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Pesticide-free but not organic: Adoption of a large-scale wheat production standard in Switzerland

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A B S T R A C T

The sustainable intensification of agriculture requires solutions for a large-scale reduction of pesticide use while sustaining agricultural yields. Pesticide-free production standards, which bring together the strengths of all the food value chain actors, could be a cornerstone of this transformation. In Switzerland, a non-organic, private–public standard for pesticide-free wheat production is currently being introduced by the producer organization IP-SUISSE. It is the first of its kind in Europe and may reach a market share of 50% of Swiss wheat production. We here assess the determinants of farmers' participation and willingness to participate in the future. For our analysis, we combine a survey of the entire population of IP-SUISSE wheat producers (4749 farmers, 23.3% response rate) with data on historical farm-level wheat yields, soil properties, weather, climate, weed pressure, and spread of herbicide resistance. Our results indicate that a large-scale establishment of pesticide-free wheat production in Switzerland is possible. We find that farmers' perceptions of positive environmental effects of the production program are key for adoption. Moreover, farmers' expectations of the program's production effects play a central role. Farmers perceiving large yield losses and increases in production risks are less likely to enter the program. Based on our results, we discuss implications, leverage points, and challenges for designing and implementing large-scale pesticide-free production programs.

1. Introduction

Agriculture faces the challenge of increasing agricultural production while reducing adverse environmental and health impacts (Godfray et al., 2010; Pretty, 2018). Effective and sustainable pest management plays a central role in achieving these goals (Larsen et al., 2017; Oerke, 2005; Savary et al., 2019; Stehle and Schulz, 2015). Reducing pesticide use on a large scale without harnessing food supply requires novel, more flexible production systems with fewer trade-offs to complement organic farming systems (Meemken and Qaim, 2018; Seufert and Ramankutty, 2017). Crop rotations, which are partly pesticide-free, could play a vital role in the future of agriculture. Establishing such production systems requires the combined efforts of all actors of the food-value chain (Möhring et al., 2020b). Public-private production standards may therefore be a viable tool for the large-scale implementation of such production systems. Importantly, farmers' decision-making in such production systems determines their total economic and environmental effects and is key for a successful implementation.

In this article, we conduct an *ex-post* analysis of determinants, barriers, and challenges for adopting pesticide-free (but non-organic) wheat production in Switzerland. It is the first large-scale program for pesticide-free production in Europe. The voluntary production scheme builds on a combination of public compensation (via direct payments) and private compensation (via price mark-ups) mechanisms for farmers. We base our analysis on a survey with 4749 Swiss wheat producers. Survey data is complemented with spatially-explicit data on structural farm and farmers' characteristics, weed pressure, herbicide resistances, soil conditions, and climate.

Previous literature on pesticide-free production has primarily focused on consumers' willingness to pay for different production standards (Bazoche et al., 2013; Edenbrandt et al., 2018; Magnusson and Cranfield, 2005). However, information on determinants, barriers, and challenges for adopting novel, pesticide-free production standards is required for an optimal program design and large-scale adoption. A wide range of literature on the adoption of more environmentally friendly production systems such as organic farming (Meemken and Qaim, 2018), and more generally, on agri-environmental measures, exists (see Dessart et al., 2019; Malek et al., 2019; Zimmermann and Britz, 2016 for

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Table 1
Essential characteristics of Swiss wheat production systems.

	Conventional	Extenso	Pesticide-free
Average yield	70 dt/ha	55 dt/ha	(52 dt/ha)*
Market price	50 CHF/dt	50 CHF/dt + 5 CHF/dt for Extenso production	50 CHF/dt + 15 CHF/dt for pesticide-free production*
Federal direct payments	–	400 CHF/ha	650 CHF/ha
Production restrictions	Cross compliance obligations (proof of ecological performance)	Cross compliance obligations (proof of ecological performance) IP-SUISSE farm-level compliance criteria. No growth regulators, fungicides, or insecticides in wheat production.	Cross compliance obligations (proof of ecological performance) IP-SUISSE farm-level compliance criteria. No synthetic pesticides

Information on average yields, market prices, and price add-ons are for the year 2019/2020 and come from AGRIDEA (2019). Information on direct payments comes from the Swiss Federal Office for Agriculture. Information on restrictions comes from IP-SUISSE. 1dt = 100 kg, 1 CHF (Swiss Franc) = 1.02 $ (average exchange rate for 2019). Note that all Swiss farmers receiving direct payments have to follow cross-compliance obligations called "proof of ecological performance" (Huber et al., 2017). IP-SUISSE farm-level compliance criteria include some general rules for sustainable production, e.g., regulating the use of genetically modified organisms (Böcker et al., 2019). *Note that the pesticide-free production system has been introduced in 2018/19 for the first time – information on yields is therefore based on estimates from a bio-economic model (Böcker et al., 2019), and information on prices is based on previous prices in 2018/19.

an overview). Results for different production systems, agri-environmental schemes, or environmental and social contexts can, though not be generalized (Knowler and Bradshaw, 2007). The adoption of non-organic, pesticide-free production systems has rarely been addressed (Christensen et al., 2011; Finger and El Benni, 2013). However, the adoption of these systems poses different challenges to farmers and has distinctly lower adoption barriers than systems that require adjustments on the entire farm, such as organic farming. Moreover, large-scale production systems of this kind have not been established, and only *ex-ante* analyses with bio-economic models on potential economic and environmental effects have been conducted so far (Böcker et al., 2020; Böcker et al., 2019; Schmidt et al., 2019).

We contribute to the literature with the first analysis of adoption determinants, barriers, and challenges of a large-scale, private–public program for non-organic, pesticide-free production. We conducted a large-scale survey and analyzed the farmers' adoption decisions using regression analysis. The detailed dataset used for the analysis allowed us to perform extensive robustness checks regarding our sample's internal validity and the results of the regression analysis.

We find that adoption is mainly driven by the farmers' expectations of the program's effects. More specifically, we find that farmers' adoption is driven by the perception of pesticide-free production's positive environmental effects. Furthermore, farmers' expectations regarding the program's production effects are key. Farmers expecting large yield losses and increases in production risks are less likely to enter the program. Moreover, adjustment costs reflecting farmers' current tillage practices and machinery endowment for mechanical weed control determine participation decisions. We find that neither structural farm and farmers' characteristics, such as age, education, farm size, farm orientation, farm location or average yield levels, nor environmental conditions play a role in the adoption decision. We conclude that communication of environmental benefits to farmers and resolving uncertainty regarding program outcomes for production levels and risks play a central role in adopting novel (pesticide-free) production systems and discuss implications for their design to achieve a large-scale adoption.

The remainder of the article is structured as follows. First, we give background information on the pesticide-free wheat production system, summarize relevant literature, and present our theoretical and empirical model. Then we present the data used for the analysis, followed by the descriptive analysis and regression analysis results. Finally, we discuss the results and conclude.

2. Background

Following, we introduce the Swiss pesticide-free wheat production program and then present relevant literature and our conceptual adoption model.

2.1. The Swiss pesticide-free wheat production program

The producer organization IP-SUISSE is currently introducing a non-organic, pesticide-free wheat production standard in Switzerland – the first large-scale production program of its kind in Europe. Starting from 1992/93,[1] IP-SUISSE members have started to produce wheat under the so-called "Extenso" program. In this program, participants are neither allowed to use insecticides, fungicides, nor growth regulators in wheat production. They further face some additional restrictions, including a restriction to growing stubble wheat ("wheat-after-wheat" rotations) and complying with some general on-farm sustainability criteria (Böcker et al., 2019). The novel "pesticide-free wheat" production program goes even further by restricting farmers from using conventional pesticides in wheat production.

Contrary to organic farming, the program neither restricts fertilization in wheat nor input use or crop management in the rest of the crop rotation. It, therefore, poses significantly fewer adoption barriers for farmers than organic farming. To incentivize adoption, the program relies on both public and private compensation mechanisms for farmers. Participants are remunerated with a market-based price add-on, as well as governmental (per hectare) direct payments for pesticide-free production (see Table 1 for an overview[2]).

The pesticide-free wheat production program has started in 2018/19 with a pilot of 1200 ha. From the growing season 2019/20 on, it has been opened up for all IP-SUISSE producers. The goal is a large-scale adoption of pesticide-free wheat production. The program envisions that a large share of the 50% of Swiss wheat surface under Extenso production will be under pesticide-free production in the long run. The program was introduced by IP-SUISSE in the context of strong signals from citizens and consumers in Switzerland to switch to a more sustainable and especially pesticide-free production. More specifically, two popular initiatives on banning synthetic pesticides and tightening cross-compliance regulations towards use of no synthetic pesticides were voted on in Switzerland in June 2021 and a large debate on the effects of

[1] Note that in Switzerland the growing season of winter wheat usually starts in October and wheat is harvested in July/August of the following year.

[2] Note that organic wheat production in Switzerland is renumerated by 1600 CHF/ha (including organic production payments) but also poses significantly higher adoption barriers. It requires farmers to comply with organic farming regulations on a whole farm-level in Switzerland, for example restricting pesticide use and the use of synthetic fertilizers in the whole crop rotation.

pesticides on Swiss drinking water was taking place in Swiss society[3] (see Finger, 2021 for an overview). Wheat production plays an important role for pesticide use, as the major crop in Switzerland and Europe more generally.

The largest Swiss retailer (Migros) has recently announced selling only bread made from “pesticide-free wheat” from 2023 on (making up for around 20% of Swiss wheat production), further leveraging efforts to establish the program and expand participation.[4] Note that this decision does not directly affect conventional wheat producers and other marketing channels for Extenso wheat still exist (e.g. to other retailers, bakeries). Thus, Extenso and pesticide-free wheat production programs will co-exist. This will leave current Extenso producers the possibility to continue Extenso production.

