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Journal Article

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Publication date:
2022-09

Permanent link:
https://doi.org/10.3929/ethz-b-000566527

Originally published in:
Journal of the Agricultural and Applied Economics Association 1(3), https://doi.org/10.1002/jaa2.22

Funding acknowledgement:
172433 - Reconciling innovative farming practices and networks to enable sustainable development of smart Swiss farming systems (SNF)

Received: 27 January 2022 | Accepted: 5 August 2022

DOI: 10.1002/jaa2.22

ARTICLE

JOURNAL OF THE AGRICULTURAL AND APPLIED ECONOMICS ASSOCIATION
Open Access

Incentivizing the adoption of precision agricultural technologies in small-scaled farming systems: A choice experiment approach

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Funding information
Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung, Grant/Award Number: 407340_172433

Abstract
Precision farming technologies are expected to reduce nutrient surplus in agriculture. Uptake of these technologies in European farming systems, however, is low and policy incentives are needed to promote environmental benefits. We conducted a choice experiment with 418 Swiss farmers to elicit their preferences for site-specific nitrogen fertilization technologies. Using a split-sample approach, we elicit both willingness-to-accept and willingness-to-pay welfare measures. Results show that welfare measures for the nitrogen reduction potential vary significantly between the two samples. This indicates that the policy design affects farmers' preferences and willingness to adopt precision farming technologies that reduce nitrogen losses from agricultural production.

KEYWORDS
choice experiment, nitrogen, precision agriculture, variable-rate technologies

JEL CLASSIFICATION
Q16, Q18

1 | INTRODUCTION

Digital and geospatial technologies to monitor, assess, and manage crops have great potential to reduce the negative environmental impacts of agriculture, such as nitrogen loss or pesticide use (e.g., Basso & Antle, 2020; Walter et al., 2017). Precision agricultural technologies such as variable rate technologies (VRT) are designed to help reduce these negative impacts by providing timely and site-specific crop production information (Schimmelpfennig & Ebel, 2016). However, those technologies with the highest potential to reduce environmental footprints, such as VRT, number among those with the lowest adoption rates, especially in small-scaled European farming systems (Finger et al., 2019; Griffin & Yeager, 2018; Groher et al., 2020; Lowenberg-DeBoer & Erickson, 2019). Farmers view high costs implied by technology adoption and low direct economic benefits of site-specific nitrogen fertilization as major deterrents against the adoption of these technologies (Späti et al., 2021). Thus, policy measures may be needed to encourage adoption and thus pave the way toward the environmental and economic opportunities of precision agriculture, for example, large-scale reductions in nitrogen losses (Finger et al., 2019).

In this study, we elicit farmers' preferences and estimate welfare measures for the environmental, risk-related, and technical attributes associated with the use of VRT. To this end, an online survey, including a choice experiment, was conducted involving 418 crop-producing farmers in Switzerland. We used a split-sample approach to estimate both willingness-to-accept (WTA) and willingness-to-pay (WTP) welfare measures and to discuss different types of policies that can be used to encourage the adoption of VRT. Such policies can aim either at increasing the costs of nonadoption (e.g., tax on nitrogen) or at decreasing the costs of adoption (subsidies). The split sample thereby implies two different decision contexts for the farmer. In the WTP sample, farmers bear the cost of adoption to save (private) input costs and/or to provide an environmental benefit. This implies that the public benefit of nitrogen reduction is within the farmers duty (polluter pays). Taxing the use of nitrogen would thus increase the farmers' incentive to adopt input saving technologies. In the WTA sample, the farmers are, due to already high environmental regulation standards, entitled to use nitrogen for food production. In this case, any nitrogen reduction, which generates public environmental benefits, and that goes beyond what society can reasonably expect from the farmer should be compensated.

Previous literature revealed that the adoption of precision agricultural technologies in general, and site-specific nitrogen management in particular, is influenced by a wide range of socioeconomic and technological factors (Aubert et al., 2012; Barnes et al., 2019b; Blasch et al., 2020; Jensen et al., 2012, Pierpaoli et al., 2013; Schimmelpfennig, 2016; Tey & Brindal, 2012). Potential economic adoption barriers can be classified into two main categories. First, farmers face high costs from adoption (e.g., due to investment costs) and learning costs and perceive profitability to be too low to cover this expenditure. In particular, in Europe where small-scaled farming systems are prevalent, the high investment cost facing the individual farmer is viewed as a major entry barrier (Barnes et al., 2019b, Späti et al., 2021). Second, farmers face high uncertainty regarding cost savings and/or additional revenues from the use of the novel technology (D'Antoni et al., 2012), resulting in doubts regarding economic benefits (Barnes et al., 2019a, 2019b; Pannell, 2006; Rogers et al., 2016). Thus, in small-scaled farming systems, low profitability and high economic risks imply that, unless political support is forthcoming, the adoption of precision technologies will most probably remain low. Incentives are needed to make full use of environmental and social benefits from these technologies.

Previous research has also found that most farm-level studies focus on farm and operator characteristics, but pay less attention to attributes of the technology, interactions, institutional and psychological factors (Shang et al., 2021). In this context, Blasch et al. (2020), used a choice experiment to examine social influence (i.e., social networks) on farmers' willingness to adopt VRT in Italy. They conclude that a combination of financial support and the promotion of networking and knowledge sharing among farmers is essential to increase the adoption rate of precision farming technologies. However, there are multiple ways of implementing political support designed to incentivize more environmentally friendly behavior, for example, via a tax that increases the cost of nonadoption or a payment to compensate the farmer for reducing nitrogen inputs. Thus, no specific link has been identified between major adoption barriers and potential implications for the design of policies aiming to support the adoption of these technologies.

