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Title:

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

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Abstract

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.

Keywords: Pesticide; pesticide-free; sustainable agriculture; adoption; wheat; public-private; sustainability standard; Switzerland

1 **Pesticide-free but not organic: adoption of a large-scale wheat**
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29 1. INTRODUCTION

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

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

50 Previous literature on pesticide-free production has primarily focused on consumers'
51 willingness to pay for different production standards (Bazoche et al., 2013; Edenbrandt et al.,
52 2018; Magnusson and Cranfield, 2005). However, information on determinants, barriers, and
53 challenges for adopting novel, pesticide-free production standards is required for an optimal

54 program design and large-scale adoption. A wide range of literature on the adoption of more
55 environmentally friendly production systems such as organic farming (Meemken and Qaim,
56 2018), and more generally, on agri-environmental measures, exists (see Dessart et al., 2019;
57 Malek et al., 2019; Zimmermann and Britz, 2016 for an overview). Results for different
58 production systems, agri-environmental schemes, or environmental and social contexts can,
59 though not be generalized (Knowler and Bradshaw, 2007). The adoption of non-organic,
60 pesticide-free production systems has rarely been addressed (Christensen et al., 2011; Finger
61 and El Benni, 2013). However, the adoption of these systems poses different challenges to
62 farmers and has distinctly lower adoption barriers than systems that require adjustments on
63 the entire farm, such as organic farming. Moreover, large-scale production systems of this
64 kind have not been established, and only *ex-ante* analyses with bio-economic models on
65 potential economic and environmental effects have been conducted so far (Böcker et al.,
66 2020; Böcker et al., 2019; Schmidt et al., 2019).

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

73 We find that adoption is mainly driven by the farmers' expectations of the program's effects.
74 More specifically, we find that farmers' adoption is driven by the perception of pesticide-free
75 production's positive environmental effects. Furthermore, farmers' expectations regarding the
76 program's production effects are key. Farmers expecting large yield losses and increases in
77 production risks are less likely to enter the program. Moreover, adjustment costs reflecting
78 farmers' current tillage practices and machinery endowment for mechanical weed control

79 determine participation decisions. We find that neither structural farm and farmers`
80 characteristics, such as age, education, farm size, farm orientation, farm location or average
81 yield levels, nor environmental conditions play a role in the adoption decision. We conclude
82 that communication of environmental benefits to farmers and resolving uncertainty regarding
83 program outcomes for production levels and risks play a central role in adopting novel
84 (pesticide-free) production systems and discuss implications for their design to achieve a
85 large-scale adoption.

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

91 **2. BACKGROUND**

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

94 **2.1. The Swiss pesticide-free wheat production program**

95 The producer organization IP-SUISSE is currently introducing a non-organic, pesticide-free
96 wheat production standard in Switzerland – the first large-scale production program of its
97 kind in Europe. Starting from 1992/93¹, IP-SUISSE members have started to produce wheat
98 under the so-called "Extenso" program. In this program, participants are neither allowed to
99 use insecticides, fungicides, nor growth regulators in wheat production. They further face
100 some additional restrictions, including a restriction to growing stubble wheat ("wheat-after-
101 wheat" rotations) and complying with some general on-farm sustainability criteria (Böcker et

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.

102 al., 2019). The novel "pesticide-free wheat" production program goes even further by
103 restricting farmers from using conventional pesticides in wheat production.

104 Contrary to organic farming, the program neither restricts fertilization in wheat nor input use
105 or crop management in the rest of the crop rotation. It, therefore, poses significantly fewer
106 adoption barriers for farmers than organic farming. To incentivize adoption, the program
107 relies on both public and private compensation mechanisms for farmers. Participants are
108 remunerated with a market-based price add-on, as well as governmental (per hectare) direct
109 payments for pesticide-free production (see Table 1 for an overview²).

110 The pesticide-free wheat production program has started in 2018/19 with a pilot of 1200 ha.
111 From the growing season 2019/20 on, it has been opened up for all IP-SUISSE producers. The
112 goal is a large-scale adoption of pesticide-free wheat production. The program envisions that
113 a large share of the 50% of Swiss wheat surface under Extensio production will be under
114 pesticide-free production in the long run. The program was introduced by IP-SUISSE in the
115 context of strong signals from citizens and consumers in Switzerland to switch to a more
116 sustainable and especially pesticide-free production. More specifically, two popular initiatives
117 on banning synthetic pesticides and tightening cross-compliance regulations towards use of no
118 synthetic pesticides were voted on in Switzerland in June 2021 and a large debate on the
119 effects of pesticides on Swiss drinking water was taking place in Swiss society³ (see Finger,
120 2021 for an overview). Wheat production plays an important role for pesticide use, as the
121 major crop in Switzerland and Europe more generally.

² Note that organic wheat production in Switzerland is remunerated 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.

³ Both popular initiatives were rejected, but agricultural producers, policy maker and retail initiated steps in response 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).

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

129 **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

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

139 Yields for Extenso wheat are around 20% lower and more volatile than conventional wheat,
 140 but profits have been found to be higher for most farmers due to additional direct payments

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

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

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

160 **2.2. Conceptual Model**

161 Following, we present a conceptual model for the adoption of pesticide-free production
162 systems and then apply this model to our case study. As a basis for the conceptual model, we

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

163 build upon previous literature on farmers' adoption decisions and interviews with IP-SUISSE
164 farmers and Swiss extension service experts.

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

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

$$172 \quad (1) \max_{A_{it}} E[U(\tilde{\pi}_{it}(A_{it}, X_{it}, Env_{it}, \varepsilon_{it}^A), PE_{it})],$$

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

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

$$179 \quad (2) E \left[U \left(\tilde{\pi}_{it} \left(A_{it}^{A=1}, X_{it}, Env_{it}, Adj_{it}, \varepsilon_{it}^{A=1} \right), \right. \right. \\ 180 \quad \left. \left. PE_{it} \right) \right] \geq E \left[U \left(\tilde{\pi}_{it} \left(A_{it}^{A=0}, X_{it}, Env_{it}, \varepsilon_{it}^{A=0} \right), PE_{it} \right) \right],$$

181 where Adj_{it} denotes the farmers' one-time and long-term costs costs of switching to pesticide-
182 free production⁶. While farmers expectations on expected revenues and costs, risks and other

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, J.K., Lichtenberg, E., 1994. Risk-reducing and Risk-increasing Effects of Pesticides. J.