Yields for Extenso wheat are around 20% lower and more volatile than conventional wheat, but profits have been found to be higher for most farmers due to additional direct payments and price mark-ups (Finger, 2014; Finger and El Benni, 2013). In an *ex-ante* analysis with a bio-economic model, Böcker et al. (2019) find that the adoption of pesticide-free wheat production is economically viable for the great majority of IP-SUISSE producers. Even though Böcker et al. (2019) predict on average yield reductions of around 6% compared to Extenso production, additional price add-ons (10 CHF/dt) and direct payments (250 CHF/ha) compared to Extenso production would outweigh these yield reductions. In pesticide-free production systems, mechanical weed control measures like tillage and harrowing replace herbicides, which are allowed in Extenson production. They may be accompanied by a range of agronomic measures, such as changes in the crop rotation or planted varieties and the use of undergrowth, catch crops, or increased stubble work.

Further, farmers can receive direct payments for soil conservation. For example, adopting no-till, strip-till, and mulch-tillage are remunerated with 250, 200, and 150 CHF/ha and year, respectively.[5] Participation in these programs is relevant, as soil conservation programs restrict mechanical weed control techniques, such as plowing, which are important substitutes for herbicide use in pesticide-free production. Wheat production which is soil-conserving and pesticide-free at the same time is still possible: For example, the use of comb harrows (together with adjustments in the crop rotation) is an alternative to ploughing. However, alternative strategies might yield lower efficiency (lower efficacy and higher costs) in weed control than ploughing or herbicide use (Böcker et al., 2019).

2.2. Conceptual model

Following, we present a conceptual model for the adoption of pesticide-free production systems and then apply this model to our case study. As a basis for the conceptual model, we build upon previous literature on farmers’ adoption decisions and interviews with IP-SUISSE farmers and Swiss extension service experts.

Let $\pi_{it}(A_{it}, X_{it}, Env_{it}, \varepsilon_{it}^{A})$ denote random profit of farmer i in year t, where A_{it} denotes the farmers’ adoption decision of the pesticide-free production program (with $A_{it}^{A=1}$ reflecting adoption). X_{it} (very generally) denotes structural farm- and farmers characteristics, Env_{it} denotes environmental conditions (e.g., soil conditions, weather or pest pressure) and ε_{it}^{A} very generally denotes uncertainty concerning production (e.g., yield and quality) in the chosen program.

We can describe the utility-maximizing problem of the farmer as:

$$\max_{A_{it}} E[U(\pi_{it}(A_{it}, X_{it}, Env_{it}, \varepsilon_{it}^{A}), PE_{it})] \tag{1}$$

where U is the von-Neumann-Morgenstern utility function of the farmer and PE_{it} denotes the farmer’s expectations of the program’s effects on production (beyond effects of structural and environmental characteristics captured in the profit function) and on reducing environmental and human health effects.

A utility-maximizing farmer would then choose to adopt pesticide-free production, ceteris paribus, if:

$$E\left[U\left(\pi_{it}\left(A_{it}^{A=1}, X_{it}, Env_{it}, Adj_{it}, \varepsilon_{it}^{A^{A=1}}\right), PE_{it}\right)\right] \geq E\left[U\left(\pi_{it}\left(A_{it}^{A=0}, X_{it}, Env_{it}, \varepsilon_{it}^{A^{A=0}}\right), PE_{it}\right)\right] \tag{2}$$

where Adj_{it} denotes the farmers’ one-time and long-term costs costs of switching to pesticide-free production.[6] While farmers expectations on expected revenues and costs, risks and other effects arising from program adoption have a multiple year perspective, further dynamic aspects, such as the choice of crop rotations and adjustments on a farm-level are out of the scope of our analysis, as we are looking at program adoption in an early stage. However, they should be considered in further analyses concerning environmental and farm-level effects of the program introduction. We therefore here assume farmers to choose a crop rotation, which maximizes expected utility given the adoption decision, without explicitly modelling these decisions.

Following, we apply our conceptual model to the adoption of the Swiss pesticide-free wheat production program by IP-Suisse Extenso wheat producers.[7] We discuss potential adoption determinants in four main categories: i) characteristics of the production system before adoption, ii) environmental conditions and structural farm and farmers’ characteristics, iii) farmers’ perceptions and expectations of the program (behavioral characteristics), and iv) one-time and long-term adjustment costs to pesticide-free production:

i) production system before adoption

We expect that the farm’s current production orientation determines opportunity costs of the adoption decision and is, therefore, an adoption determinant (Bravo-Monroy et al., 2016; Ma et al., 2012; Pavlis et al., 2016; Reimer et al., 2014). Important characteristics describing the farm’s production orientation in the context of our analysis are the current type of wheat production system (i.e., reflected in average yield levels) and currently used tillage systems (e.g., participation in soil conservation schemes), which are represented by X_{it} in Eq. (2).

[3] Both popular initiatives were rejected, but agricultural producers, policy maker and retail iniated steps in reponse societal concerns, e.g. by establishing new production schemes, direct payments and labels. The here presented case study is one of these outcomes of this process (see Finger, 2021, for details).

[4] https://generation-m.migros.ch/de/nachhaltige-migros/aktuelles/news-template/news/nachhaltigkeit/2020/pestizidfreies-brot.html?utm_source=Social%20Media&utm_medium=LinkedIn&utm_campaign=nachhaltigkeit&utm_term=Pestizide.

[5] If soil conservation measures are combined with herbicide-free production, farmers receive an additional 400 CHF/ha and year.

[6] Note that this basic model may easily be extended to include uncertainty in the farmers’ adjustment costs or to differentiate different types of uncertainty in the utility function (e.g. with regard to crop growth and pest development, see Horowitz and Lichtenberg, 1994 and Möhring et al., 2020a).

[7] Where program characteristics, prices and direct payments are fixed to the year of analysis, i.e. the wheat growing season 2019/20.

ii) Farm- and farmers' characteristics, environmental conditions

We further expect that farm characteristics, such as size, type (i.e., the income share of wheat production), labor force, as well as long-term plans for the farm (i.e., if the farm succession is established) and on-farm growing conditions might play an important role in the farmers' adoption decisions (which are a part of X_{it} in Eq. (2)). Important growing conditions (for pesticide-free wheat) may include soil conditions, topography, climate conditions, and pest pressure. Further, especially weed pressure and potential resistances to herbicides may play an important role in switching from Extenso to pesticide-free wheat production, as synthetic herbicides are allowed under Extenso production (the two latter being part of Env_{it} in Eq. (2)). We further account for potential differences concerning culture and extension service systems between Switzerland's French and German speaking parts (Möhring et al., 2020a). Further, we consider that the program's uptake might be linked to farmers' age or education through differences in farmers attitudes across demographic and education groups. But age and education might also constitute potential barriers to adoption in themselves e.g. through reduced ability and higher costs to learn new techniques and adapt management strategies (Burton, 2014) (the two latter being part of X_{it} in Eq. (2)).

iii) Farmers' perceptions and expectations

The literature on the adoption of sustainable farming practices shows that behavioral factors often play a key role in farmers' adoption decisions (see Dessart et al., 2019 for an overview). We, therefore, expect that farmers' preferences, attitudes, and expectations, will influence adoption (which are part of PE_{it} in Eq. (2)). We expect that due to the novelty of the program, especially farmers' (potentially heterogeneous) expectations concerning yield effects and production risks of the pesticide-free production system will play an important role in adoption (Lequin et al., 2019; Pannell, 2003; Reimer et al., 2012; Star et al., 2019). Farmers' experiences with pesticide-free production and their risk preferences are expected to influence how these uncertainties are weighed in the farmers' decisions (Serra et al., 2008). Finally, we expect that the farmers' perception of potential environmental and health benefits of the production program (i.e., effects of reducing overall pesticide use in wheat production) and their personal preferences will influence participation decisions (Greiner and Gregg, 2011; Sulemana and James, 2014; Toma and Mathijs, 2007; Van Herzele et al., 2013).

iv) Adjustment costs

Adjustment costs include one-time and long-term costs of switching from one production system to another following (Gardebroek and Lansink, 2004) (represented by variable Adj_{it} in Eq. (2)). They are closely linked to the farm orientation and farmers' characteristics described above. Important adjustment costs in the context of our study may include endowment, accessibility, and costs of machinery required for pesticide-free production (i.e., for mechanical weed control), as well as (expected) changes in costs of weed management strategies under pesticide-free production.[8]

Finally, differences in adoption determinants might occur concerning the timing of adoption (adoption pioneers vs. farmers intending to adopt in the future) and should therefore be accounted for. This might be especially relevant in the context of our analysis, where some farmers have already participated in a one-year pilot program. In contrast, others decide about adoption for the first time.

[8] Note that due to the recent introduction of the system we rely on farmers' expectations for measuring potential machinery risks and costs. These variables are therefore closely linked to category iii) on farmers' perceptions and expectations.

3. Empirical strategy

3.1. Empirical model

Based on our conceptual model, we analyze the farmers' adoption decision of the pesticide-free wheat production program with regression analysis. Using the unobserved difference in expected utility in equation two as a latent variable and setting t = 2019/20, we can write the empirical model as:

$$Adopt_{i,t=2019/20} = \beta_1 + \boldsymbol{\beta}^* \boldsymbol{\omega}_i + \eta_i \quad (3)$$

where $Adopt_{i,t=2019/20}$ denotes the adoption decision of the producer, β_1 is the intercept, $\boldsymbol{\omega}_i$ and $\boldsymbol{\beta}$ represent the vectors of potential adoption determinants and their respective regression coefficients and η_i is the error term of the regression analysis. Equation (3) and variations thereof are estimated using linear probability models based on OLS and cluster error terms at the cantonal level[9] in our main model.