We add to the existing literature by examining wheat producing farmers' preferences for specific VRT characteristics, and by determining their WTA and WTP for these characteristics in a Swiss case study. This allows us to analyze how policy measures can be designed to incentivize the adoption of more environmentally friendly technologies. More specifically, we aim to improve the understanding of farmers' decision making on the adoption of VRT in small-scaled farming systems in two ways. First, we identify farmers' preferences for different attributes of VRT, including the costs or gross margin, the type of ownership (i.e., who owns the machinery/technology: the farmer, a collective of farmers or a contractor), the nitrogen reduction potential, uncertainties about the effect of technology use on yields, and the speed of support provided in case of technical difficulties. Given that the adoption rate in the here investigated farming system is still low, we apply a discrete choice experiment with hypothetical choice options to elicit farmers' preferences for these attributes and estimate their economic value. We preregistered our hypothesis[1] and combine the discrete choice experiment with farm-specific characteristics collected from an online survey and census data to analyze and explore the role of farm structures, farmers' attitudes, and risk preferences, as well as social factors influencing the hypothetical adoption decisions. Second, we identify differences in farmers' preferences for, and welfare estimates of, these attributes between the two samples. To this end, we vary the framing of the policy context. In the WTA sample, we assume that farmers would receive compensation for adopting VRT for example, via a governmental payment. In the WTA sample, we imply that farmers must bear the costs and that a policy incentive for example, a tax would result in higher costs of nonadoption. Knowledge about farmers preferences and the welfare estimates is an important information when choosing and designing appropriate policy support aiming at increasing the adoption of VRT and thus reducing nitrogen losses in agriculture.

2 | PRECISION FARMING AND VRT IN SWISS AGRICULTURE

Nitrogen pollution is a severe problem in European and Swiss agriculture. For example, about two-thirds of nitrous oxide emissions in Switzerland originate from agriculture, that is, fertilization and manure management (BAFU, 2020). Furthermore, the nitrate levels in ground and surface waters caused by nitrogen inputs have a negative impact on (drinking) water quality, whereby 38% of the total nitrogen input into water bodies comes from arable land, including vegetable production (Hürdler et al., 2015). Consequently, reduction of nitrogen losses and the corresponding mitigation of negative impacts on the environment is of crucial importance in Switzerland. VRT can be an important tool in this context, as they allow nitrogen use to be optimized, without implying reductions in food production (Basso & Antle, 2020; Schimmelpfennig & Ebel, 2016). The practical implementation comprises (i) data collection (e.g., using sensors mounted on tractors, satellite imagery, soil testing, handheld sensors), (ii) interpretation of the data collected, and (iii) implementation of appropriate management response, for example, predetermined, adjusted nitrogen fertilization rates. This technology can reduce nitrogen use by up to 40% without lowering crop yields (Argento et al., 2021; Finger et al., 2019). Thus, it offers both environmental benefits (less nitrogen losses) and lower input expenditures for farmers. It follows that new equipment may be needed to perform all the above-mentioned steps (data collection, processing, and adjusted nitrogen application) and this incurs costs for the technology adoption (Späti et al., 2021). At present, these VRT are not widely used in Switzerland with its' small-scaled farming structures and only 6.4% of arable farmers reported that they already used electronic measuring systems for nutrient supply (Groher et al., 2020).

Swiss agriculture is characterized by strong financial support to farmers, especially using direct payments, often aiming to promote sustainable agricultural practices (BLW, 2021). For example, there are payments to improve the sustainable use of natural resources and increase efficiency in

[1]https://aspredicted.org/8kn4q.pdf

input applications by promoting techniques with a proven favorable impact (BLW, 2022). In addition, also policy instruments like taxes on critical inputs like nitrogen are frequently discussed, but not yet introduced (Finger, 2012; Schmidt et al., 2021). This policy background opens opportunities to set incentives which encourage the use of technologies such as VRT. Therefore, it is important to study which factors influence farmers' VRT adoption decisions and determine how they would respond to specific policy measures.

3 | CONCEPTUAL FRAMEWORK

3.1 | Factors influencing adoption decisions for VRT

We assume that farmers make decisions that maximize their utility (McFadden, 1974). The adoption decision will depend on the utility derived from (a) increased profitability of a given VRT including public payments for environmental benefits, taxes, and so forth (Pierpaoli et al., 2013; Schimmelpfennig & Ebel, 2016; Tey & Brindal, 2012), (b) nonmonetary utility from increased environmental services (Balafoutis et al., 2017; Tey & Brindal, 2012; Zhang et al., 2015), and (c) the reduction in uncertainty about gains (monetary and nonmonetary) from the technology (Figure 1).

The influencing factors can be divided into three categories. First, the technology characteristics themselves affect farmers' decisions about its use ([1] in Figure 1). Profitability, or the lack thereof, due to high adoption costs, low returns (Barnes et al., 2019b; Schimmelpfennig, 2016), or inadequate compensation for the public benefits generated can also be of critical importance. The perceived risk associated with the use of the technology (Knight et al., 2003; Sunding & Zilberman, 2001) is another key issue that may lower the rate of adoption. These risks include a high degree of uncertainty regarding the potential yield of a field (Isik & Khanna, 2002), or the actual impact of the

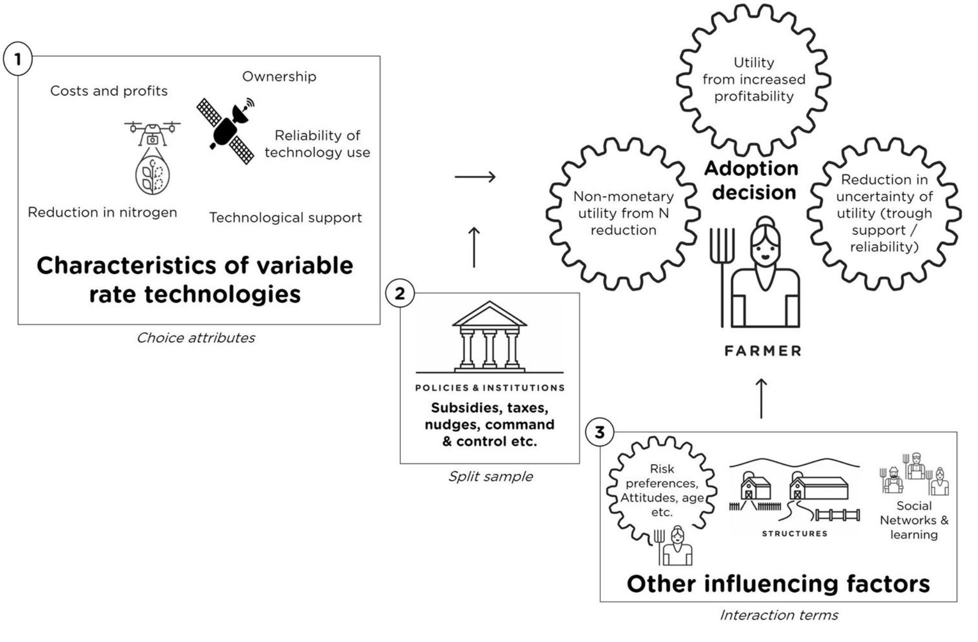
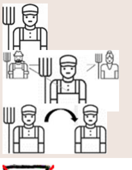
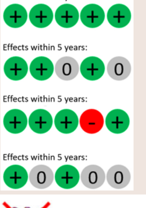