183 effects arising from program adoption have a multiple year perspective, further dynamic
184 aspects, such as the choice of crop rotations and adjustments on a farm-level are out of the
185 scope of our analysis, as we are looking at program adoption in an early stage. However, they
186 should be considered in further analyses concerning environmental and farm-level effects of
187 the program introduction. We therefore here assume farmers to choose a crop rotation, which
188 maximizes expected utility given the adoption decision, without explicitly modelling these
189 decisions.

190 Following, we apply our conceptual model to the adoption of the Swiss pesticide-free wheat
191 production program by IP-Suisse Extensio wheat producers⁷. We discuss potential adoption
192 determinants in four main categories: i) characteristics of the production system before
193 adoption, ii) environmental conditions and structural farm and farmers' characteristics, iii)
194 farmers' perceptions and expectations of the program (behavioral characteristics), and iv) one-
195 time and long-term adjustment costs to pesticide-free production:

196 *i) Production system before adoption.*

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

204 *ii) Farm- and farmers' characteristics, environmental conditions.*

Agr. Econ. 45, 82-89. and Möhring, N., Bozzola, M., Hirsch, S., Finger, R., 2020a. Are pesticides risk decreasing? The relevance of pesticide indicator choice in empirical analysis. Agr. Econ.).

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

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

221 *iii) Farmers' perceptions and expectations.*

222 The literature on the adoption of sustainable farming practices shows that behavioral factors
223 often play a key role in farmers' adoption decisions (see Dessart et al., 2019 for an
224 overview). We, therefore, expect that farmers' preferences, attitudes, and expectations, will
225 influence adoption (which are part of PE_{it} in Eq. 2). We expect that due to the novelty of
226 the program, especially farmers' (potentially heterogeneous) expectations concerning yield
227 effects and production risks of the pesticide-free production system will play an important
228 role in adoption (Lequin et al., 2019; Pannell, 2003; Reimer et al., 2012; Star et al., 2019).
229 Farmers' experiences with pesticide-free production and their risk preferences are expected
230 to influence how these uncertainties are weighed in the farmers' decisions (Serra et al.,

231 2008). Finally, we expect that the farmers' perception of potential environmental and health
232 benefits of the production program (i.e., effects of reducing overall pesticide use in wheat
233 production) and their personal preferences will influence participation decisions (Greiner
234 and Gregg, 2011; Sulemana and James Jr, 2014; Toma and Mathijs, 2007; Van Herzele et
235 al., 2013).

236 iv) *Adjustment costs*.

237 Adjustment costs include one-time and long-term costs of switching from one production
238 system to another following (Gardebroek and Lansink, 2004) (represented by variable Adj_{it}
239 in Eq.2). They are closely linked to the farm orientation and farmers' characteristics
240 described above. Important adjustment costs in the context of our study may include
241 endowment, accessibility, and costs of machinery required for pesticide-free production
242 (i.e., for mechanical weed control), as well as (expected) changes in costs of weed
243 management strategies under pesticide-free production⁸.

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

249 **3. EMPIRICAL STRATEGY**

250 **3.1. Empirical Model**

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

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.

254 empirical model as:

$$255 \quad (3) \text{ Adopt}_{i,t=2019/20} = \beta_1 + \boldsymbol{\beta} * \boldsymbol{\omega}_i + \eta_i ,$$

256 Where $\text{Adopt}_{i,t=2019/20}$ denotes the adoption decision of the producer, β_1 is the intercept,
257 $\boldsymbol{\omega}_i$ and $\boldsymbol{\beta}$ represent the vectors of potential adoption determinants and their respective
258 regression coefficients and η_i is the error term of the regression analysis. Equation 3 and
259 variations thereof are estimated using linear probability models based on OLS and cluster
260 error terms at the cantonal level⁹ in our main model.

261 We choose explanatory variables in line with the four sets of potential adoption determinants
262 described in our conceptual framework (see Table 2 for an overview). We depict the
263 production system before adoption using dummy variables indicating participation in direct
264 payment schemes for soil conservation and cantonal programs for pesticide reduction¹⁰ and
265 average municipality-level (Extenso wheat) yields from 2008-2018. Structural farm
266 characteristics include farm size in hectares of agricultural land, the share of wheat in
267 agricultural land, the workforce's size, the share of arable farming in the farm income, and a
268 dummy variable for differences between language regions (e.g. concerning extension service,
269 see Möhring et al., 2020c¹¹). Farmers' characteristics further include a dummy variable for
270 established farm succession and variables for age and education of the farmer. We
271 characterize growing conditions using i) the topography of the farm (share of land in
272 mountainous zones), ii) soil conditions (soil suitability for grain production), climate

⁹ Cantons may differ with respect to the provision of extension services (see e.g. Wuepper, D., Roleff, N., Finger, R., 2021. Does it matter who advises farmers? Pest management choices with public and private extension. Food Policy 99, 101995.) 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.

273 conditions on the farm (average temperature as well as the mean precipitation in periods
274 critical for mechanical weed control). Moreover, we account for the regional weed pressure
275 and local occurrence of herbicide resistance.

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

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

285 **3.2. Robustness checks**

286 We provide several robustness checks to the main specification of Equation 3 provided above.
287 First, we use Probit and Logit estimation to estimate our model and compare sign and
288 significance of results to the main specification, i.e. the linear probability model (also see
289 Angrist and Pischke, 2008). Second, we estimate the model in Eq. 3, using different
290 configurations of the sets of control variables, i.e., i) characteristics of the farming system
291 before adoption, ii) structural farm and producers' characteristics and environmental
292 conditions, iii) producers' expectations and perceptions and iv) adjustment costs and compare
293 results concerning coefficient estimates and significance of the variables of interest in the
294 main model.