We choose explanatory variables in line with the four sets of potential adoption determinants described in our conceptual framework (see Table 2 for an overview). We depict the production system before adoption using dummy variables indicating participation in direct payment schemes for soil conservation and cantonal programs for pesticide reduction[10] and average municipality-level (Extenso wheat) yields from 2008 to 2018. Structural farm characteristics include farm size in hectares of agricultural land, the share of wheat in agricultural land, the workforce's size, the share of arable farming in the farm income, and a dummy variable for differences between language regions (e.g. concerning extension service, see Möhring et al., 2020c).[11] Farmers' characteristics further include a dummy variable for established farm succession and variables for age and education of the farmer. We characterize growing conditions using i) the topography of the farm (share of land in mountainous zones), ii) soil conditions (soil suitability for grain production), climate conditions on the farm (average temperature as well as the mean precipitation in periods critical for mechanical weed control). Moreover, we account for the regional weed pressure and local occurrence of herbicide resistance.

Variables depicting farmers' perceptions and expectations in our analysis include expectations regarding yield decreases and production risk increases under pesticide-free production, risk preferences in the plant protection domain, the farmers' prior experience with pesticide-free wheat production (outside of the program), and the farmers' expectation of the program's contribution to the reduction of adverse environmental and health effects.

Adjustment costs are represented by the availability of machinery for mechanical weed control, the expected risks of investing in such machinery, and the costs of the additional weed management strategies farmers indicated they would employ in pesticide-free wheat production.

[9] Cantons may differ with respect to the provision of extension services (see e.g. Wuepper et al., 2021) as well as cantonal initiatives to foster specific farming practices.

[10] Note that we do not control for federal direct payments for herbicide reduction (see Table 1). These were introduced at the same time as the pesticide-free production system and therefore do not indicate use of pesticide-free production techniques previous to adoption. Moreover, we assume that a utility maximizing farmer would always apply for these direct payments when adopting pesticide-free wheat production. Including them as an explanatory variable may therefore cause severe problems of endogeneity in the regression analysis, while not contributing additional information. Consequently, we also choose variables for cantonal direct payments for pesticide reduction that only indicate participation prior to the creation of the pesticide-free production system.

[11] Note that there are only a few Extenso wheat producer in the Italian speaking part of Switzerland.

Table 2
Descriptions, mean, and standard deviation of all variables used in the analysis.

Name	Unit	Description	Mean*	Sd
Adopt	binary	Has already participated or wants to participate in pesticide-free wheat production (1) or not (0).	0.60	–
Soil conservation	binary	Participated in federal soil conservation program (1) or not (0) in the growing season 2019/20.	0.46	–
DP_canton	binary	Has been participating in the cantonal program for pesticide reduction (1) or not (0) since before the start of the PestiFreeWheat program in 2018/19.	0.88	–
Canton_fr	Binary	The farm is located in a mainly French-speaking canton (1) or not (0).	0.25	0.43
Share_mountain	ratio	Share of the farms agricultural land in the mountain region.	0.05	0.20
Suitability_grains	binary	High suitability for grain cultivation (1) or not (0), according to the Swiss Federal Office for Agriculture.	0.63	–
Temperature	°C	The average of the yearly mean temperatures on the farm over the last ten years preceding the study.	9.00	0.63
Precipitation	l/m2	The average of the sum of precipitation in the wheat growing season per year on the farm, over the last ten years preceding the study.	425.25	50.59
Weed	ratio	Share of weeds present on the farm out of the 21 economically most important weeds for wheat production in Switzerland described in detail in (Böcker et al., 2019), according to Info Flora.	0.48	0.29
Herbicide_resistance	Scale 1–4	The number of herbicide-resistant weed species found in the municipality (herbicide resistance of weeds in wheat production has been observed in Switzerland for the weed species *Alopecurus myosuroides*, *Chenopodium album*, *Lolium multiflorum*, and *Apera spica-venti*).	0.11	0.33
Avg_yield	dt/ha	Mean delivered Extenso wheat yield in the postcode area of the producer from 2008 to 2018.	51.14	4.75
Ag_land	ha	Agricultural land of the farm in hectares.	34.63	21.65
Share_Wheat	Ratio	The ratio of wheat in agricultural land on the farm-level.	0.16	0.11
Workforce	Working units	Standard working units (equals 280 working days (Hoop and Schmid, 2015)) indicating the availability of labor force on the farm.	1.68	1.19
Income_arable	ratio	Share of income from arable farming.	36.08	23.93
Succession	binary	Farm succession is established/not relevant yet (1) or not (0).	0.67	–
Age	Number of years	Producers age in years.	47.08	9.35
Education	Binary	Indicates if the producer has received higher education: at least a "Meister" degree at an agricultural school (1) or not (0).	0.64	–
Experience	Level 0–2	The producer has no experience (0), knows somebody (friend, neighbor, adviser) with experience (1) or has own experience (2) with herbicide-free wheat production.	1.00	–
Availability_machinery	Binary	The producer has access to machinery necessary for mechanical weed control in pesticide-free wheat production (1) or not (0).	0.86	–
Exp_yield_decr	Level 1–5	Producer expects no yield decrease (1) or decrease of 0–5% (2), 5–10% (3), 10–15% (4) or > 15% (5) in pesticide-free wheat production.	3.00	–
Exp_yield_risk	Binary	Producer expects almost no increase in years with crop failure or heavy yield losses (at most every 20 years) (0), or a more severe increase (1) in pesticide-free wheat production.	4.00	–
Risk_pref	Scale 0–10	The producer indicated no willingness to take risks (0) to a very high willingness to take risks (10) in the plant protection domain.	4.80	2.63
Pos_Environ	Scale 1–5	The producer believes that the program has no (1) to very positive (5) effects on the environment.	3.16	1.31
Pos_Health	Scale 1–5	The producer believes that the program has no (1) to very positive	2.57	1.27

(continued on next page)

Table 2 (*continued*)

Name	Unit	Description	Mean*	Sd
		(5) effect on the health of farmers and consumers.		
Exp_risk_machinery	Scale 1–5	The producer expects that the investment in machinery necessary for pesticide-free wheat production (i. e., mechanical weed control) is not risky (1) to very risky (5).	3.45	1.14
Exp_costs	CHF/ha	Costs of pest management practices (e.g., mechanical weed control and adjustments in crop management) that the producer (expects) to additionally deploy for pesticide-free wheat production.	353.86	101.58

Summary statistics are computed for the whole sample of complete observations used in the analyses (excluding producers that did not know the program; N = 1073). Note that for variables, which are in levels, the mode is indicated instead of the mean.

3.2. *Robustness checks*

We provide several robustness checks to the main specification of Eq. (3) provided above.

First, we use Probit and Logit estimation to estimate our model and compare sign and significance of results to the main specification, i.e. the linear probability model (also see Angrist and Pischke, 2008). Second, we estimate the model in Eq. (3), using different configurations of the sets of control variables, i.e., i) characteristics of the farming system before adoption, ii) structural farm and producers' characteristics and environmental conditions, iii) producers' expectations and perceptions and iv) adjustment costs and compare results concerning coefficient estimates and significance of the variables of interest in the main model.

Third, we address potential concerns regarding inference on data with clusters of heterogeneous size (i.e., here cantons), using a wild bootstrap approach (Wu, 1986). Further, on a similar note, error terms might not be correlated within cantons but rather more locally within districts (e.g., due to local initiatives, clubs, associations, discussions with neighboring farmers). We therefore additionally check the robustness of our results clustering error terms at a district level instead of a cantonal level.

Fourth, we investigate if the identified determinants of adoption differ between farmers who have already adopted the production system (further called "adoption pioneers") and farmers who intend to adopt in the future (further called "intended adopters"). Differences between the two groups may reveal important information for the design of pesticide-free production programs (see above). In the robustness checks, we, therefore, create two additional dependent variables: $Pioneer_i$ states that farmers have participated in the program in 2019/20 (1) or not (0). $Intended_i$ indicates if farmers who have not participated in the program in 2019/20 intend to participate in the future (1) or not (0). We then perform two separate regression analyses to identify determinants of "adoption pioneers" and "intended adopters," using $Pioneer_i$ and $Intended_i$ as dependent variables but the same set of explanatory variables as for the main model described above, respectively. Then we compare the results of these two regression analyses to the results of the main analysis.

Finally, we test for the robustness of our estimates to omitted variables, using Oster bounds. To this end, we compute the "delta" indicator suggested by Oster: The indicator gives an estimate of how large selection on unobservables would have to be, compared to observables, to cancel out the statistical significance of the relationships previously estimated, taking into account movements of both, coefficients and R^2 (Oster, 2019). We compute delta for key explanatory variables from our main model, i.e., previous production systems, farmers' perception of the programs' environmental benefits, and expectations regarding production effects and adjustment costs. See Oster (2019) for an extensive presentation and discussion of this approach and (Schaub, 2020) for an implementation in R.