FIGURE 1 Three categories of factors influencing adoption decisions of variable rate technologies and their representation in the study design. (1) Technology characteristics represented as attributes of the choice experiment. (2) Different framing of policy incentives reflected in the split sample design. (3) Other influencing factors used as interaction terms in the econometric analysis of the choice experiment.

technology on yields, that is, the technology might seem unreliable in the sense that it does not generate benefits in each application. This aspect is considered in the design of the choice experiment through the reliability attribute (see also Table 1). In addition, some farmers might lack sufficient technical know-how, and this can also inhibit adoption (Fountas et al., 2005a). This, in turn, implies that technical support may be needed. Therefore, we included an attribute that reflects the technical support provided. Finally, the ownership structure, that is, who owns the machinery/ technology also influences the adoption decision. In this context, individual ownership that is, the farmer him- or herself invested in the technology may come with high costs. Collective use of precision farming technologies or the hiring of contractors could be a way to overcome economic barriers in the uptake VRT and facilitate adoption and diffusion (Kutter et al., 2011; Wang et al., 2022). This aspect is captured in the ownership attribute.

Second, policies and institutions can also influence adoption decisions ([2] in Figure 1). Typical options to support greener technologies include command-and-control measures

TABLE 1 Choice attributes and attribute levels

Attribute name	Description	Levels	Symbols
Gross margin (WTA)/ Costs (WTP)	WTA: Additional annual gross margins resulting from the application of the technology WTP: Additional annual costs of the technology	• 100 CHF/ha and year • 200 CHF/ha and year • 300 CHF/ha and year • 400 CHF/ha and year	
Ownership of the technology	The farmer can either own the technology himself, together with other farmers, or purchase the service from a contractor	• Selfowned • Jointly owned • Contractor	
Reduction of applied nitrogen	Annual reduction of applied nitrogen, without yield loss	• No Reduction • −20% • −40%	
Reliability	How often does the technology generate a positive effect during a 5 year's period (+), no change (0) or a negative effect (−)	• +++++ • ++0 + 0 • +++−+ • +0 + 00	
Support	How long does it take for the farmer to receive support in the case of technical difficulties	• No support • Within 1 h • On the same day • On the next day	 <1 h on the same day on the next day

Abbreviations: WTA, willingness-to-accept; WTP, willingness-to-pay.

(regulations and laws), economic instruments to guide farmer behavior via financial incentives (Dowd et al., 2008), such as subsidies for technology adoption (Baerenklau, 2005), increasing the cost of inputs through taxation, environmental nudges, or the introduction of a bonus/malus system related to environmental pollution (e.g., Kuhfuss et al., 2016; Peth & Musshoff, 2020).

Third, the characteristics of the farm, the farmer and his social networks can also have a strong influence on the adoption decision ([3] in Figure 1) whereby the impact of endogenous learning and neighborhood effects should not be neglected (Manski, 1993). For instance, Blasch et al. (2020) showed that peer farmer knowledge of technology adoption had a positive influence on evaluations of VRT characteristics, highlighting the importance of social networks in the adoption process.

Figure 1 also shows how this conceptual framework translates into the choice experiment design. The characteristics of the technology serve as attributes in our discrete choice experiment. The split-sample approach allows us to test the effect of the policy framing (see also next section). Finally, we control for the other influencing factors in our econometric approach (see Supporting Information: Section S3). In line with previous research, we expect the preferred ownership structure to depend on the farm characteristics (e.g., crops, farm size, and farm type), as these have a significant effect on the profitability of the technology application. We anticipate that farmers will prefer technologies with higher nitrogen reduction potential as they increase environmental benefits and hence the utility. We assume that higher uncertainty associated with new technologies has a negative impact on the adoption decision and decreases utility. Rapid availability of support in cases of technical problems is likely to have positive effect on adoption decisions. We preregistered our study with these hypotheses on the online platform aspredicted.org (https://aspredicted.org/8kn4q.pdf).

3.2 | WTA versus WTP for site-specific nitrogen fertilization

Discrete choice experiments can be used to conduct ex-ante evaluations of different policy measures, for example, the Common Agricultural Policy in the European Union (Lefebvre et al., 2021; Thoyer & Préget, 2019). They have also been widely used to investigate the preferences of farmers for agri-environmental schemes (e.g., Espinosa-Goded et al., 2010; Lienhoop & Brouwer, 2015; Tyllianakis & Martin-Ortega, 2021; Villanueva et al., 2015). The method has already been applied to explore farmers' willingness to adopt VRT in Italy (Blasch et al., 2020) or precision agriculture technology in general (Thompson et al., 2019). Although other methods can be used for eliciting preferences, such as contingent evaluation (e.g., Hudson & Hite, 2003), choice experiments are nowadays considered state-of-the-art stated preference method (Hoyos, 2010). They have several advantages over the contingent valuation method, such as mimicking choices from real life that respondents are more familiar with than stating a price for a good, minimizing some of the biases associated with the contingent valuation method or allowing to estimate a separate welfare measure for each characteristic of a product being valued (Hanley et al., 1998, 2001). Specifically, in our case, this feature of the choice experiment enables us to estimate welfare measures for the different factors that have been identified in the conceptual framework to influence the decision to use VRT and, consequently, to inform the policy design on the relative importance of environmental, technical and ownership characteristics of variable rate fertilization. Given the currently low adoption rate of these technologies in Switzerland, this kind of experiment is ideal for investigating preferences for, and welfare estimates of, potential characteristics of the technology in small-scaled farming systems.

