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ARTICLE

Farmer behavior toward herbicide-free agriculture and conservation tillage

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Abstract

Balancing conflicting policy goals is a key challenge in the transition to sustainable agricultural systems. An important example is herbicide use reduction potentially conflicting with conservation tillage—which often strongly relies on herbicide use. We investigate the joint uptake of two agri-environmental schemes, conservation tillage and herbicide-free agriculture systems. To this end, we use a combination of detailed survey data on farmer behavior, environmental and agronomic data, and census data on the complete population of all farmers from Switzerland. Findings based on a multinomial logit and fixed effects multinomial logit indicate that, conditional on observable factors, the systems are not complementary, but joint adoption occurs for 35% of farmers. Behavioral factors explain 26% of joint adoption behavior, emphasizing the role of risk taking, openness to innovation, and biodiversity valuations in farmers' decisions. Our analysis provides broader implications for assessing and navigating conflicting sustainability goals in agriculture globally.

KEYWORDS

agri-environmental schemes, farming goals, innovativeness, noncognitive skills, risk preferences

JEL CLASSIFICATION

Q16, Q20, D81

1 | INTRODUCTION

There is an urgent need for agriculture to become more sustainable (Pe'er et al., 2019), reducing pesticide and nutrient pollution, greenhouse gas emissions, and soil degradation (Wezel et al., 2014). For example, it is estimated that 33% of land worldwide is degraded due to erosion, salinization, compaction, and chemical pollution (FAO and ITPS, 2015). To encourage sustainable practices in agriculture, integrating policies and leveraging synergies between different practices are seen as promising ways forward (Canales et al., 2020; Möhring et al., 2023). However, farmers and policy makers often face tradeoffs implementing measures to achieve these goals. Herbicide use reduction and the uptake of conservation tillage practices is an example of these tradeoffs in agricultural systems that is of high relevance in the US, Europe, and globally (e.g., Finger et al., 2023; Ye et al., 2021). This is because conservation tillage often relies on herbicide use for weed control (Böcker et al., 2019; Derpsch et al., 2010; Springmann et al., 2018). Even though these kinds of tradeoffs are well documented from agronomic perspectives (e.g., Soane et al., 2012; Wittwer et al., 2021), farmers' actual behaviors and the individual characteristics and preferences that could help overcome such tradeoffs are yet to be understood.

We here investigate the joint uptake of two agri-environmental schemes with potentially conflicting sustainability goals. More specifically, we analyze the uptake of conservation tillage and herbicide-free agriculture systems in Swiss agriculture, using survey data from 1073 farmers capturing agricultural practices, farm structural characteristics, and behavioral characteristics. We merge this data with environmental and agronomical factors relevant for the adoption of conservation tillage and/or herbicide-free agriculture. As a robustness check, we further complement our analysis with the Swiss agricultural census data from all Swiss wheat producers spanning the years 2019 to 2022 ($N = 12{,}440$). Our case study focuses on wheat production. Wheat is the most cultivated crop globally and constitutes over 50% of the cereals grown in Europe. The Swiss case study provides a unique setting that allows us to understand farmer's decisions to adopt voluntary agri-environmental schemes in the face of opportunity costs and tradeoffs, and provides broader implications for navigating potentially conflicting sustainability goals in agriculture globally.

Two streams of literature speak to the (joint) adoption of sustainable practices in this setting. The first stream focuses on the different agri-environmental measures that can exhibit synergies or tradeoffs, including the adoption of multiple conservation practices (e.g., crop rotations, agroforestry, conservation tillage) (Casagrande et al., 2016; Teklu et al., 2023; Upadhyay et al., 2003), assessments of the complementarity and multifunctionality of sustainable practices (Ayoub, 2023; Kirchner et al., 2015; Wittwer et al., 2021), and tradeoffs between food production and biodiversity (Phalan et al., 2011). See Breure et al. (2024) for a systematic review of trade-off analysis in agriculture. More closely related to our setting is Rodríguez-Entrena and Arriaza (2013), who test for the complementarity between three different conservation agriculture practices. We define noncomplementarities as scenarios where the utility (i.e., benefits and costs) of adoption of one system does not enhance the utility of the other. Note that under this definition, noncomplementarity does not mean that both systems might not be jointly adopted, but that their joint adoption does not increase utility. For example, Canales et al. (2020) analyze the case of US producers and find evidence of complementarities between conservation agriculture practices when producers that previously adopted crop rotations are more likely to adopt continuous no-till. Potential sources of noncomplementarities (i.e., increased costs derived from joint adoption) have also been observed in conservation agriculture systems. For example, Van Deynze et al. (2022) find that a significant reduction in conservation tillage use in soybean production can be attributed to the proliferation of glyphosate-resistant weeds, hinting at tradeoffs between conservation tillage and low-input agriculture.

The second stream of literature focuses on the determinants of the adoption of agri-environmental schemes for specific individual measures such as conservation tillage (Skaalsveen et al., 2020), conservation agriculture (Lahmar, 2010), cover crops (Kathage et al., 2022), organic practices (Bravo-Monroy et al., 2016), and herbicide-free and even pesticide-free production systems

(Möhring & Finger, 2022b).[1] Behavioral factors and opportunity costs are key determinants of the adoption of voluntary agri-environmental schemes (Schaub et al., 2023). Behavioral aspects for the adoption of herbicide-free systems and conservation tillage, for example, comprise risk preferences, perceptions of benefits and risks, different farming goals, and environmental concerns (Wuepper et al., 2023; Dessart et al., 2019). Besides behavioral factors, opportunity costs such as the forgone utility after the adoption of certain practices due to production costs, farm management, and subsidies, play an important role for adoption (e.g., Schaub et al., 2023). In the context of conservation tillage and herbicide-free systems, aspects such as economic incentives (e.g., subsidies and price mark ups), the availability of machinery and soil quality, and presence of herbicide-resistant weeds, are key for opportunity costs of adoption (e.g., Böcker et al., 2019).