4. Data

We conducted an online-survey on program participation and potential adoption determinants, barriers, and challenges for our analysis. We sent out the survey to the whole population of IP-SUISSE wheat producers (4749 producers) and received 1105 complete answers

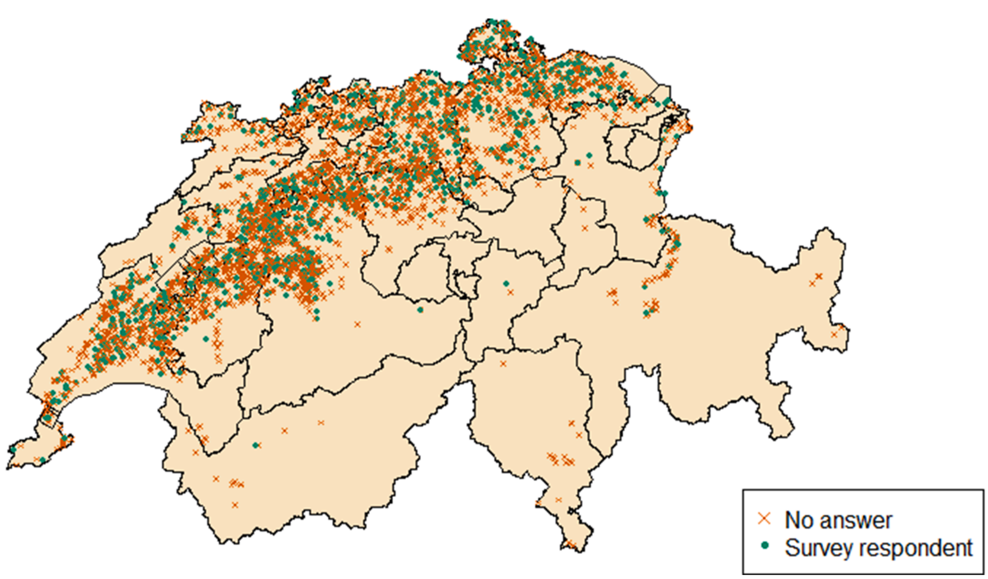

Fig. 1. Distribution of the population of IP-SUISSE farmers by survey participation. The map shows locations of farmers contacted in the survey. "no answer" and "survey respondent" describe farmers, who did not take part in the survey and those who participated in the survey, respectively. N = 4749, response rate (ratio of respondents to contacted farmers) = 23.3%.

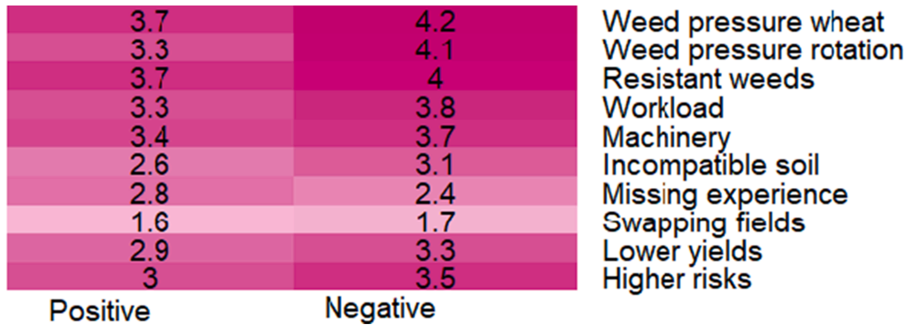

Fig. 2. Rating of potential adoption barriers by survey respondents. The heat map shows the average rating of potential adoption barriers by producers in the survey (N = 1073), rated from 1 (no barrier) to 5 (very strong barrier). "Positive" and "Negative" indicate groups of producers, which stated a positive or a negative attitude towards program participation in the survey, respectively.

(response rate of 23.3%). For an overview of the spatial distribution of the population of IP-SUISSE wheat producers and survey respondents, see Fig. 1.

In the invitation to, the introduction of and throughout the survey, we made clear that we appreciate answers from both producers, who have a positive, and those who have a negative attitude towards the program. As an incentive for participation, we drew twenty shopping vouchers à 50 CHF among participants who filled out the entire survey. Additionally, IP-SUISSE supported the survey by informing members that participation in the survey is important for further developing the pesticide-free wheat production program in the e-mail containing the link to the survey. The survey was conducted between December 2019 and January 2020 and was available both in German and French (farmers self-selected their preferred language). We designed the survey based on the potential adoption determinants from our conceptual and empirical adoption model (see above). The survey questions were then reviewed by several extension service experts, IP-SUISSE experts and producers, and farm advisors. Finally, before sending out the survey, we conducted a pre-test with ten IP-SUISSE producers. Survey results were further verified for consistency of answers against experiences of IP-SUISSE experts from exchanges with a wide range of prdocuers after the season.

The survey contained three major parts: i) program participation, assessment, expectations ii) structural farm and producerss' characteristics, and iii) behavioral characteristics. More specifically, in the first part, we asked producers about their participation decision and intention to participate in the future, costs and benefits of program adoption, expected crop management decisions under participation (e.g., herbicide substitution strategies), and expected changes in production. The second part focused on farm and producers' characteristics, such as age, education, farm type, and farm succession. Finally, in the third part of the survey, we asked producers questions concerning their risk preferences, expected environmental and health benefits of the program, environmental attitudes, farming objectives, self-efficacy, and locus of control. For a detailed description and transcript of survey questions, see the accompanying data article. Answering the survey took participants a median time of 17.9 min.

We combined data from the survey with data on historical yields and structural farm and producers' characteristics from the IP-SUISSE database for our analysis. IP-SUISSE data includes information on average, historical Extenso wheat yields, years of IP-SUISSE membership, farm size, animal stocking, topography, and wheat surface. We also incorporated information on weed pressure of the economically most important weeds in Swiss wheat production according to Böcker et al. (2019) from Info Flora (Info Flora, 2019). Moreover, we accounted for local information on spread of herbicide resistances from Agroscope (i.e., for the weed species *Alopecurus myosuroides*, *Chenopodium album*, *Lolium multiflorum,* and *Apera spica-venti,* see Tschuy and Wirth, 2015). We include ten year averages of temperature and precipitation at a farm-level, as a general control for suitability of long-term climatic conditions for wheat production (i.e. affecting yield potential) from MeteoSuisse (Frei, 2014; Frei et al., 2006). Finally, we accounted for soil conditions (e.g., suitability for wheat production) from the Swiss Federal Office for Agriculture (Swiss Federal Office for Agriculture, 2009). Except for IP-SUISSE data, which is confidential, all datasets are freely available upon request from the indicated sources and are included in the published dataset (see the accompanying data article). All data are matched on a farm-level, except for information on herbicide resistance, which is only available on a municipality level. Data on average historical yields is further matched on a postcode level to account for potential empty entries and measurement errors in single years.

We further checked the internal validity of our sample of survey respondents, i.e., how representative the sample is of the whole population of IP-SUISSE wheat producers. We here exploit that information on historical yields and structural farm and producers' characteristics from the IP-SUISSE database is available for the entire population of IP-SUISSE producers (including all non-respondents). The IP-SUISSE data allows us to check internal validity concerning i) the distribution of survey respondents across space (see Fig. 1), ii) historical Extenso wheat yields, and iii) structural farm and producers' characteristics from the IP-SUISSE database. More specifically, we compare sample (respondents) and population concerning the following characteristics: first year of participation in IP-SUISSE production, agricultural land, wheat surface, the share of wheat in total agricultural land, animal units, the share of land in mountain regions, average annual temperature and precipitation, soil suitability for wheat production and mean and standard deviation of delivered Extenso wheat quantities[12] over the ten years preceding program introduction (2008–2018).

Results show that our sample covers all regions where Extenso wheat is grown (see Fig. 1) and closely resembles population averages of IP-SUISSE wheat producers concerning important structural characteristics and yields (see Table A1). If any, deviations from population averages can only be found for wheat surface (higher for respondents) and land share in mountain regions (lower for respondents). These findings indicate that our sample slightly over-represents output in terms of delivered wheat. Therefore, it is not a troubling sign for conclusions concerning the large-scale conversion of Extenso wheat surfaces to pesticide-free wheat production.

For a short description and summary statistics of all variables used in

[12] Note that these are quantities of Extenso wheat delivered by producers to IP-SUISSE. They are therefore similar to yields, but slightly lower as they account for losses from bad quality, drying etc.

Table 3
Regression results main model.

Adopt	Coefficient (standard error)	
Soil conservation	−0.0972**	(0.0369)
DP_canton	−0.0851*	(0.0415)
Avg_yield	−0.0015	(0.0023)
Canton_fr	0.0286	(0.0318)
Ag_land	−0.0002	(0.0007)
Share_Wheat	−0.0082	(0.1401)
Workforce	−0.0027	(0.0105)
Income_arable	0.0000	(0.0006)
Succession	−0.0146	(0.0297)
Share_mountain	−0.0487	(0.0431)
Suitability_grains	−0.0268	(0.0203)
Temperature	−0.0223	(0.0284)
Precipitation	0.0002	(0.0003)
Weed	0.0004	(0.0445)
Herbicide_resistance	−0.0756	(0.0687)
Age	−0.0022	(0.0018)
Education	−0.0259	(0.0278)
Exp_yield_decr		
1	0.0022	(0.0522)
2	0.1761**	(0.0626)
3	0.1261**	(0.0563)
4	0.1111*	(0.0536)
Exp_yield_risk	−0.1049***	(0.0281)
Risk_pref	0.0178***	(0.0046)
Pos_Environ	0.0994***	(0.0155)
Pos_Health	−0.0029	(0.0112)
Experience		
1	−0.0344	(0.0281)
2	−0.0289	(0.0236)
Availability_machinery	0.1409***	(0.0426)
Exp_risk_machinery	−0.0342***	(0.0116)
Exp_costs	−0.0002	(0.0002)
Constant	0.7921*	(0.3888)

Note that we use standard errors clustered by cantons. The sample size is N = 1073. *,** and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively. Reference levels for the variables expected yield decrease and experience are “producer expects yield losses greater 15% from program introduction” and “producer has no experience with pesticide-free production,” respectively.

our analysis, see Table 2. For a more detailed description of variables and data sources, see the accompanying data article.