295 Third, we address potential concerns regarding inference on data with clusters of
296 heterogeneous size (i.e., here cantons), using a wild bootstrap approach (Wu, 1986). Further,

297 on a similar note, error terms might not be correlated within cantons but rather more locally
298 within districts (e.g., due to local initiatives, clubs, associations, discussions with neighboring
299 farmers). We therefore additionally check the robustness of our results clustering error terms
300 at a district level instead of a cantonal level.

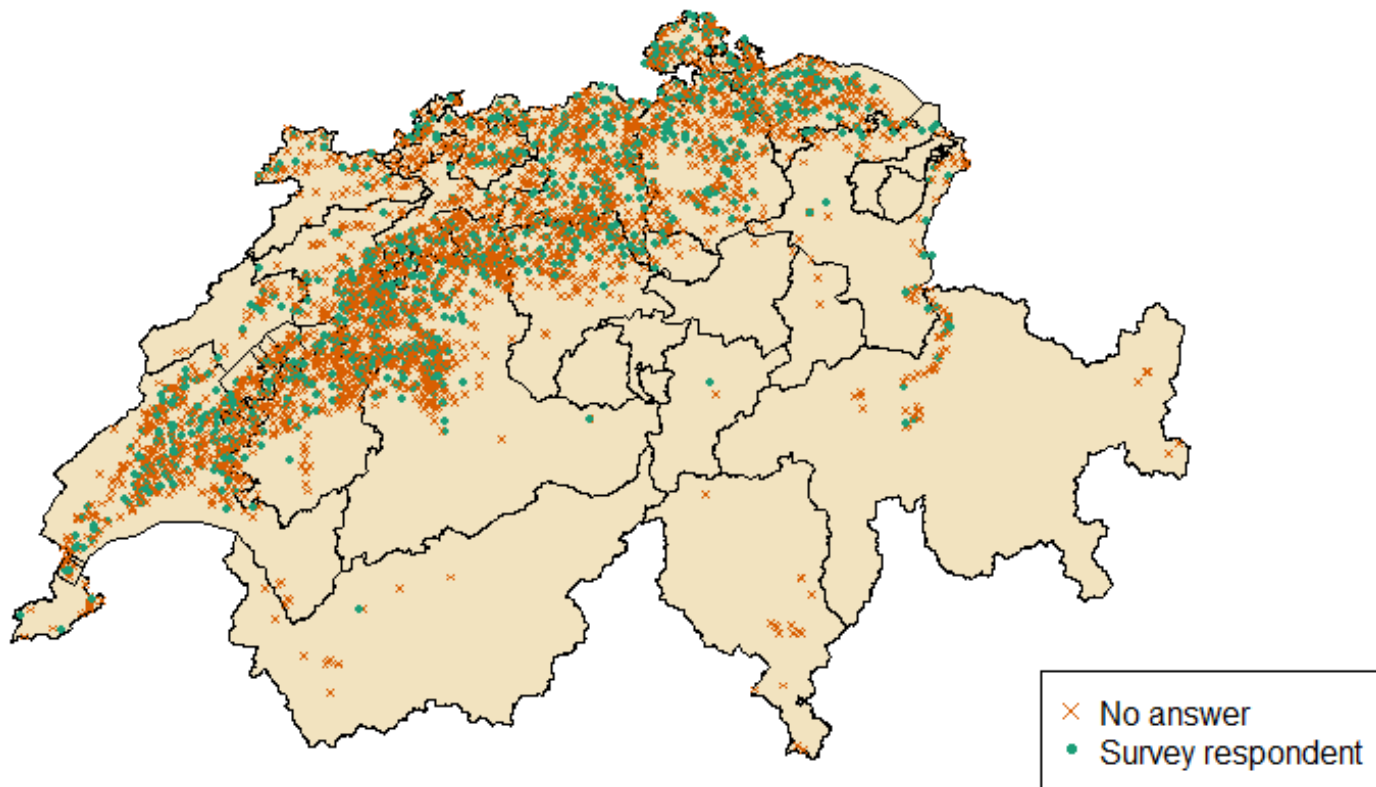
301 Fourth, we investigate if the identified determinants of adoption differ between farmers who
302 have already adopted the production system (further called "adoption pioneers") and farmers
303 who intend to adopt in the future (further called "intended adopters"). Differences between the
304 two groups may reveal important information for the design of pesticide-free production
305 programs (see above). In the robustness checks, we, therefore, create two additional
306 dependent variables: *Pioneer_i* states that farmers have participated in the program in 2019/20
307 (1) or not (0). *Intended_i* indicates if farmers who have not participated in the program in
308 2019/20 intend to participate in the future (1) or not (0). We then perform two separate
309 regression analyses to identify determinants of "adoption pioneers" and "intended adopters,"
310 using *Pioneer_i* and *Intended_i* as dependent variables but the same set of explanatory
311 variables as for the main model described above, respectively. Then we compare the results of
312 these two regression analyses to the results of the main analysis.

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

322 4. DATA

323 We conducted an online-survey on program participation and potential adoption determinants,
324 barriers, and challenges for our analysis. We sent out the survey to the whole population of
325 IP-SUISSE wheat producers (4749 producers) and received 1105 complete answers (response
326 rate of 23.3%). For an overview of the spatial distribution of the population of IP-SUISSE
327 wheat producers and survey respondents, see Figure 1.

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



343

344 **Figure 1.** Distribution of the population of IP-SUISSE farmers by survey participation

345 The map shows locations of farmers contacted in the survey. “no answer” and “survey respondent” describe
 346 farmers, who did not take part in the survey and those who participated in the survey, respectively. N=4749,
 347 response rate (ratio of respondents to contacted farmers) = 23.3%.