Discrete choice experiments can be framed to elicit either WTA or WTP welfare measure. The WTP welfare measure represents the amount of money an individual is willing to give up either for an environmental improvement (compensating surplus), to avoid environmental damage (equivalent surplus), to obtain a price decrease (compensating variation), or to avoid the price increase (equivalent variation). In our study, the decision context for the farmer in the WTP sample is that he/she is willing to pay for the technology adoption to save nitrogen input. This economic benefit for farmers from of saving nitrogen would increase with higher input prices for example, due to a tax on nitrogen. In addition, farmers might also be willing to pay for an environmental improvement, that is, a public good, resulting from avoided nitrogen surpluses. WTP estimates can hence be obtained by framing the monetary attribute in the discrete choice experiment as the cost of the technology that he/she would be willing to pay for gaining private and public benefits. From a policy perspective, the WTP format implies that the farmer must bear the costs of technology adoption and the society profits from the reduction in nitrogen.

The WTA welfare measure represents the minimum amount of money an individual is willing to receive as a compensation for foregoing a benefit (price decrease or environmental improvement) or for incurring a loss (price increase or environmental damage). In the context of the adoption of VRT, the decision context for the WTA sample is that the farmer already complies with high environmental regulations and any environmental improvement that increases his/her costs should be compensated, implying that the public should bear the cost of reducing nitrogen surplus. The WTA welfare estimates can then be derived by framing the monetary attribute, for example, as a subsidy paid for the application of the technology.

Therefore, in both the WTA and WTP framing, policies can be designed in a way that makes the VRT adoption more appealing. More specifically, by increasing the price of nonadoption (WTP sample) or reducing the price of adoption (WTA sample). Moreover, our analysis allows to[2] compare the welfare estimates between the samples.

According to the standard economic theory, the WTA is only assumed to differ from the WTP if income, wealth, or substitution effects exist and otherwise to be comparable (Hanemann, 1991; Knetsch, 2020; Nguyen et al., 2021). However, in practice, this may not be the case. Various studies have shown that there is a substantial disparity between WTA and WTP welfare measures (Brown, 2022; Graves, 2009; Horowitz & McConnell, 2002; Koetse & Brouwer, 2016; Tunçel & Hammitt, 2014), whereby the differences are smaller for ordinary private goods than for public and nonmarket goods. Moreover, a farmer might perceive the benefit of the technology either as reductions in losses or as gains. This has important implications for the welfare estimates since existing literature suggests that WTA estimates tend to be higher than WTP estimates (Knetsch, 2020; Koetse & Brouwer, 2016). The discrete choice experiment provides information about the importance of different VRT characteristics for the farmers under differently framed policies. These insights facilitate to study the effect of differently designed policy options on the degree of technology adoption among the farming population. If the environmental benefits generated by policy-supported VRT adoption are to be reaped, it is important to understand how policies and VRT characteristics drive farmers' adoption decisions and target them in the policy design.

4 | METHODOLOGY

4.1 | Questionnaire

The online questionnaire consisted of five parts. The first part involved the choice experiment, before which the attributes and attribute levels were explained and the participants were shown a

[2]This is possible because the two samples have similar socio-demographic characteristics, and we use the same choice attributes and attribute levels for both samples.

text and a video to help them understand the survey method and content and guide them when answering the choice experiment questions. In the second part, the farmers were asked about their experiences with and perceptions of VRT. The full questionnaire (and data) is provided in the supplementary material and in an accompanying data article (Späti et al., 2022). The combination of the survey with farm census data allowed us to assess the representativeness of our sample with respect to structural farm characteristics (Supporting Information: Table S1) and to use these variables as explanatory factors in the econometric model.

4.2 | Choice experiment design

Based on the existing literature, we selected four choice attributes to assess the environmental and technical attributes of VRT: annual costs, ownership of the technology, nitrogen reduction potential and uncertainty in the application of the technology. A focus group of five Swiss farmers confirmed the relevance of the selected attributes, but also highlighted that the availability of technical support can be an important factor in a farmer's adoption decisions, so we added this as a fifth attribute (Table 1). We use a split-sample approach and vary the policy context, resulting in the monetary attribute being defined as the amount of annual additional gross margins gained through higher yields, label premiums, or subsidies minus the technology costs in the WTA sample. The difference in returns minus costs reflects the compensation farmers expect for adopting the technology. In the WTP sample, the monetary attribute reflects the annual additional cost of the technology (deduction, maintenance, and other costs), thereby assuming that farmers would bear the costs for the technology. The levels of nitrogen reduction were based on results from a study by Argento et al. (2021), who found that nitrogen reductions in Swiss cereal production systems of up to 40% can be achieved with VRT. Uncertainty is reflected by the reliability attribute where we indicate how often the technology actually provides a benefit to the farmer during 5 years of application. Prompt, readily available support is captured by the support attribute.

A separate choice experiment design was generated for each sample. The main reason for using two designs is that we theoretically expect the opposite signs of the coefficients associated with the monetary attribute in the two samples, that is, a negative coefficient in the WTP sample and a positive coefficient in the WTA sample. We generated D-efficient choice experiment designs using Bayesian priors and 2000 Sobol draws in the Ngene software. For the survey pretest, we used the same priors for all the choice attributes in both samples, except for the monetary attribute. To generate the design for the final survey, we used priors from the survey pretest data from 29 young farmers. These prior values vary slightly between the two designs. To make sure that the two designs are comparable, we tested and compared them using simulations. The simulation results showed that the designs are comparable and expected to provide very similar results if respondents' preferences are the same, implying that there is no bias introduced by the two designs. The choice experiment design for each sample included eight choice tasks (see Supporting Information: Tables S12 and S13). Each choice task consisted of three alternatives: two hypothetical scenarios of VRT adoption and the status quo option. Participants were assigned randomly to one of the samples and asked to answer a sequence of eight choice tasks.