5. Results

5.1. Descriptive results

In the survey, we find that 156 (14%) producers have already participated in the program (starting from 2018/19 or 2019/20), and 487 (44%) indicated that they would like to participate in the future. Thus, 643 (58%) producers have already adopted or want to adopt the program. In contrast, 430 (39%) producers would not like to adopt the program, and 32 (3%) do not know the program. For further analyses, we exclude those respondents, which did not know the program. The spatial distribution of survey respondents and their respective participation decision is shown in Fig. A1 in the appendix.

We use a heat map to depict producers’ responses concerning the most important barriers for program adoption (Fig. 2). Responses indicate that a major concern for adoption seems to be weed pressure under the new production system, followed by a higher workload and a lack of suitable machinery. Generally, concerns are more pronounced among producers with a negative attitude towards program participation than those with a positive attitude. We account for producers’ major concerns with suitable variables in our regression analysis (see Section 5.2).

The spatial distribution and patterns of important potential drivers of producers’ adoption decisions reveal heterogeneity across space (see maps in the Appendix, Figs. A2–A5). We can see that larger farms with a higher historical Extenso wheat yield can mainly be found in the south-west and north-east of Switzerland (see Figs. A2 and A3 in the appendix). They stretch along the “Swiss plateau,” where the best soils for wheat cultivation in Switzerland are located (see Fig. A4 in the appendix). However, these regions also show the highest abundance of weed varieties impeding grain production (see Fig. A5 in the appendix). Looking at the spatial distribution of respondents with a positive and negative attitude towards the program, we see no clear spatial pattern (see Fig. A1 in the appendix) – suggesting that these spatially heterogeneous, structural characteristics do not have a strong influence on the adoption decisions.

Furthermore, it is interesting to note for potential environmental effects of the program that only 20% of farmers who (intend to) adopt the program want to use more herbicides in the rest of the crop rotation. This result indicates a robust effect of the program on pesticide use reduction in Switzerland.

Although descriptive statistics give a first impression of the data, they do not allow assessing the importance of adoption determinants and barriers while controlling for variation in other important characteristics. Therefore, we conducted regression analyses on the producers’ adoption decisions. We report the results in the following section.

5.2. Regression results

In the main model, we define adoption very generally (participates already/wants to participate (1) or not (0)) and do not differentiate between adoption pioneers and intended adopters.

We find that adoption is mainly driven by producers’ expectations of the program (Table 3). More specifically, we find that the producers' perception of the program's positive environmental effects is a key driver of adoption. Further, expectations of the program's production effects are essential. Producers who expect a higher yield loss or higher production risks under pesticide-free production and those who expect higher investment risks in machinery (i.e., for mechanical weed control) are less likely to adopt pesticide-free wheat production.[13] In line with the above results on the important role of expected risks, a higher risk aversion of producers in the plant protection domain leads to lower adoption.

The prior farming system further influences adoption decisions. We find that less flexible producers, who are already engaged in soil conservation programs or cantonal programs for pesticide use reduction, are less likely to adopt pesticide-free wheat production.

Moreover, adjustment costs reflecting farmers' current tillage practices and endowment of machinery for mechanical weed control determine participation decisions. Prior experience with pesticide-free production and expected additional management costs do not have a significant effect on adoption. However, producers who do not have machinery for mechanical weed control and expect higher risks of investments in such machinery are less likely to adopt.

We find that structural farm and farmers' characteristics and environmental conditions do not significantly influence the producers' adoption decisions. Moreover, producers' expectations regarding the program's potential positive health effects do not significantly affect adoption.

Looking at the size of estimated regression coefficients of the statistically significant variables, i.e. their importance for adoption, we find that especially the participation in soil conservation and cantonal direct payment programs, the availability of machinery, the expected effects of program participation on the environment and expected yield decrease and yield risk seem to be of high importance for the participation decision. For example, our results indicate that, ceteris paribus, a farm having access to machinery necessary for mechanical weed control in pesticide-free wheat production has a 14% higher adoption probability.

5.3. Results of robustness checks

First, we confirm that marginal effects of the linear probability model are in line with those of the logit and probit models and find no differences in sign and significance of results (Tables A1 and A2 in the appendix). Second, we check for the robustness of key adoption variables from the main model when changing the sets of control variables used. We find that all key adoption variables in the main model seem to be remarkably stable to the exclusion of different sets of control variables (see Table A3 in the appendix). The only difference we observe is that the expected costs of additional weed management strategies additionally become significant when excluding expectations and preferences from the regression.

Third, we check the robustness of inference on the clustered standard errors using wild bootstrapping and district instead of canton-level clusters. Again all results are very much in line with the results of the main model. Generally, district-clustered standard errors lead to the highest significance levels of coefficients in our analyses (see Table A4 in the appendix).

Fourth, we analyze potential differences in adoption determinants between adoption pioneers, i.e. producers who have already adopted pesticide-free production, and intended adopters, i.e. those who have stated that they want to adopt the production program in the future. Regression results in Table A5 in the appendix show that results are qualitatively in line with the main results, but we find interesting differences between adoption pioneers and intended adopters. Results are similar for the effect of expectations on yields and the environmental effects of program adoption. In contrast to the main results and results for stated adopters, we find that risks and risk preferences do not seem to be an important adoption determinant for adoption pioneers. Expected production risks are less significant, and expected investment risks in machinery and risk preferences do not significantly affect their adoption decision. Regarding adjustment costs, adoption pioneers seem to have positive prior experiences with pesticide-free production, and the expected costs of additional management measures are important for them. In contrast, intended adoption seems to be influenced by negative prior experiences. Additionally, flexibility in the prior farming system (no commitment to cantonal pesticide-reduction programs/soil conservation programs) and an established farm succession seems to be of importance for adoption pioneers an not for intended adopters. Further, we find that adoption pioneers are more likely situated in the Western, i.e. French speaking part of Switzerland.

Finally, we assess the robustness of our estimates to omitted variable bias, using Oster bounds. For all key adoption variables from the main model, we find that the degree of selection on unobservables would have to be at least as large as selection on observables (with the delta value of exp_risk_machinery just slightly under this threshold) to render effects insignificant. See Table A6 in the appendix for results. An exception from this result are those levels of the expected yield decrease variable, which were highly insignificant in the regression analysis. However, when we regroup levels this result disappears, indicating no general problem pertaining to this variable.[14] Results of Oster bounds therefore indicate robustness of our analysis to potential omitted variable bias.

6. Discussion

We analyze determinants, barriers, and challenges of Swiss Extenso wheat farmers to participate in a novel, pesticide-free wheat production program. Pesticide-free production systems have a high potential for pesticide load abatement while sustaining yield levels. Due to their broader adoption potential compared to production systems that restrict input use in the complete crop rotation, such as in organic farming, they could be of high relevance for sustainable intensification of (European) agriculture (Pretty, 2018; Reganold and Wachter, 2016).

Our findings show that the pesticide-free wheat production program's incentive mechanism, combining direct payments with price add-ons, works well in making the program attractive to a wide range of different farm types. It has led to a high, early-stage acceptance of the program of 58% of producers. Our results indicate that addressing expectations concerning the program's environmental benefits and economic effects and the availability of substitutes for herbicide use is key to achieve a higher adoption.

Our central finding is that producers' expectations of the program's economic and environmental effects strongly matter for adoption. Negative expectations may constitute crucial adoption barriers. The higher producers expect yield losses or production risks to be, the less likely they are to adopt the program. A large share of producers in our survey expects yield losses of over 10, 15, or even 20% in pesticide-free production compared to Extenso production. However, using a bio-economic model, Böcker et al. (2019) predict average yield losses from program uptake to only be around 6%. While some of the farmers might have given strategic answers in the survey to influence discussions on price premia and the loss might be higher for producers in unfavorable production locations, producers' expectations do not always seem to be driven by underlying production conditions but may also be attributed to a lack of experience and a substantial uncertainty

[13] Note that although adoption increases in expectations of higher yield reduction from program adoption for levels 2, 3 and 4, the first level is not significantly different from the last one. This might be related to some strategic answers of farmers, e.g. if aiming to signal higher than actually expected yield loss expectations in order to obtain higher price premia.

[14] Results are available on request.

associated with adopting this very novel production system. Similarly, Cerroni (2020) finds that the adoption of new crop varieties is strongly linked to uncertainty aversion.

Further, we find that producers who expect a higher investment risk in machinery for mechanical weed control and who are more risk-averse in the plant protection domain are less likely to adopt the program. This finding is in line with findings on the adoption of organic farming (Kallas et al., 2010; Serra et al., 2008). The results confirm our hypothesis that the adoption of novel production systems, which have not been established before, constitutes a high risk for some producers, which can be strongly detrimental for establishing the production system. Adoption is, therefore, strongly driven by expectations, risk considerations, and preferences.

Interestingly, we find that not only the producers' expectations concerning economic effects are driving adoption but also their expectations regarding the program's environmental benefits. Producers who believe that the program contributes to more sustainable agriculture are more likely to adopt. The importance of perceived environmental benefits for the adoption decision is further confirmed when looking at the magnitude of estimated coefficients, as they range among the most important adoption determinants, together with the availability of machinery and expected yield losses and risks of program adoption. The important role of the sustainability of farming systems for adoption decisions is in line with recent findings on Dutch farmers (Bakker et al., 2020). The result is not significant for the program's health effects. We suggest that most producers in a developed country like Switzerland believe that health effects are negligible when they correctly apply pesticides and therefore do not value a potential reduction of health effects - while evidence for environmental effects of pesticides has been very present in the public debate in Switzerland recently (Huber and Finger, 2019).