348 The survey contained three major parts: i) program participation, assessment, expectations ii)

349 structural farm and producers' characteristics, and iii) behavioral characteristics. More

350 specifically, in the first part, we asked producers about their participation decision and

351 intention to participate in the future, costs and benefits of program adoption, expected crop

352 management decisions under participation (e.g., herbicide substitution strategies), and

353 expected changes in production. The second part focused on farm and producers'

354 characteristics, such as age, education, farm type, and farm succession. Finally, in the third

355 part of the survey, we asked producers questions concerning their risk preferences, expected

356 environmental and health benefits of the program, environmental attitudes, farming

357 objectives, self-efficacy, and locus of control. For a detailed description and transcript of

358 survey questions, see the accompanying data article. Answering the survey took participants a

359 median time of 17.9 minutes.

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

379 We further checked the internal validity of our sample of survey respondents, i.e., how
380 representative the sample is of the whole population of IP-SUISSE wheat producers. We here
381 exploit that information on historical yields and structural farm and producers' characteristics
382 from the IP-SUISSE database is available for the entire population of IP-SUISSE producers
383 (including all non-respondents). The IP-SUISSE data allows us to check internal validity
384 concerning i) the distribution of survey respondents across space (see Figure 1), ii) historical
385 Extenso wheat yields, and iii) structural farm and producers' characteristics from the IP-

386 SUISSE database. More specifically, we compare sample (respondents) and population
 387 concerning the following characteristics: first year of participation in IP-SUISSE production,
 388 agricultural land, wheat surface, the share of wheat in total agricultural land, animal units, the
 389 share of land in mountain regions, average annual temperature and precipitation, soil
 390 suitability for wheat production and mean and standard deviation of delivered Extenso wheat
 391 quantities¹² over the ten years preceding program introduction (2008-2018).

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

400 For a short description and summary statistics of all variables used in our analysis, see Table
 401 2. For a more detailed description of variables and data sources, see the accompanying data
 402 article.

403 **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	-

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.

Canton_fr	Binary	The farm is located in a mainly French-speaking canton (1) or not (0).	0.25	0.43
Share_mount ain	ratio	Share of the farms agricultural land in the mountain region.	0.05	0.20
Suitability_gr ains	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_res istance	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 <i>Alopecurus myosuroides</i> , <i>Chenopodium album</i> , <i>Lolium multiflorum</i> , and <i>Apera spica-venti</i>).	0.11	0.33
Avg_yield	dt/ha	Mean delivered Extensio wheat yield in the postcode area of the producer from 2008-2018.	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_arabl e	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_de cr	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_ris k	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-	The producer indicated no willingness to take risks (0) to a	4.80	2.63

	10	very high willingness to take risks (10) in the plant protection domain.		
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 (5) effect on the health of farmers and consumers.	2.57	1.27
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

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

407 5. RESULTS

408 5.1. Descriptive Results

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

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

3.7	4.2	Weed pressure wheat
3.3	4.1	Weed pressure rotation
3.7	4	Resistant weeds
3.3	3.8	Workload
3.4	3.7	Machinery
2.6	3.1	Incompatible soil
2.8	2.4	Missing experience
1.6	1.7	Swapping fields
2.9	3.3	Lower yields
3	3.5	Higher risks
Positive	Negative	

423

424 **Figure 2.** Rating of potential adoption barriers by survey respondents

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

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

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

443 Although descriptive statistics give a first impression of the data, they do not allow assessing
 444 the importance of adoption determinants and barriers while controlling for variation in other

445 important characteristics. Therefore, we conducted regression analyses on the producers'
446 adoption decisions. We report the results in the following section.

447 **5.2. Regression results**

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

451 We find that adoption is mainly driven by producers' expectations of the program (Table 4).
452 More specifically, we find that the producers' perception of the program's positive
453 environmental effects is a key driver of adoption. Further, expectations of the program's
454 production effects are essential. Producers who expect a higher yield loss or higher production
455 risks under pesticide-free production and those who expect higher investment risks in
456 machinery (i.e., for mechanical weed control) are less likely to adopt pesticide-free wheat
457 production.¹³ In line with the above results on the important role of expected risks, a higher
458 risk aversion of producers in the plant protection domain leads to lower adoption.

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

462 Moreover, adjustment costs reflecting farmers' current tillage practices and endowment of
463 machinery for mechanical weed control determine participation decisions. Prior experience
464 with pesticide-free production and expected additional management costs do not have a
465 significant effect on adoption. However, producers who do not have machinery for

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.

466 mechanical weed control and expect higher risks of investments in such machinery are less
 467 likely to adopt.

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

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

479 **Table 4.** 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)

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

484 5.3. Results of robustness checks

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

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

497 Fourth, we analyze potential differences in adoption determinants between adoption pioneers,
498 i.e. producers who have already adopted pesticide-free production, and intended adopters, i.e.
499 those who have stated that they want to adopt the production program in the future.

500 Regression results in Table A5 in the appendix show that results are qualitatively in line with
501 the main results, but we find interesting differences between adoption pioneers and intended
502 adopters. Results are similar for the effect of expectations on yields and the environmental
503 effects of program adoption. In contrast to the main results and results for stated adopters, we
504 find that risks and risk preferences do not seem to be an important adoption determinant for
505 adoption pioneers. Expected production risks are less significant, and expected investment
506 risks in machinery and risk preferences do not significantly affect their adoption decision.

507 Regarding adjustment costs, adoption pioneers seem to have positive prior experiences with
508 pesticide-free production, and the expected costs of additional management measures are
509 important for them. In contrast, intended adoption seems to be influenced by negative prior
510 experiences. Additionally, flexibility in the prior farming system (no commitment to cantonal
511 pesticide-reduction programs/soil conservation programs) and an established farm succession
512 seems to be of importance for adoption pioneers and not for intended adopters. Further, we find
513 that adoption pioneers are more likely situated in the Western, i.e. French speaking part of
514 Switzerland.

515 Finally, we assess the robustness of our estimates to omitted variable bias, using Oster
516 bounds. For all key adoption variables from the main model, we find that the degree of
517 selection on unobservables would have to be at least as large as selection on observables (with

518 the delta value of exp_risk_machinery just slightly under this threshold) to render effects
519 insignificant. See Table A6 in the appendix for results. An exception from this result are those
520 levels of the expected yield decrease variable, which were highly insignificant in the
521 regression analysis. However, when we regroup levels this result disappears, indicating no
522 general problem pertaining to this variable.¹⁴ Results of Oster bounds therefore indicate
523 robustness of our analysis to potential omitted variable bias.