4.3 | Survey administration

In March 2021, the online survey was sent to 4911 crop farmers in the cantons of Bern and Solothurn in Switzerland (Figure 2). More specifically, based on census data, we approached all farmers in these cantons with over 20% open cropland to participate in the survey. The selected

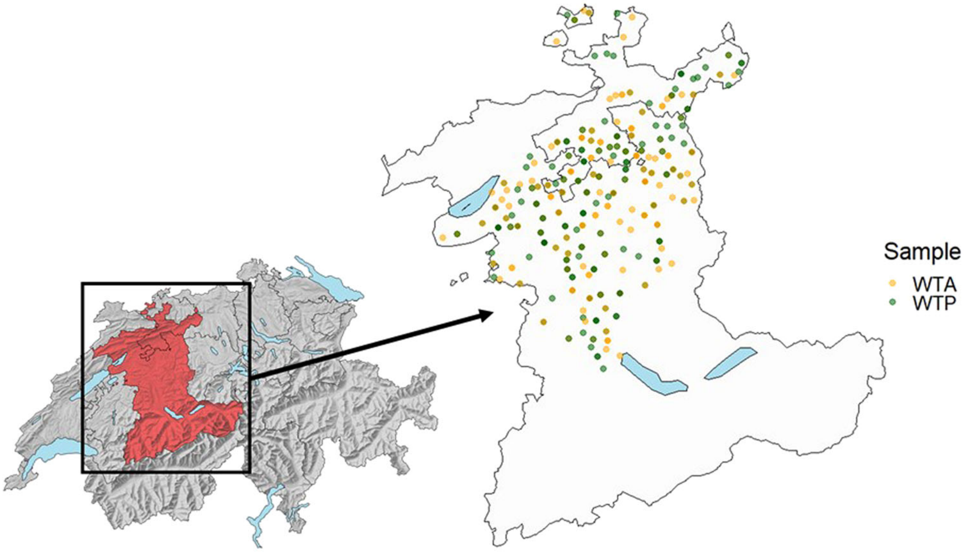


FIGURE 2 Map of Switzerland with the study area in the cantons of Bern and Solothurn (in red, Solothurn is top right) and the distribution of farmers in the willingness-to-accept (WTA) and willingness-to-pay (WTP) samples. Darker colors indicate more respondents from this municipality and mixed colors indicate respondents from both samples.

farmers were contacted by email (i.e., email sent to the address they also use for administrative purposes). The survey was linked to the census data of the two cantons, which gave us a basis for matching information on farm type and size.

4.4 | Sample description

We received a total of 424 complete and valid responses, with 216 completed questionnaires in the WTA sample and 208 in the WTP sample. This results in an overall response rate of 9.2% with a slightly higher response rate of 9.4% in the WTA sample compared to 9.0% in the WTP sample.[3] Four participants were removed from the WTA and two from the WTP sample because they were protest responses or stated that they did not understand the questions. This left us with 418 valid questionnaires (i.e., 212 for the WTA sample and 206 for the WTP sample). For our main analysis, we removed all participants who indicated that they were already using VRT. This resulted in a final sample of 399 individuals, 200 in the WTA sample and 199 in the WTP sample. The sample characteristics (Supporting Information: Table S2) are comparable to those of the farmer population (reflected in the census data).

Adoption of VRT is very low in the sample. Only 4.6% of the respondents indicated that they use VRT on their farms (Supporting Information: Table S2). More specifically, the share is 5.2% in the WTA sample and 3.9% in the WTP sample. A total of 68.8% of the farmers indicated that they had no experience with the use of VRT.

[3]Looking at the cantons, the response rate in the canton of Bern is 7.1% and in the canton of Solothurn 16.9%.

4.5 | Data analysis

The choice data were analyzed using R (R Core Team, 2020) and are based on the random utility theory framework (Marschak, 1960; McFadden, 1974) (details in Supporting Information: Section S2). We first explored the data using a multinomial logit model (Train, 2003; Louviere et al., 2000) and estimated mixed logit models with 2000 Halton drwas using the R package mlogit (Croissant, 2020). We also estimated the choice models in the WTP-space, using the logitr package (Helveston, 2021). The results, including the welfare estimates, turned out to be very similar to the choice models estimated in the preference space. We also analyzed the influence of socio-demographics by integrating them as interaction terms in the choice models (details in Supporting Information: Section S2). Finally, we performed different robustness checks (details in Supporting Information: Section S3).

5 | RESULTS

Our results show that 26 participants (6.5%) always chose the opt-out option: nine (4.5%) in the WTA sample and 17 (8.5%) in the WTP sample. The overall VRT adoption rate is low (Supporting Information: Table S2). Only 4.3% of the respondents stated that they already use VRT on their farm and a large majority (68.8%) stated that they have no experience, which is in line with the findings of Groher et al. (2020) (Table 2).

5.1 | Choice model results

The results of the mixed logit model for the WTP sample support our (pre-registered) hypotheses regarding the preferences for technology features of VRT. In the WTP sample, the insignificant coefficient for the alternative-specific constant (ASC) associated with the status quo alternative in the attribute-only model suggests that all else equal, farmers are indifferent between the status quo option and the adoption of VRT options. However, in the model with interaction terms the coefficient for alternative-specific constant becomes significant and negative, implying that farmers prefer the adoption of VRT over the status quo. The standard deviations of the alternative-specific constants are significant in both models, suggesting that preferences vary significantly across individuals.