Further, we find that adjustments costs are important adoption determinants. Participation in soil conservation programs (i.e., mulch seeding and direct seeding) seems to be an adoption barrier. This finding highlights the challenge of substituting herbicide use that wheat producers face in the new production system. This challenge is even more pronounced for producers participating in soil conservation programs. While techniques for pesticide- and tillage-free wheat production exist (and are already established in organic agriculture: such as harrowing and agronomic adjustments, e.g., adjusting seeding dates or crop rotations), these techniques often require more knowledge and are costlier than, for example, plowing. Simultaneously, these management measures often require machinery, to which conventional farmers do not have access. It also highlights trade-offs between the reduction of herbicides and its potential adverse environmental and health effects and the use of mechanical weed control with potential adverse effects of less soil conservation practices, e.g. for soil health and increasing fuel emissions (Böcker et al., 2020, Van Deynze et al., 2018). Considering these trade-offs holistically in the design of farming systems and policies will be key for developing more sustainable agricultural systems (Möhring et al., 2020b). Moreover, these trade-offs need to be minimized rapidly, e.g. by supporting the development of efficient soil conservation practices without herbicide use (e.g. Vincent-Caboud et al., 2019).

Our results support the importance of access to machinery. We find that adoption is lower when no machinery for mechanical weed control is available to producers. Therefore, it will be essential for large-scale adoption of the pesticide-free production program to establish knowledge of alternative management practices among producers and support the widespread availability of required machinery at low costs. This may, for example, be achieved through incentives for investments or the support of machinery rings. Along these lines, also contractors providing mechanical weed control will be of increasing importance to facilitate the widespread adoption of pesticide-free production in small-scale agricultural systems.

Moreover, participation in cantonal programs for a reduced pesticide use only seems to be an adoption barrier for adoption pioneers, indicating a lack of flexibility of producers in these programs.

Descriptive spatial analyses show that while yields and wheat surface are heterogeneous across producers and seem to be spatially distributed along a gradient of soil suitability for wheat production, adoption decisions do not seem to follow this spatial pattern. This confirms the results of Böcker et al. (2019), who analyzed the economic effects of the program *ex-ante* in a bio-economic model, and found that adoption of the pesticide-free wheat production program should be profitable for the majority of producers. We confirm this hypothesis in the regression analyses and find that structural characteristics of farms and producers and environmental conditions do not significantly affect adoption. This result is contrary to previous findings, e.g., on the adoption of agri-environmental measures. However, the finding reflects that the current program design, combining direct payments and price add-ons for producers, seems to be sufficient to balance out potential differences in opportunity costs across farm types, locations, and business models. These differences could otherwise constitute adoption barriers, for example, for farms with a more intensive wheat production system or farms in locations, which are more unfavorable to wheat production.

Results are stable over a range of robustness checks. Comparing adoption determinants of adoption pioneers (already participating in the program) and intended adopters (intend to participate in the future), we find that results are qualitatively in line with the main results. However, adoption pioneers seem to be driven by positive prior experiences with pesticide-free production and flexibility (no involvement in soil conservation/cantonal programs). In contrast, intended adoption seems to be driven more by (expected) risks and negative prior experiences with pesticide-free production. Stable, long-term planning horizons (established succession) and language region are further associated with the decision of adoption pioneers. The latter finding reflects the high number of initiatives for sustainable farming systems recently established in Western Switzerland.

Our results, therefore, suggest a differentiated approach to encourage large-scale adoption of pesticide-free production. We find that convincing future adopters especially requires information and data on potential yield and production risk effects to reduce uncertainties. Further, information and extension service advice on agronomic techniques and mechanical weed control is needed, in addition to the above discussed support of investments in machinery. Results further show that positive environmental effects of the program are central for adoption. Highlighting these effects and providing information on their extent, can increase adoption.

Based on our internal validity checks, we are confident that our sample reflects the population well and that results are representative for IP-SUISSE producers. However, we have so far not addressed our results' external validity as our survey did not include conventional or organic wheat farmers. Finger and El Benni (2013) find that especially farmers with a lower wheat yield tend to adopt Extenso wheat production. Translating their results to pesticide-free production would mean that, especially, conventional farms with very intensive wheat production and potentially high environmental effects would not be willing to adopt the program. However, they also find that changes in prices and direct payments significantly affected adoption. In our results, we have seen that the incentive mechanisms established in the program seem to be attractive for a wide range of Extenso producers – and did not find adoption to vary by yield level. This result indicates that pesticide-free production could be an attractive option for conventional wheat producers as well. At the same time, some of the pesticide-free producers may switch to organic production in the long-run. However, these farms have previously not converted to organic farming, although Extenso production has long been established in Switzerland. Their decisions to not convert, albeit higher prices and direct payments in organic production, suggest that farm-level restrictions in organic farming constitute an important adoption barrier to most producers. Past experiences with the Extenso program have shown a high long-term stability of market shares, prices, direct payments and price mark-ups of Extenso wheat after its establishment (Finger and El Benni, 2013). For example, the direct payment for Extenso has not been changed since 1999. However, long-term effects of the introduction of the pesticide-free wheat production program cannot be evaluated at this point. The development of market shares, prices, direct payments and price mark-ups for conventional, Extenso and pesticide-free wheat will be important to consider for the evaluation of the pesticide-free production program in the long-run.

The focus of our analysis has been on Switzerland and wheat production. However, we believe that our analysis's basic results concerning the design of the production scheme and important groups of adoption determinants and barriers are also valid more generally for the design and adoption of pesticide-free production programs, for example, in other countries and for other crops. Our case study of Swiss wheat production shows that a private–public production standard, which combines strengths of different actors of the food-value chain, is a valuable tool to enable large-scale adoption of a wide range of producers. On the one hand, the producer organization IP-SUISSE guarantees producers' trust in the stability of the program (as a long-term actor in the field). On the other hand, they enable a market valuation of the program together with the retailer Migros, which is important for the program's long-term success. Additionally, federal direct payments enable producers to cover adjustments costs, such as investments in knowledge and machinery, and encourage participation despite expectations of higher production risks.

Our analysis shows that uncertainty, preferences, and farmers' expectations can be essential adoption barriers for establishing novel, pesticide-free production programs. Most farmers do not have any experience or knowledge of these novel production systems yet, leading to a high uncertainty regarding expected production outcomes. Adoption is therefore perceived to be very risky and rendered unattractive for more risk-averse farmers. Further, the stability and duration of policy programs may constitute a large risk to producers. While new machinery needed for pesticide-free wheat production may have an expected lifetime of 20 years and more, policy programs may be removed and replaced in new policy cycles (in Switzerland, major agricultural policy adjustments occur every four years).

7. Conclusion

We analyze determinants, barriers, and challenges for the adoption of a large-scale non-organic, pesticide-free wheat production program – the first of its kind in Europe. Pesticide-free production standards could be an important cornerstone for sustainable intensification of agriculture, complementing organic farming systems. They combine lower participation requirements than organic production with a high potential for pesticide load reduction.

Our results indicate that the establishment of a large-scale, non-organic pesticide-free wheat production program is possible. We find that the large-scale adoption of such production programs seems to i) hinge on a program design, which makes participation attractive for a large range of farm types, ii) critically depends on uncertainties associated with adoption and the producers' expectations of the program and iii) relies on the accessibility of substitutes for pesticide use.

More specifically, we find that adoption is consistently driven by producer perception of the positive environmental effects of pesticide-free production. Furthermore, producer expectation of production effects is central for adoption. Producers expecting larger yield losses and increases in production risks are less likely to enter the program.

Moreover, adjustment costs reflecting producers' participation in soil conservation programs and endowment of machinery for mechanical weed control determine adoption decisions. Central for adjustment costs is the substitution of herbicides and, therefore, availability and costs of mechanical alternatives.

Our analysis thus provides important conclusions for policy and industry. The communication of environmental benefits to producers and resolving uncertainties regarding program outcomes for production (risks) play a central role in adopting novel, pesticide-free production systems. Extension services, experimentation, and integration of research programs can be vital to facilitate these steps. Further, dissemination of information and advice on efficient and cheap management techniques and positive experiences with pesticide-free production (i.e., adjusting expectations) are essential. Finally, our findings underline that establishing risk management tools, such as targeted insurances or mutual funds, could be an important cornerstone for the large-scale establishment of such production programs.

Further research should extend to other countries or crops to deliberate how generic the design of pesticide-free systems can be. Moreover, it should investigate adoption mechanisms in more detail, especially concerning risks, risk preferences, and producers' expectations. The potential long-term effects of the introduction of a growing pesticide-free production program on prices and participation in conventional, pesticide-free and organic wheat production will further be an important subject for future research.

CRediT authorship contribution statement

Niklas Möhring: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Funding acquisition. **Robert Finger:** Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Funding acquisition.

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.

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Appendix A

See Figs. A1–A5 and Tables A1–A6.

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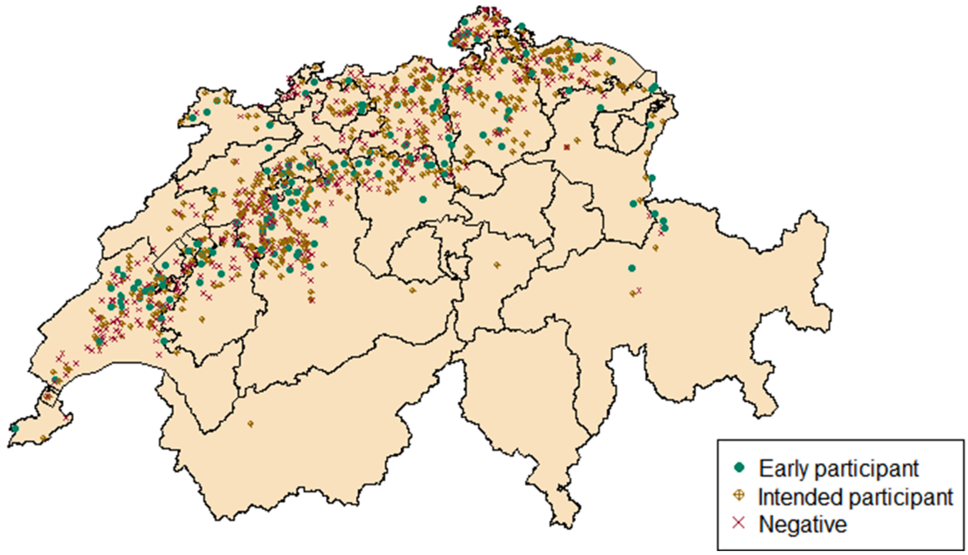

Fig. A1. Participation decision in the pesticide-free wheat production program. The map shows participation decisions in the pesticide-free wheat production program of survey respondents (N = 1073). "Early participation" indicates producers who have already participated in the program, "intended participation" indicates producers who have stated their willingness to participate in the future, and "negative" indicates producers who are not willing to participate.