524 **6. DISCUSSION**

525 We analyze determinants, barriers, and challenges of Swiss Extensio wheat farmers to
526 participate in a novel, pesticide-free wheat production program. Pesticide-free production
527 systems have a high potential for pesticide load abatement while sustaining yield levels. Due
528 to their broader adoption potential compared to production systems that restrict input use in
529 the complete crop rotation, such as in organic farming, they could be of high relevance for
530 sustainable intensification of (European) agriculture (Pretty, 2018; Reganold and Wachter,
531 2016).

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

538 Our central finding is that producers' expectations of the program's economic and
539 environmental effects strongly matter for adoption. Negative expectations may constitute
540 crucial adoption barriers. The higher producers expect yield losses or production risks to be,

¹⁴ Results are available on request.

541 the less likely they are to adopt the program. A large share of producers in our survey expects
542 yield losses of over 10, 15, or even 20% in pesticide-free production compared to Extenso
543 production. However, using a bio-economic model, Böcker et al. (2019) predict average yield
544 losses from program uptake to only be around 6%. While some of the farmers might have
545 given strategic answers in the survey to influence discussions on price premia and the loss
546 might be higher for producers in unfavorable production locations, producers' expectations do
547 not always seem to be driven by underlying production conditions but may also be attributed
548 to a lack of experience and a substantial uncertainty associated with adopting this very novel
549 production system. Similarly, Cerroni (2020) finds that the adoption of new crop varieties is
550 strongly linked to uncertainty aversion.

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

559 Interestingly, we find that not only the producers' expectations concerning economic effects
560 are driving adoption but also their expectations regarding the program's environmental
561 benefits. Producers who believe that the program contributes to more sustainable agriculture
562 are more likely to adopt. The importance of perceived environmental benefits for the adoption
563 decision is further confirmed when looking at the magnitude of estimated coefficients, as they
564 range among the most important adoption determinants, together with the availability of
565 machinery and expected yield losses and risks of program adoption. The important role of the

566 sustainability of farming systems for adoption decisions is in line with recent findings on
567 Dutch farmers (Bakker et al., 2020). The result is not significant for the program's health
568 effects. We suggest that most producers in a developed country like Switzerland believe that
569 health effects are negligible when they correctly apply pesticides and therefore do not value a
570 potential reduction of health effects - while evidence for environmental effects of pesticides
571 has been very present in the public debate in Switzerland recently (Huber and Finger, 2019).
572 Further, we find that adjustments costs are important adoption determinants. Participation in
573 soil conservation programs (i.e., mulch seeding and direct seeding) seems to be an adoption
574 barrier. This finding highlights the challenge of substituting herbicide use that wheat
575 producers face in the new production system. This challenge is even more pronounced for
576 producers participating in soil conservation programs. While techniques for pesticide- and
577 tillage-free wheat production exist (and are already established in organic agriculture: such as
578 harrowing and agronomic adjustments, e.g., adjusting seeding dates or crop rotations), these
579 techniques often require more knowledge and are costlier than, for example, plowing.
580 Simultaneously, these management measures often require machinery, to which conventional
581 farmers do not have access. It also highlights trade-offs between the reduction of herbicides
582 and its potential adverse environmental and health effects and the use of mechanical weed
583 control with potential adverse effects of less soil conservation practices, e.g. for soil health
584 and increasing fuel emissions (Böcker et al., 2020, Van Deynze et al., 2018). Considering
585 these trade-offs holistically in the design of farming systems and policies will be key for
586 developing more sustainable agricultural systems (Möhring et al., 2020b). Moreover, these
587 trade-offs need to be minimized rapidly, e.g. by supporting the development of efficient soil
588 conservation practices without herbicide use (e.g. Vincent-Caboud et al., 2019).

589 Our results support the importance of access to machinery. We find that adoption is lower
590 when no machinery for mechanical weed control is available to producers. Therefore, it will

591 be essential for large-scale adoption of the pesticide-free production program to establish
592 knowledge of alternative management practices among producers and support the widespread
593 availability of required machinery at low costs. This may, for example, be achieved through
594 incentives for investments or the support of machinery rings. Along these lines, also
595 contractors providing mechanical weed control will be of increasing importance to facilitate
596 the widespread adoption of pesticide-free production in small-scale agricultural systems.

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

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

614 Results are stable over a range of robustness checks. Comparing adoption determinants of
615 adoption pioneers (already participating in the program) and intended adopters (intend to

616 participate in the future), we find that results are qualitatively in line with the main results.
617 However, adoption pioneers seem to be driven by positive prior experiences with pesticide-
618 free production and flexibility (no involvement in soil conservation/cantonal programs). In
619 contrast, intended adoption seems to be driven more by (expected) risks and negative prior
620 experiences with pesticide-free production. Stable, long-term planning horizons (established
621 succession) and language region are further associated with the decision of adoption pioneers.
622 The latter finding reflects the high number of initiatives for sustainable farming systems
623 recently established in Western Switzerland.

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

632 Based on our internal validity checks, we are confident that our sample reflects the population
633 well and that results are representative for IP-SUISSE producers. However, we have so far not
634 addressed our results' external validity as our survey did not include conventional or organic
635 wheat farmers. Finger and El Benni (2013) find that especially farmers with a lower wheat
636 yield tend to adopt Extenso wheat production. Translating their results to pesticide-free
637 production would mean that, especially, conventional farms with very intensive wheat
638 production and potentially high environmental effects would not be willing to adopt the
639 program. However, they also find that changes in prices and direct payments significantly
640 affected adoption. In our results, we have seen that the incentive mechanisms established in

641 the program seem to be attractive for a wide range of Extenso producers – and did not find
642 adoption to vary by yield level. This result indicates that pesticide-free production could be an
643 attractive option for conventional wheat producers as well. At the same time, some of the
644 pesticide-free producers may switch to organic production in the long-run. However, these
645 farms have previously not converted to organic farming, although Extenso production has
646 long been established in Switzerland. Their decisions to not convert, albeit higher prices and
647 direct payments in organic production, suggest that farm-level restrictions in organic farming
648 constitute an important adoption barrier to most producers. Past experiences with the Extenso
649 program have shown a high long-term stability of market shares, prices, direct payments and
650 price mark-ups of Extenso wheat after its establishment (Finger and El Benni, 2013). For
651 example, the direct payment for Extenso has not been changed since 1999. However, long-
652 term effects of the introduction of the pesticide-free wheat production program cannot be
653 evaluated at this point. The development of market shares, prices, direct payments and price
654 mark-ups for conventional, Extenso and pesticide-free wheat will be important to consider for
655 the evaluation of the pesticide-free production program in the long-run.