The significant and positive coefficient for self-owned indicates that farmers prefer to own the technology rather than hire a contractor. The coefficient for jointly owned is insignificant, implying that this feature does not affect their choices. As expected, farmers prefer technologies with higher nitrogen reduction potential (without affecting production levels). The standard deviations for these parameter estimates are insignificant, which implies that farmers' preferences are homogenous for this technology characteristic. The reliability of the technology has a major influence on the adoption decision and in this case farmers' preferences seem to be homogenous. As expected, farmers have a stronger preference for technologies that are more reliable, reflected by larger coefficients for more reliable technologies. In this context, farmers prefer technologies which provide failure-free performance, that is, they prefer technologies that may only perform better three times in 5 years but without any losses compared to those that deliver a benefit four times but cause a loss once in these 5 years. Promt support in case of technical problems, that is, less than 1 h, has a positive influence on farmers' adoption decisions.

As expected, the cost coefficient in the WTP sample is negative and significant, which means that farmers prefer technologies with lower costs. When interaction terms are introduced in the WTP sample, the factors that further explain the probability of choosing

TABLE 2 Mixed logit models for the willingness-to-pay (WTP) and willingness-to-accept (WTA) samples

	WTA sample	WTP sample		
	Mixed logit	Mixed logit with interactions	Mixed logit	Mixed logit with interactions
Mean estimates of random parameters				
Alternative specific constant (ASC_{SQ})	−1.026*** (0.316)	−1.893*** (0.361)	−0.120 (0.338)	−1.231*** (0.377)
Selfowned	−0.117 (0.222)	−0.141 (0.227)	0.908*** (0.202)	0.861*** (0.198)
Jointly owned	0.392** (0.188)	0.399** (0.191)	0.310 (0.237)	0.298 (0.232)
20% N Reduction	1.195*** (0.195)	1.203*** (0.198)	0.893*** (0.171)	0.870*** (0.170)
40% N Reduction	2.012*** (0.241)	2.028*** (0.251)	1.276*** (0.259)	1.286*** (0.263)
Partially reliable (+++−+)	0.311 (0.254)	0.322 (0.257)	0.956*** (0.272)	0.979*** (0.263)
Reliable (++0+0)	0.532** (0.207)	0.568*** (0.211)	1.238*** (0.209)	1.227*** (0.209)
Fully reliable (+++++)	0.887*** (0.182)	0.885*** (0.188)	1.804*** (0.241)	1.844*** (0.238)
Support within 1 h	0.397* (0.220)	0.827*** (0.276)	1.053*** (0.259)	1.250*** (0.321)
Support on the same day	0.395** (0.191)	0.594** (0.262)	0.726*** (0.223)	1.088*** (0.276)
Support on the next day	0.137 (0.202)	0.229 (0.257)	0.818*** (0.193)	1.060*** (0.252)
Cost/Gross margin	0.003*** (0.001)	0.003*** (0.001)	-0.006*** (0.001)	−0.006*** (0.001)
Nonrandom parameters				
ASC_{SQ} × Farm size		−0.006*** (0.002)		−0.017* (0.009)
ASC_{SQ} × Age		−0.005 (0.011)		0.040*** (0.013)
ASC_{SQ} × High education		0.884** (0.380)		−2.086*** (0.343)
ASC_{SQ} × Innovator		0.687*** (0.219)		1.203*** (0.248)
ASC_{SQ} × Positive effect on environment		0.786*** (0.208)		1.523*** (0.254)
Self-owned × Farm size		0.005* (0.003)		0.017* (0.009)
Jointly owned × Farm size		0.001 (0.003)		0.032*** (0.012)
Selfowned × Age		−0.019* (0.011)		−0.040*** (0.012)
Jointly owned × Age		−0.031*** (0.012)		−0.058*** (0.018)
Partially reliable (+++−+) × Risk averse		−0.108 (0.654)		−1.061* (0.619)
Reliable (++0+0) × Risk averse		−1.011 (0.703)		−0.503 (0.543)
Fully reliable (+++++) × Risk averse		0.378 (0.514)		−1.564*** (0.583)
Support within 1 h × Technical solution		−0.683** (0.272)		−0.317 (0.277)
Support on same day × Technical solution		−0.312 (0.262)		−0.528** (0.265)
Support on next day × Technical solution		−0.156 (0.241)		−0.390 (0.254)
Standard deviations of random parameters				
SD Alternative specific constant (ASC_{SQ})	2.902*** (0.239)	2.810*** (0.248)	3.750*** (0.328)	3.428*** (0.309)
SD Self-owned	1.182*** (0.179)	1.173*** (0.183)	1.403*** (0.235)	1.291*** (0.236)

(Continues)

TABLE 2 (Continued)

	WTA sample		WTP sample	
	Mixed logit	Mixed logit with interactions	Mixed logit	Mixed logit with interactions
SD Jointly owned	1.858*** (0.246)	1.842*** (0.246)	2.449*** (0.368)	2.134*** (0.346)
SD 20% N Reduction	0.006 (2.245)	0.011 (2.437)	0.296 (0.394)	0.252 (0.448)
SD 40% N Reduction	0.002 (3.020)	0.021 (2.580)	0.288 (0.732)	0.326 (0.692)
SD Partially reliable (+++−+)	0.009 (2.667)	0.025 (2.571)	0.769* (0.445)	0.579 (0.446)
SD Reliable (++0+0)	0.007 (2.961)	0.012 (3.012)	0.049 (1.341)	0.034 (1.757)
SD Fully reliable (+++++)	0.112 (1.122)	0.071 (1.665)	0.034 (1.503)	0.004 (1.928)
SD Support within 1 h	0.549* (0.333)	0.497 (0.351)	0.075 (1.347)	0.012 (2.126)
SD Support on the same day	0.004 (3.080)	0.007 (3.127)	0.887*** (0.290)	0.738** (0.308)
SD Support on the next day	0.037 (2.391)	0.163 (0.918)	−0.214 (0.704)	0.221 (0.733)
SD Cost/Gross margin	0.002* (0.001)	0.002 (0.001)	0.006*** (0.001)	0.006*** (0.001)
Observations	1600	1600	1592	1592
Log likelihood	−1363.302	−1350.125	−1284.348	−1265.237
AIC	2774.604	2778.250	2616.696	2608.475

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

adoption are: size of the farm, age, high education, innovativeness of the farmer, and a positive attitude towards the environment. However, apart from the alternative-specific constant we do not observe any major changes in our main estimates due to the integration of interaction variables.