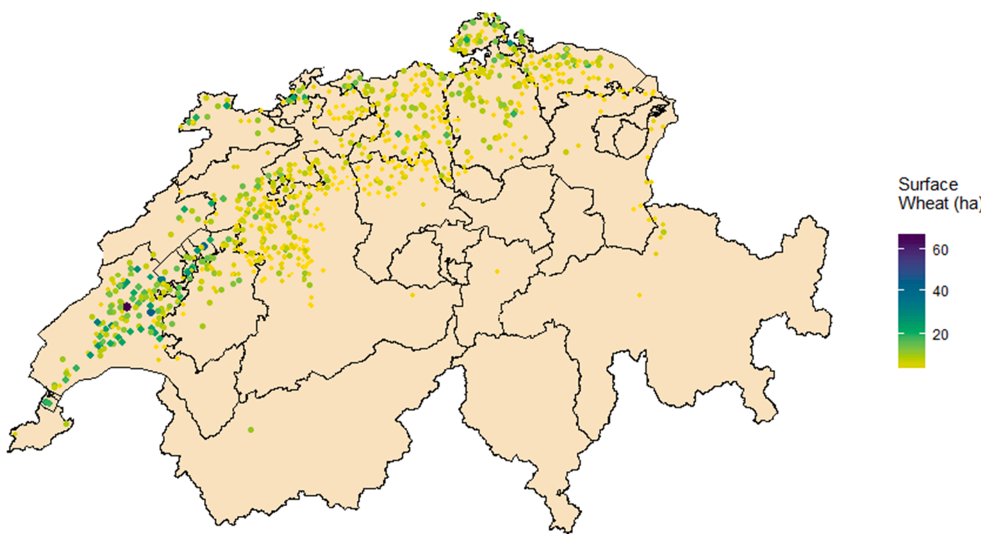

Fig. A2. The wheat surface of survey respondents. The map shows the wheat surface of producers in the survey (N = 1073) in hectares.

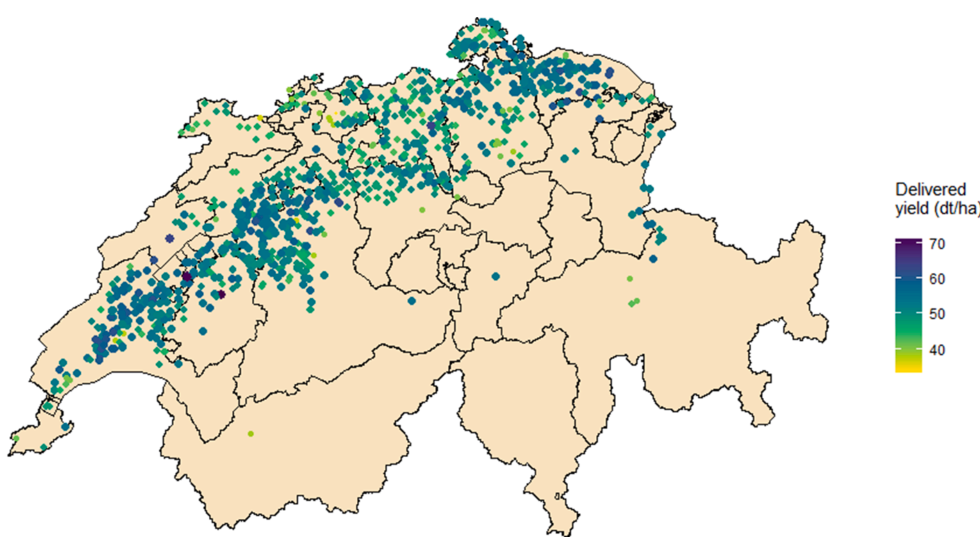

Fig. A3. Average delivered wheat yields of survey respondents. The map shows average wheat yields of producers in the survey (N = 1073) delivered to IP-SUISSE from 2008 to 2018 in decitons (1dt = 100 kg) per hectare. Delivered quantities are slightly lower than harvested quantities, as they account for losses from bad quality, drying, etc.

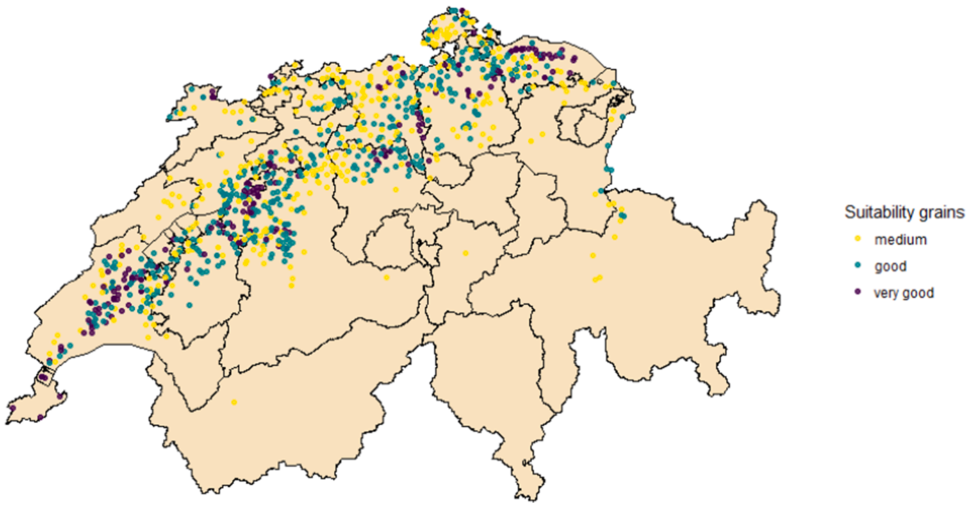

Fig. A4. Soil suitability for wheat cultivation. The map shows soil suitability for wheat cultivation of producers in the survey according to the Swiss Federal Office for Agriculture (Swiss Federal Office for Agriculture, 2009).

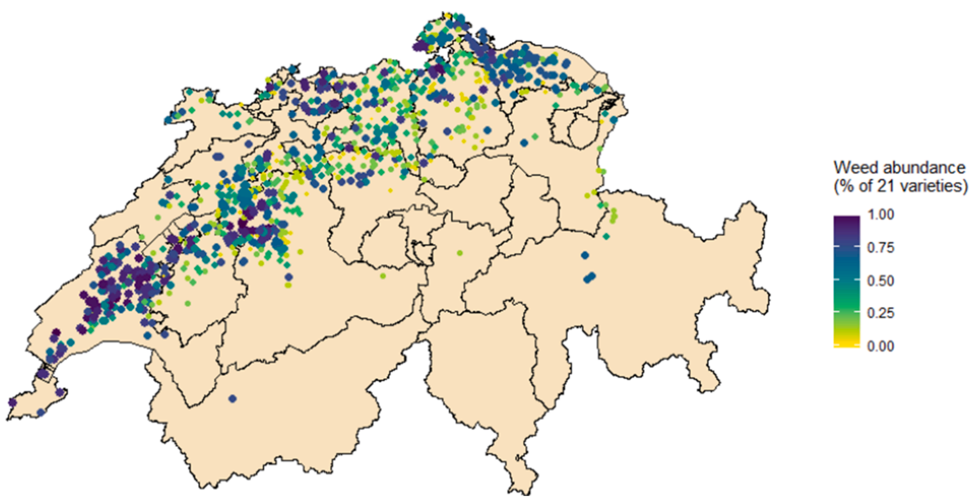

Fig. A5. Weed abundance. The map shows abundance of the 21 most important weeds in Swiss wheat production listed in (Böcker et al., 2019) on farms of producers in the survey, according to Info Flora (Info Flora, 2019).

Table A1
Comparison of population and sample averages (internal validity).

Variable (unit)	Population Average	Sample Average	Difference (%)
First-year of participation in Extenso wheat production	1999	1999	–
Wheat surface (ha)	4.78	5.68	0.19
Share wheat of agricultural land (%)	0.15	0.16	0.1
Agricultural land (ha)	32.39	34.49	0.06
Animal stock (Animal units)	31.12	31.24	0
Share of land in mountain regions (%)	0.07	0.05	−0.25
Yearly average temperature (°C)	8.96	9.01	0.01
Yearly average precipitation (mm)	1093	1077	−0.01
Delivered yields (dt/ha)	50.7	51.13	0.01
Standard deviation delivered yields	13.09	13.33	0.02
Soil suitability for grain cultivation (%)	0.76	0.81	0.06

Note that we calculate mean values for population and sample averages, except for the variable “first year of participation”, for which we use the respective mode values.

Table A2
Robustness regression results: Marginal effects probit regression.