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

667 costs, such as investments in knowledge and machinery, and encourage participation despite
668 expectations of higher production risks.

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

678 **7. CONCLUSION**

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

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

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

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

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

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

714

715 **Conflict of Interest**

716 The authors declare that they have no known competing financial interests or personal
717 relationships that could have influenced the work reported in this paper.

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725

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857

858

859 **APPENDIX**

860

861 **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

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

864

865 **Table A1.** Robustness regression results: Marginal effects logit regression

Adopt	Coefficient	Standard error
Soil conservation	-0.0932***	0.0360
DP_canton	-0.0904*	0.0476
Avg_yield	-0.0011	0.0023
Canton_fr	0.0272	0.0323
Ag_land	-0.0002	0.0007
Share_Wheat	-0.0216	0.1344
Workforce	-0.0037	0.0105
Income_arable	0.0000	0.0006
Succession	-0.0149	0.0296
Share_mountain	-0.0458	0.0395
Suitability_grains	-0.0191	0.0202
Temperature	-0.0189	0.0303
Precipitation	0.0002	0.0003
Weed	-0.0006	0.0439
Herbicide_resistance	-0.0752	0.0700
Age	-0.0022	0.0016
Education	-0.0232	0.0278
Exp_yield_decr		
1	-0.0090	0.0508
2	0.1701***	0.0658
3	0.1142**	0.0570
4	0.1010**	0.0522
Exp_yield_risk	-0.1104***	0.0322
Risk_pref	0.0170***	0.0047
Pos_Environ	0.0910***	0.0136
Pos_Health	0.0001	0.0110
Experience		
1	-0.0276	0.0266
2	-0.0175	0.0235
Availability_machinery	0.1301***	0.0427
Exp_risk_machinery	-0.0326***	0.0116
Exp_costs	-0.0002	0.0002

866 We show marginal effects at mean values of all other variables of a logit model estimated with standard errors clustered by cantons. We
 867 compute standard errors of marginal with the delta method. The sample size is N=1073. *, ** and *** indicate statistical significance at the
 868 10%, 5%, and 1% level, respectively. Reference levels for the variables expected yield decrease and experience are "producer expects yield
 869 losses greater 15% from program introduction" and "producer has no experience with pesticide-free production," respectively.

870 **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

871 We show marginal effects at mean values of all other variables of a probit model estimated with standard errors clustered by cantons. We
872 compute standard errors of marginal with the delta method. The sample size is N=1073. *,** and *** indicate statistical significance at the
873 10%, 5%, and 1% level, respectively. Reference levels for the variables expected yield decrease and experience are "producer expects yield
874 losses greater 15% from program introduction" and "producer has no experience with pesticide-free production," respectively.

875 **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

876 Standard errors are clustered by cantons. The sample size is N=1073. *,** and *** indicate statistical
877 significance at the 10%, 5%, and 1% level, respectively. Reference levels for the variables expected yield
878 decrease and experience are "producer expects yield losses greater 15% from program introduction" and
879 "producer has no experience with pesticide-free production," respectively. "Production system," "Structural

880 characteristics," "Behavioural characteristics," and "Adjustment costs" denote models without control variables
881 from the respective categories

882

883 **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

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

888 **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

889 Standard errors are clustered by cantons. Reference levels for the variables expected yield decrease and
890 experience are "producer expects yield losses greater 15% from program introduction" and "producer has no
891 experience with pesticide-free production," respectively. Adoption variables in models (1), (2), and (3) denote
892 (has adopted/intends to adopt or not), (has adopted or not), and (intends to adopt or not). Note that in model (2),

893 pioneer adopters are excluded from the regression. Sample sizes are $N_{(1,2)}=1073$ and $N_{(3)}=917$, respectively. *,**
894 and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively.