In the WTA sample, the alternative-specific constants are negative and significant, meaning that farmers generally prefer hypothetical alternatives, that is, adoption of VRT and receiving compensation for it, over the status quo option. This result is in line with our hypothesis that the adoption rates of VRT are higher in this sample (based on a comparison of attribute-only models).

Contrary to the WTP sample, a jointly owned is here preferred over the use of a contractor, while the coefficient for selfowned is insignificant. There is a preference for technologies with a high nitrogen reduction potential. Higher reliability of technologies also has a positive impact and, as in the WTP sample, technologies that do not cause years with losses increase the farmers' willingness to adopt VRT. Interestingly, the provision of technical support seems to be a less relevant characteristic for the adoption decision in this sample, which is reflected in lower significance levels of coefficients for this attribute and the insignificant coefficient for the attribute level support on the next day.

The significant and positive monetary coefficient is theoretically expected in the WTA sample and indicates that the higher the compensation offered, the higher the probability that farmers will choose the technology adoption. In the WTA sample, the introduction of interactions terms (Supporting Information: Table S12) increases the strength and the significance level of the coefficient associated with the support within 1 h, aligning the preferences for the levels of this attribute more with initial theoretical expectations (stronger preferences and higher welfare estimates for quicker technical support). As expected, farm size affects preferences for the ownership structure. In the WTP sample, farmers with larger farms prefer self or joint property over a contractor (Supporting Information: Table S13). In the

TABLE 3 Marginal-willingness-to-pay (MWTP) and marginal-willingness-to-accept (MWTA) estimates for technology characteristics (CHF/ha/year)

	MWTP	2.50%	97.50%	MWTA	2.50%	97.50%	Significance level of difference between MWTA and MWTP
Self-owned	−32.99	−211.29	88.33	149.15	87.76	227.78	0.0046
Jointly owned	113.7	4.84	269.36	50.9	−28.14	125.52	0.1768
20% N reduction	355.69	218.71	616.68	146.66	90.74	225.79	0.0045
40% N reduction	598.04	397.93	1002.91	209.52	118.36	347.62	0.0011
+ + 0 + 0	92.32	−52.76	303.28	156.94	65.45	297.5	0.2593
+ + + - +	157.64	37.31	333.07	203.27	124.1	325.25	0.2947
+ + + + +	263.52	141.74	489.62	296.18	208.1	432.44	0.3657
Support within 1 h	117.51	−12.68	245.65	172.95	93.07	268.39	0.2281
Support on same day	117.65	7.32	249.15	119.21	50.08	195.66	0.4865
Support on next day	41.16	−85.97	165.93	134.37	71.28	221.15	0.0937

WTA sample, this only applies to selfowned. Participants, who declare themselves to be innovative, are more likely to choose the technology adoption options. Furthermore, farmers, who expect VRT to have a positive effect on the environment, are also more willing to adopt the technology.

5.2 | Welfare estimates for technology characteristics

Our results imply that farmers in the WTP sample have, on average, the highest WTP for a technology which is constantly reliable (Table 3). Farmers would be willing to pay 296 CHF/ha/year for a technology that provides stable gains over the years. The second highest average MWTP is 210 CHF/ha/year for a technology that can reduce nitrogen application by 40%. On average, farmers are willing to pay 147 CHF/ha/year for a 20% nitrogen reduction. The MWTP amounts to 173 CHF/ha/year for technology support provided within 1 h. Farmers are willing to pay 149 CHF/ha/year in the form of selfowned in the technology. While all attributes played a role in the hypothetical decision of the farmers we surveyed, when looking at the most preferred level of each attribute, there seems to be a tendency with respect to these attributes, that is, reliability > nitrogen reduction > technical support > ownership.

The WTA sample exhibits a different preference order and significantly different welfare estimates, in particular for the same environmental and ownership attributes. The marginal willingness-to-accept estimates suggest that farmers request the highest compensation for the nitrogen reduction. They are willing to reduce nitrogen by 20% for a compensation of 356 CHF/ha/year, while they expect a compensation amounting to 598 CHF/ha/year for a 40% nitrogen reduction. Compared to the WTP sample, farmers claim a significantly higher compensation than they would be willing to pay for the same environmental characteristic of the technology, possibly