Adopt	Coefficient	Standard error
Soil conservation	−0.0899***	0.0344
DP_canton	−0.0893**	0.0476
Avg_yield	−0.0012	0.0023
Canton_fr	0.0224	0.0309
Ag_land	−0.0002	0.0007
Share_Wheat	−0.0415	0.1299
Workforce	−0.0022	0.0107
Income_arable	−0.0001	0.0006
Succession	−0.0163	0.0301
Share_mountain	−0.0504	0.0415
Suitability_grains	−0.0196	0.0189
Temperature	−0.0161	0.0309
Precipitation	0.0002	0.0003
Weed	0.0018	0.0439
Herbicide_resistance	−0.0725	0.0692
Age	−0.0022	0.0016
Education	−0.0232	0.0264
Exp_yield_decr		
1	−0.0087	0.0514
2	0.1748***	0.0642
3	0.1123**	0.0550
4	0.1012*	0.0534
Exp_yield_risk	−0.1099***	0.0301
Risk_pref	0.0169***	0.0045
Pos_Environ	0.0914***	0.0135
Pos_Health	0.0000	0.0105
Experience		
1	−0.0275	0.0254
2	−0.0199	0.0247
Availability_machinery	0.1330***	0.0435
Exp_risk_machinery	−0.0326***	0.0119
Exp_costs	−0.0002	0.0002

We show marginal effects at mean vaues of all other variables of a probit model estimated with standard errors clustered by cantons. We compute standard errors of marginal with the delta method. The sample size is N = 1073. *,** and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively. Reference levels for the variables expected yield decrease and experience are "producer expects yield losses greater 15% from program introduction" and "producer has no experience with pesticide-free production," respectively.

Table A3
Robustness checks: reduced sets of control variables.

Adopt	Main model	(1) Production system	(2) Structural characteristics	(3) Behavioural characteristics	(4) Adjustment costs
Soil conservation	−0.0972**	–	−0.1005***	−0.1282***	−0.0973**
DP_canton	−0.0851*	–	−0.0841*	−0.0896**	−0.0935**
Avg_yield	−0.0015	–	−0.0025	0.0002	−0.0018
Canton_fr	0.0286	0.0263	–	0.0323	−0.0020
Ag_land	−0.0002	−0.0002	–	−0.0008	0.0001
Share_Wheat	−0.0082	−0.0802	–	−0.0421	−0.0457
Workforce	−0.0027	−0.0001	–	−0.0012	−0.0005
Income_arable	0.0000	−0.0002	–	−0.0003	0.0001
Succession	−0.0146	−0.0106	–	−0.0399	−0.0121
Share_mountain	−0.0487	−0.0414	–	−0.0554	−0.0400
Suitability_grains	−0.0268	−0.0241	–	−0.0245	−0.0234
Temperature	−0.0223	−0.0125	–	−0.0019	−0.0226
Precipitation	0.0002	0.0003	–	0.0004	0.0002
Weed	0.0004	0.0055	–	0.0214	0.0038
Herbicide_resistance	−0.0756	−0.0803	–	−0.0848	−0.0844
Age	−0.0022	−0.0021	–	−0.0031	−0.0017
Education	−0.0259	−0.0343	–	−0.0327	−0.0278
Exp_yield_decr					
1	0.0022	0.0034	0.0047	–	0.0363
2	0.1761**	0.1781**	0.1812***	–	0.2076***
3	0.1261**	0.1271**	0.1275**	–	0.1641***
4	0.1111*	0.1100*	0.1144**	–	0.1373**
Exp_yield_risk	−0.1049***	−0.1100***	−0.1137***	–	−0.1292***
Risk_pref	0.0178***	0.0173***	0.0182***	–	0.0187***
Pos_Environ	0.0994***	0.0997***	0.0992***	–	0.1112***
Pos_Health	−0.0029	0.0022	−0.0023	–	−0.0009
Experience					
1	−0.0344	−0.0311	−0.0389	−0.0479	–
2	−0.0289	−0.0077	−0.0358	0.0159	–
Availability_machinery	0.1409***	0.1464***	0.1350***	0.2085***	–
Exp_risk_machinery	−0.0342***	−0.0349***	−0.0351***	−0.0766***	–
Exp_costs	−0.0002	−0.0002	−0.0002	−0.0004**	–
Constant	0.7921*	0.4348	0.5593	1.0823	0.6115

Standard errors are clustered by cantons. The sample size is N = 1073. *,** and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively. Reference levels for the variables expected yield decrease and experience are "producer expects yield losses greater 15% from program introduction" and "producer has no experience with pesticide-free production," respectively. "Production system," "Structural characteristics," "Behavioural characteristics," and "Adjustment costs" denote models without control variables from the respective categories.

Table A4
Robustness checks: standard errors.

Adopt	Coefficient main model	(1) P-value canton cluster	(2) P-value district cluster	(3) P-value wild bootstrap
Soil conservation	−0.0972	0.022	0.015	0.041
DP_canton	−0.0851	0.063	0.021	0.052
Avg_yield	−0.0015	0.539	0.632	0.564
Canton_fr	0.0286	0.386	0.369	0.342
Ag_land	−0.0002	0.803	0.792	0.809
Share_Wheat	−0.0082	0.954	0.951	0.951
Workforce	−0.0027	0.799	0.797	0.834
Income_arable	0.0000	0.953	0.951	0.963
Succession	−0.0146	0.633	0.541	0.608
Share_mountain	−0.0487	0.281	0.474	0.189
Suitability_grains	−0.0268	0.210	0.295	0.163
Temperature	−0.0223	0.447	0.405	0.538
Precipitation	0.0002	0.609	0.509	0.603
Weed	0.0004	0.992	0.991	0.989
Herbicide_resistance	−0.0756	0.293	0.148	0.370
Age	−0.0022	0.227	0.101	0.279
Education	−0.0259	0.370	0.311	0.377
Exp_yield_decr				
1	0.0022	0.967	0.963	0.967
2	0.1761	0.016	0.000	0.029
3	0.1261	0.045	0.010	0.050
4	0.1111	0.060	0.023	0.082
Exp_yield_risk	−0.1049	0.003	0.000	0.026
Risk_pref	0.0178	0.002	0.002	0.000
Pos_Environ	0.0994	0.000	0.000	0.000
Pos_Health	−0.0029	0.801	0.839	0.783
Experience				
1	−0.0344	0.246	0.332	0.238
2	−0.0289	0.244	0.381	0.252
Availability_machinery	0.1409	0.006	0.001	0.031
Exp_risk_machinery	−0.0342	0.012	0.008	0.018
Exp_costs	−0.0002	0.159	0.055	0.118
Constant	0.7921	0.064	0.036	0.074

The sample size is N = 1073. Reference levels for the variables expected yield decrease and experience are “producer expects yield losses greater 15% from program introduction” and “producer has no experience with pesticide-free production,” respectively. Standard errors in models (1), (2), and (3) are clustered by cantons, districts, and cantons, respectively. For model (3), t-tests were computed using wild bootstrapping techniques.

Table A5
Robustness checks: regression results for pioneer adopters and intended adopters.

Adopt	(1) Adopter (main model)	(2) Pioneer adopter	(3) Intended adopter
Soil conservation	−0.0972**	−0.1050***	−0.0666
DP_canton	−0.0851*	−0.1853***	−0.0173
Avg_yield	−0.0015	−0.0014	−0.0004
Canton_fr	0.0286	0.0581***	0.0049
Ag_land	−0.0002	−0.0002	−0.0003
Share_Wheat	−0.0082	0.0822	−0.0406
Workforce	−0.0027	0.0015	−0.0018
Income_arable	0.0000	−0.0001	−0.0001
Succession	−0.0146	0.0351**	−0.0152
Share_mountain	−0.0487	−0.0367	−0.0361
Suitability_grains	−0.0268	0.0008	−0.0228
Temperature	−0.0223	0.0138	−0.0217
Precipitation	0.0002	0.0001	0.0002
Weed	0.0004	−0.0520	0.0114
Herbicide_resistance	−0.0756	0.0294	−0.1005
Age	−0.0022	0.0009	−0.0028
Education	−0.0259	−0.0107	−0.0117
Exp_yield_decr			
1	0.0022	0.0771***	−0.0471
2	0.1761**	0.0887**	0.1512**
3	0.1261**	0.0258	0.1122*
4	0.1111*	0.0564**	0.0864
Exp_yield_risk	−0.1049***	−0.0389*	−0.1168***
Risk_pref	0.0178***	0.0056	0.0200***
Pos_Environ	0.0994***	0.0414***	0.0928***
Pos_Health	−0.0029	0.0134	−0.0037
Experience			
1	−0.0344	0.0132	−0.0353
2	−0.0289	0.1373***	−0.0644**
Availability_machinery	0.1409***	0.0427**	0.1270**
Exp_risk_machinery	−0.0342***	0.0109	−0.0433***
Exp_costs	−0.0002	−0.0002**	−0.0002
Constant	0.7921*	−0.0349	0.6932

Standard errors are clustered by cantons. Reference levels for the variables expected yield decrease and experience are “producer expects yield losses greater 15% from program introduction” and “producer has no experience with pesticide-free production,” respectively. Adoption variables in models (1), (2), and (3) denote (has adopted/intends to adopt or not), (has adopted or not), and (intends to adopt or not). Note that in model (2), pioneer adopters are excluded from the regression. Sample sizes are $N_{(1,2)} = 1073$ and $N_{(3)} = 917$, respectively. *,** and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively.

Table A6
Robustness checks: Oster bounds for key adoption variables.

Variable name	Delta
Soil conservation	2.517
DP_canton	7.657
Exp_yield_decr	
1	−0.118
2	3.364
3	4.156
4	−3.069
Exp_yield_risk	1.365
Risk_pref	1.841
Pos_Environ	1.016
Availability_machinery	1.749
Exp_risk_machinery	0.969

Oster bounds are computed for the main model and R_max = 0.33 (setting R_max = $1.3*R^2_{mainmodel}$, following the suggestions in Oster (2019)).

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