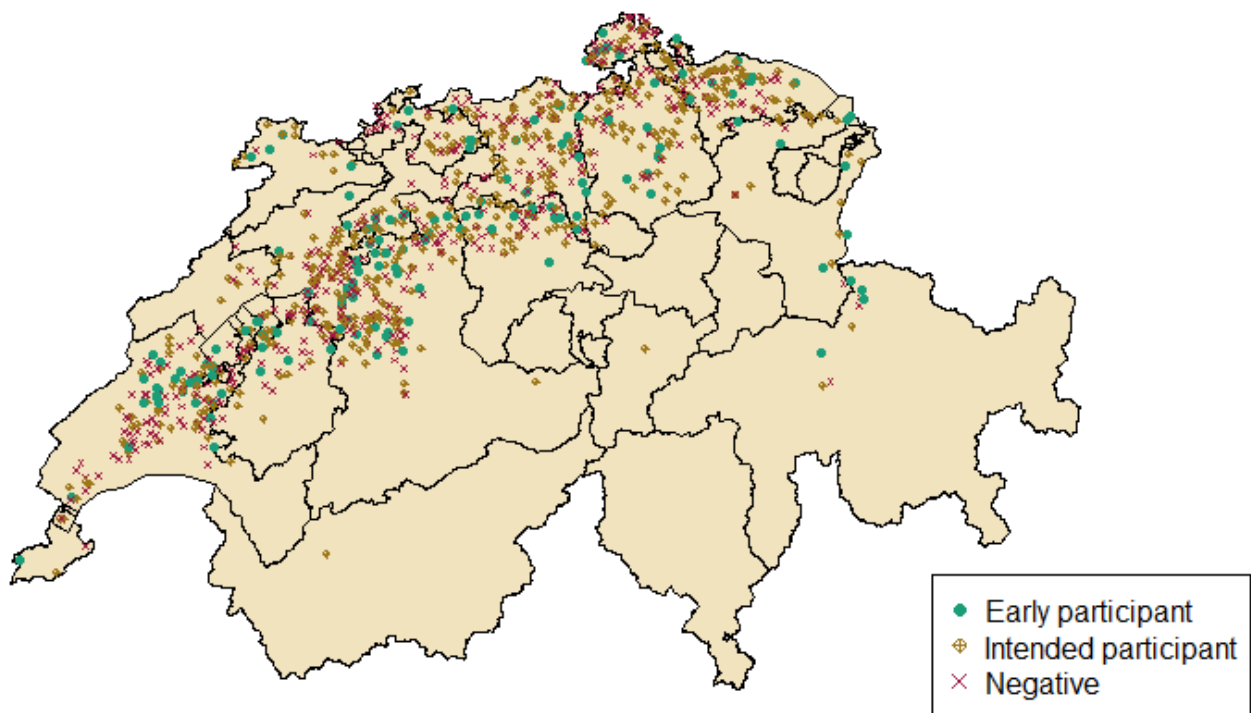
895

896 **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

897 Oster bounds are computed for the main model and $R_{max} = 0.33$ (setting $R_{max} = 1.3 * R_{main\ model}^2$, following
 898 the suggestions in Oster (2019)).

899

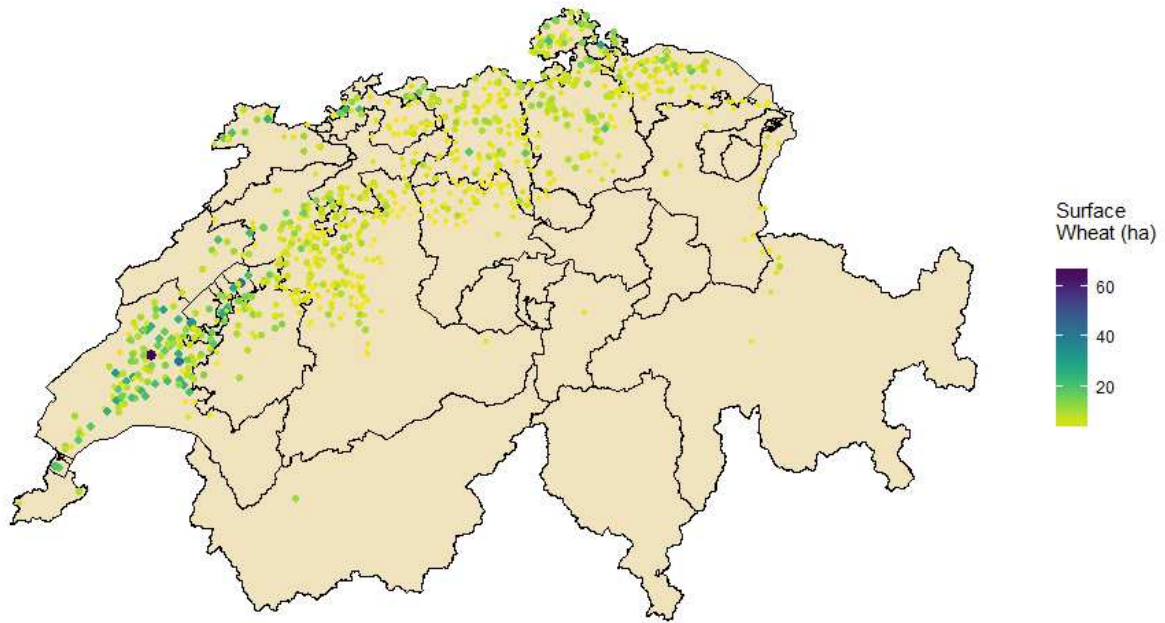


900

901 **Figure A1.** Participation decision in the pesticide-free wheat production program

902 The map shows participation decisions in the pesticide-free wheat production program of survey respondents (N
903 =1073). "Early participation" indicates producers who have already participated in the program, "intended
904 participation" indicates producers who have stated their willingness to participate in the future, and "negative"
905 indicates producers who are not willing to participate.

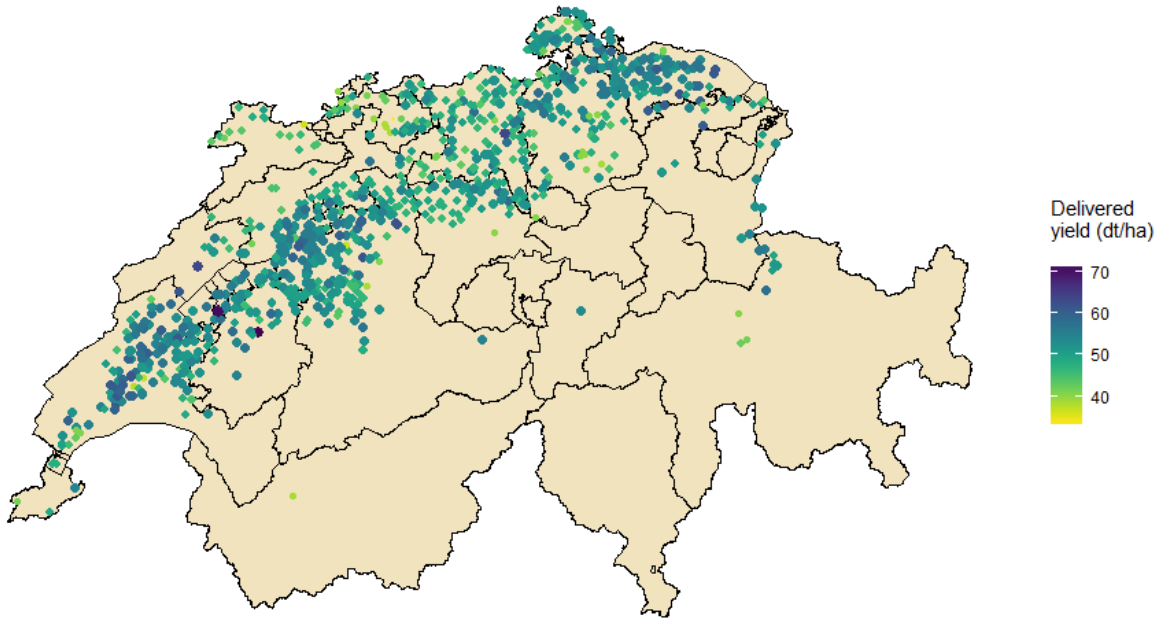
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908 **Figure A2.** The wheat surface of survey respondents
909 The map shows the wheat surface of producers in the survey (N = 1073) in hectares.

