierung-politikanalyse.html.
Mack, G., Ferjani, A., Möhring, A., von Ow, A., Mann, S., 2019a. How did farmers act? Ex-post validation of linear and positive mathematical programming approaches for farm-level models implemented in an agent-based agricultural sector model. Bio-based and Applied Economics 8 (1), 3–19. https://doi.org/10.13128/bae-8144 (ISSN 2280-6172).
Mack, G., Heitkämper, K., El Benni, N., 2019b. Welche Faktoren beeinflussen die Wahrnehmung des administrativen Aufwands? Agrarforschung 10 (3), 104–109.
Mack, G., Ritzel, C., Heitkämper, K., El Benni, N., 2021. The effect of administrative burden on farmers' perceptions of cross-compliance based direct payment policy. Public Adm. Rev. 81 (4), 664–675. https://doi.org/10.1111/puar.13335.
Malaj, E., Peter, C., Grote, M., Kühne, R., Mondy, C.P., Usseglio-Polatera, P., Schäfer, R. B., 2014. Organic chemicals jeopardize the health of freshwater ecosystems on the continental scale. Proc. Natl. Acad. Sci. 111 (26), 9549–9554.
Meemken, E.M., Qaim, M., 2018. Organic agriculture, food security, and the environment. Ann. Rev. Resour. Econ. 10, 39–63.
Meena, R.S., Kumar, S., Datta, R., Lal, R., Vijayakumar, V., Brtnicky, M., Marfo, T.D., 2020. Impact of agrochemicals on soil microbiota and management: a review. Land 9 (2), 34.
Möhring, N., Finger, R., 2022. Pesticide-free but not organic: adoption of a large-scale wheat production standard in Switzerland. Food Policy 106, 102188.
Möhring, A., Mack, G., Zimmermann, A., Ferjani, A., Schmidt, A., Mann, S., 2016a. Agent-Based Modeling on a National Scale – Experiences from SWISSland. Agroscope Science, Ettenhausen, p. 30.
Möhring, A., Ferjani, A., Mack, G., Mann, S., Zimmermann, A., 2016b. Modellprojektionen mit SWISSland zum Zahlungsrahmen 2018–2021. Agroscope Science 35, 1–28.
Möhring, N., Gaba, S., Finger, R., 2019. Quantity based indicators fail to identify extreme pesticide risks. Sci. Total Environ. 646, 503–523.
Möhring, N., Bozzola, M., Hirsch, S., Finger, R., 2020. Are pesticides risk decreasing? The relevance of pesticide indicator choice in empirical analysis. Agric. Econ. 51 (3), 429–444.
Möhring, A., Drobnik, T., Mack, G., Ammann, J., El Benni, N., 2021. Naturalertragseinbussen durch Verzicht auf Pflanzenschutzmittel im Ackerbau. Resultate einer Delphi-Studie. Agroscope Science, Ettenhausen, p. 125.
Muller, A., Schader, C., El-Hage Scialabba, N., Brüggemann, J., Isensee, A., Erb, K.H., Smith, P., Klocke, P., Leiber, F., Stolze, M., Niggli, U., 2017. Strategies for feeding the world more sustainably with organic agriculture. Nat. Commun. 8 (1), 1–13.
Munz, N., Leu, C., Wittmer, I., 2012. Pestizidmessungen in Fliessgewässern – Schweiz-weite Auswertung. Aqua & Gas 11, 32–41.
Rani, L., Thapa, K., Kanojia, N., Sharma, N., Singh, S., Grewal, A.S., Kaushal, J., 2021. An extensive review on the consequences of chemical pesticides on human health and environment. J. Clean. Prod. 283, 124657.
Renner, S., Jan, P., Hoop, D., Schmid, D., Dux-Bruggmann, D., Weber, A., Lips, M., 2019. Survey system of the Swiss farm accountancy data network with two samples: income situation sample and farm management sample. Agroscope Science 68, 1–76.
Savary, S., Willocquet, L., Pethybridge, S.J., Esker, P., McRoberts, N., Nelson, A., 2019. The global burden of pathogens and pests on major food crops. Nature Ecology & Evolution 3 (3), 430–439.
Schebesta, H., Candel, J.J., 2020. Game-changing potential of the EU's farm to fork strategy. Nature Food 1 (10), 586–588.
Schmidt, A., Mack, G., Möhring, A., Mann, S., El-Benni, N., 2019. Stricter cross-compliance standards in Switzerland: economic and environmental impacts at farm- and sector-level. Agric. Syst. 176, 102664.
Scott, C., Bilsborrow, P.E., 2019. The impact of the EU neonicotinoid seed-dressing ban on oilseed rape production in England. Pest Manag. Sci. 75 (1), 125–133.
Seufert, V., Ramankutty, N., 2017. Many shades of gray—the context-dependent performance of organic agriculture. Sci. Adv. 3 (3), e1602638.
Spycher, S., Mangold, S., Doppler, T., Junghans, M., Wittmer, I., Stamm, C., Singer, H., 2018. Pesticide risks in small streams – how to get as close as possible to the stress imposed on aquatic organisms. Environ. Sci. Technol. 52 (8), 4526–4535.
Tang, F.H., Lenzen, M., McBratney, A., Maggi, F., 2021. Risk of pesticide pollution at the global scale. Nat. Geosci. 14 (4), 206–210.
Zimmermann, A., Möhring, A., Mack, G., Ferjani, A., Mann, S., 2015. Pathways to truth: comparing different upscaling options for an agent-based sector model. Journal of Artificial Societies and Social Simulation (JASSS) 18 (4), 11.
Zorn, A., Meier, L., Clémence, S., 2022. Beurteilung alternativer Pflanzenschutzmassnahmen durch LandwirtInnen. SGA-Tagung 2022 «Evidenzbasierte Agrar- und Ernährungspolitik - Rolle der Forschung für die Politikgestaltung» 28. – 29. April 2022 in Frick beim FiBL Schweiz. https://www.conftool.org/sga2022/index.php/Zorn-Beurteilung_alternativer_Pflanzenschutzmassnahmen_durch_LandwirtInnen-128.docx?page=downloadPaper&filename=Zorn-Beurteilung_alternativer_Pflanzenschutzmassnahmen_durch_LandwirtInnen-128.docx&form_id=128.