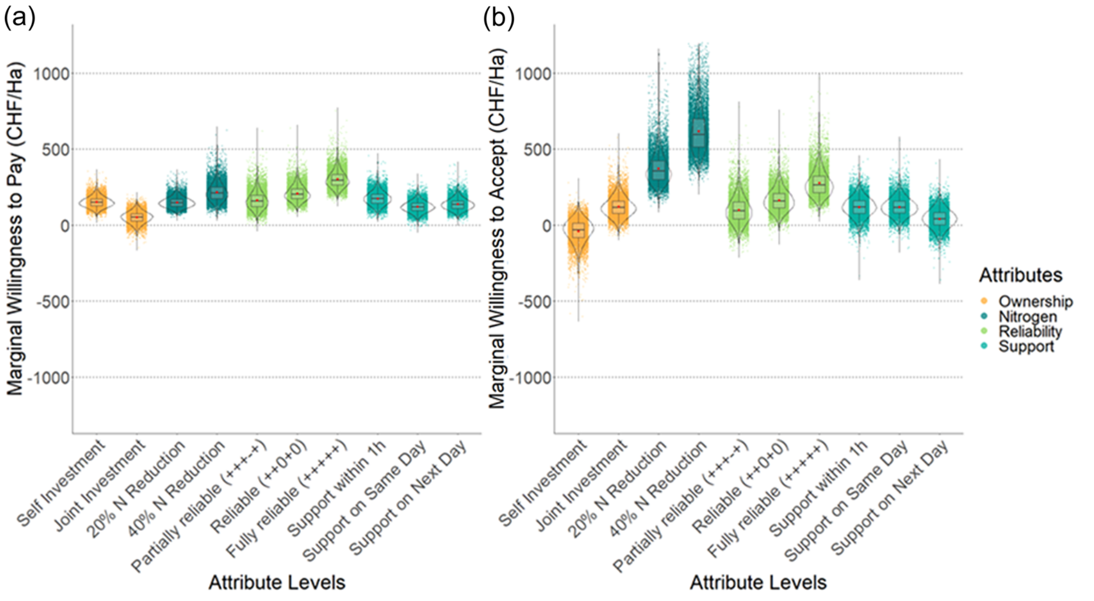


FIGURE 3 Marginal willingness-to-pay (MWTP) on the left (a) and marginal willingness-to-accept (MWTA) on the right (b). As in Table 3, the MWTA values are also presented as positive.

because they consider that they are providing public environmental benefits in the WTA sample. The MWTA estimates for the technological attributes are the same as our MWTP estimates and the order remains, that is, reliability > technical support.

Figure 3 summarizes the MWTP (A) and MWTA (B) for different technology characteristics. The p-value for the significance level of difference between the two samples is given in Table 3. The results show that the difference between MWTP and MWTA is the highest and statistically significant for the environmental characteristic, that is, N reduction levels of 20% and 40%. The difference between the welfare estimates for the N reduction levels between the two samples might be explained by the fact that the farmers in the WTA sample perceive to privately provide a public good. This tallies with the findings that the differences between WTA and WTP tend to be highest for environmental, nonmarket goods and services (Tuncel & Hammitt, 2014).

6 | CONCLUSION

We investigate the factors that influence farmers' adoption decisions regarding site-specific nitrogen fertilization technologies in small-scaled Swiss arable farming systems. We use a choice experiment approach to elicit farmers' preferences as well as WTP and WTA for environmental, technological, and ownership attributes of variable rate nitrogen fertilization technologies of Swiss wheat producers. Low current adoption rates indicate that additional political measures (e.g., a financial incentive or a nudge) are indispensable to promote the use of these technologies, thus ensuring that they contribute to reducing nitrogen surpluses in agriculture, without lowering food production.

Our findings imply that the adoption rate of VRT is influenced by the characteristics of the technology. If we consider the most preferred level of each attribute, we find a tendency in preferences regarding these characteristics, that is, high reliability of the outcome > high nitrogen reduction through technology use > fast technical support in case of technical difficulties > ownership of the technology. These results indicate that increasing the reliability of technology is a major factor in the uptake of precision agriculture technologies. Perception of potential technical failures may discourage small-scaled farmers from adopting VRT and reducing this (perceived) uncertainty is thus a key for triggering adoption. In addition, it is important for increasing uptake that the technology actually reduces the amount of nitrogen applied. Interestingly, the preferences on ownership structure, that is, who owns the machinery, shift depending on the policy context. Farmers prefer self-owned over joint-owned or accessing the technology via a contractor in the WTP sample, but prefer joint-owned in the WTA sample. The preference for self-owned in the WTP setting might represent yet another major barrier to the adoption of VRT since some of these technologies generate high costs for adoption and thus high depreciation costs that could be scaled down by joint-owned or contractor services.

The policy implications of our results are twofold. First, the currently low adoption rates of VRT indicate that a substantial increase in the adoption of VRT among Swiss farmers is unlikely without governmental intervention aimed at making the VRT more attractive. This could be achieved by reducing the costs of the technology (e.g., via subsidies), increasing and promoting the reliability of the technology, providing support to farmers in case of technical problems, compensating the farmers for providing the environmental benefits (e.g., via direct payments supporting lower N pollution practices), or combinations thereof. Regarding increases in (perceived) reliability of the technology, education and technological knowledge support provide an important leverage to increase the probability of VRT adoption. Our analysis suggests that education programs on the technology itself but also raising awareness of its positive environmental impact support adoption rates. Second, our results on the difference between WTP and compensation requirements seem to suggest that subsidizing environmental benefits or technologies come with a certain drawback. If farmers, all else equal, require a higher compensation than they would be willing to pay for the same level of environmental benefit, increasing the cost of nonadoption that is, by an incentive tax might be more efficient than a subsidy given a governmental budget constraint.

Building upon the here presented insights, future research can further test and quantify how different policy scenarios (e.g., taxes or subsidies) would affect the uptake of precision agricultural technologies while accounting for farm heterogeneities and farmers' preferences in small-scaled agriculture (e.g., in an agent-based approach). Furthermore, our choice experiment in which we used annual costs and gross margins as cost element did not account for potential staggered adoption decisions regarding these technologies. Future research could provide more insights into the uptake of precision agriculture technologies using an investment rather than a technology use perspective. In addition, there is still little empirical data concerning nitrogen savings from VRT. Providing this evidence to farmers based on future research can help to confirm the benefits of using VRT and increase the perceived usefulness, which could support the adoption of such technologies according to our findings. Future research could also investigate additional policy instruments, such as information nudging, that could encourage the adoption of precision technologies that support sustainable farming practices. Finally, while our research is based on a representative farm sample in the Swiss lowlands, further economic experiments would allow our findings to be scaled to other market and political settings.

ACKNOWLEDGMENTS

This study is supported by the Swiss National Science Foundation (SNSF), within the framework of the National Research Programme "Sustainable Economy: resource-friendly, future-oriented, innovative" (NRP 73), in the InnoFarm project, Grant-N° 407340_172433.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the ETH research collection at https://doi.org/10.3929/ethz-b-000520042 and are described in the article by Späti et al. (2022).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Späti, Karin, Robert Huber, Ivana Logar, and Robert Finger. 2022. "Incentivizing the Adoption of Precision Agricultural Technologies in Small-Scaled Farming Systems: A Choice Experiment Approach." *Journal of Agricultural and Applied Economics Association*. 1–18. https://doi.org/10.1002/jaa2.22