910



911

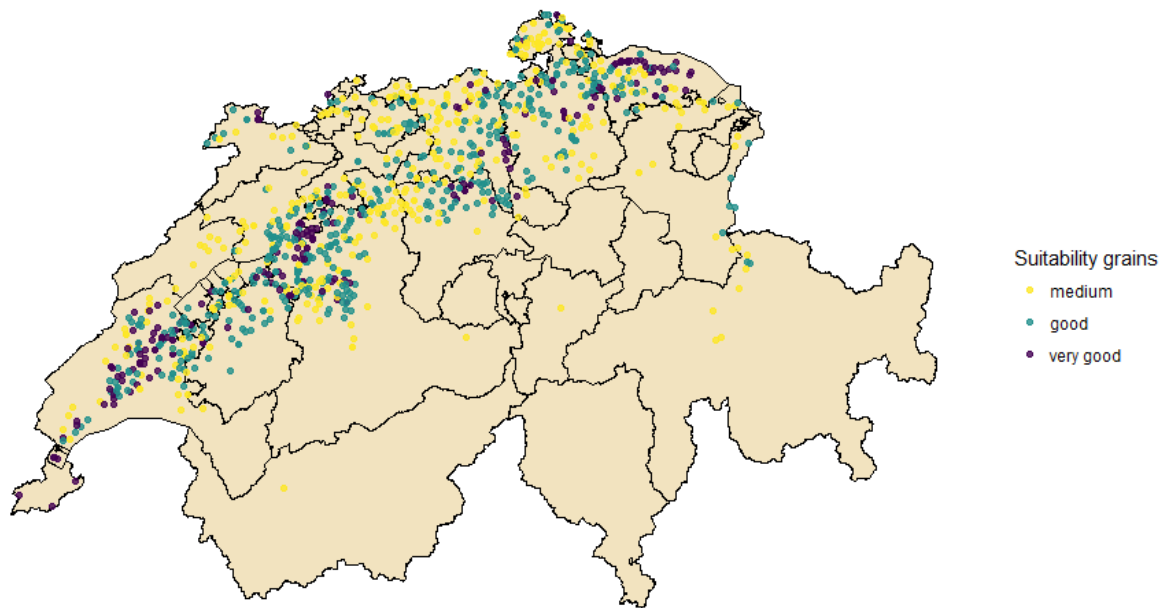
912 **Figure A3.** Average delivered wheat yields of survey respondents

913 The map shows average wheat yields of producers in the survey (N = 1073) delivered to IP-SUISSE from 2008-
914 2018 in decitons (1dt = 100kg) per hectare. Delivered quantities are slightly lower than harvested quantities, as
915 they account for losses from bad quality, drying, etc.

916

917

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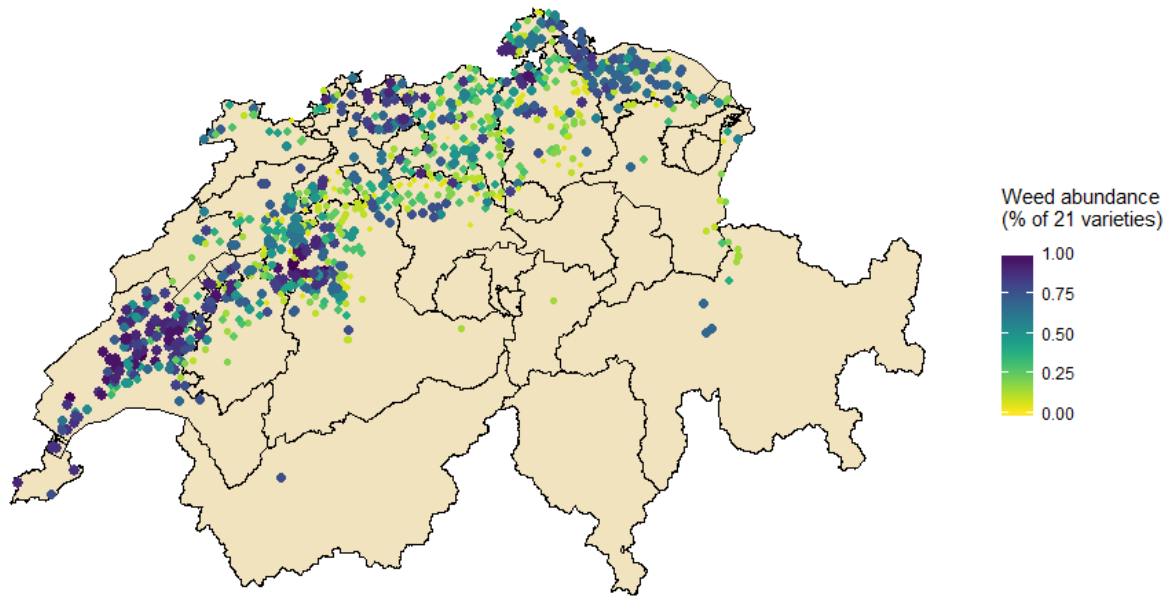


919

920 **Figure A4. Soil suitability for wheat cultivation**

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

923



924

925 **Figure A5. Weed abundance**

926 The map shows abundance of the 21 most important weeds in Swiss wheat production listed in (Böcker et al.,
927 2019) on farms of producers in the survey, according to Info Flora (Info Flora, 2019).

928