The barriers and drivers of adoption decisions are better understood when the interrelations between practices are considered. In this sense, key questions remain largely unexplored in the literature. For instance, it is unclear whether both conservation tillage and herbicide-free production systems can coexist within the context of agri-environmental schemes (i.e., whether farmers adopt conservation tillage and herbicide-free production jointly), what characterizes the farms and farmers who adopt it jointly, and last, to what extent adoption decisions are driven by behavioral (e.g., farmers' inner preferences and dispositions) or other characteristics.

Our study addresses these knowledge gaps in joint adoption. We find that, under the current payments for the participation in agri-environmental schemes, 35% of farmers adopt both conservation tillage and herbicide-free production systems, but schemes also largely exclude each other for the majority of farms; for example, 24% are using only conservation tillage without herbicide free, 28% use herbicide free without conservation tillage, and 13% use neither of the strategies. Two systems are complementary when the benefit of joint adoption is more than proportional to the sum of the adoption of the individual systems in isolation. We estimate a multinomial logit that recognizes all the possible combinations between the systems. The analysis suggests that conditional on farm and farmer's characteristics, the systems are not complementary. There is, however, important heterogeneity in the degree of these (conditional) complementarities across two types of conservation tillage that differ in the tillage intensity allowed. We further find that behavioral factors explain up to 26% of the joint adoption of the systems, with the remaining variation stemming from agronomical and structural farm characteristics. Risk loving farmers and farmers who are open to innovative practices are more likely to adopt jointly the two systems. Moreover, farmers with large valuations of biodiversity goals in their farming activities are more likely to adopt jointly herbicide free and conservation tillage and herbicide free in isolation compared to nonadoption. This indicates that there is a high potential for exploiting behavioral drivers that contribute to alleviating tradeoffs in joint adoption.

The remainder of this paper is structured as follows. Section 3 provides a background of the two systems, the policies in place to support their implementation, and the determinants of adoption explored in the literature. Section 3.1 describes the method and robustness checks, Section 4 the data. Section 5 presents the results, and Section 5.1 discusses. Section 6 concludes.

2 | BACKGROUND

2.1 | Conservation tillage and herbicide-free agriculture

The intensification of agriculture has led to problems of soil degradation, including nutrient depletion, soil loss, and subsequent productivity declines (Wuepper et al., 2020; Wuepper et al., 2021). In response to these challenges, agricultural systems aimed at restoring soils have been developed.

[1]See Knowler and Bradshaw (2007), Wauters and Mathijs (2014), Carlisle (2016), Prokopy et al. (2019) for reviews on the adoption of conservation agriculture, and Rosa-Schleich et al. (2019) for diversified farming systems.

Conservation agriculture refers to farming systems where three principles are practiced, namely, minimum soil disturbance, permanent soil cover, and species diversification (Kassam et al., 2019). These practices provide benefits for both farm productivity and environmental services such as increased carbon sequestration, reduced soil erosion, compaction, and nutrient loss (Soane et al., 2012). In certain circumstances, the set of practices has weed suppression properties, especially in contexts of herbicide resistant weeds (Carlisle, 2016; Vincent-Caboud et al., 2019; Knowler & Bradshaw, 2007).

Despite the long tradition and potential benefits of conservation agriculture, adoption remains low—approximately 12.5% of global cropland, 5% in Europe, and 5% in Switzerland—reflecting the barriers of adoption such as biophysical characteristics of the farm, access to machinery or inputs, and knowledge, among others (Kassam et al., 2019). Moreover, regardless of the potential of incorporating conservation agriculture in low input agriculture or the reverse, agronomical challenges related to weed control, availability of nutrients, ley incorporation, cover crop termination, and structural challenges such as insufficient equipment and knowledge, remain (see e.g., Peterson et al., 2018). More specifically, conservation tillage—a practice describing the principle of minimum soil disturbance in conservation agriculture—often relies on herbicide use (Fuglie, 1999; Kudsk & Mathiassen, 2020). This is due to agronomic factors such as the appearance of certain weeds that can often only effectively be controlled either by deep tillage or synthetic herbicides. In fact, one of the barriers for the adoption of conservation agriculture is the lack of herbicides and resistant weed varieties, leading adopters to quit the practice after some time when weeds cannot be controlled (Derpsch et al., 2010).

Further, the reduction of chemical inputs has increasingly gained attention in the policy discussion. For example, this is reflected in the Convention on Biological Diversity's post-2020 Global Biodiversity Framework, and well as in the policies of the European Union and Switzerland, which target a 50% reduction in pesticide use risk (e.g., Finger, 2021; Möhring et al., 2023; Schneider et al., 2023). The goal is to reduce the negative effects of chemical pesticides on the environment and human health, and requires fundamental adjustments in agricultural practices, for example, by expanding integrated pest management practices (Jacquet et al., 2022; Lefebvre et al., 2015). The reduction of herbicide use is relevant to reach these policy goals, for example, because herbicides represent 38% of pesticide use in Europe and 49% worldwide (FAO, 2023).

Herbicide- and even pesticide-free production are part of a transition to low-input production systems with lower adoption hurdles and lower tradeoffs (e.g., with respect to yields) than organic agriculture (e.g., Jacquet et al., 2022; Möhring & Finger, 2022b). Herbicide-free production is increasingly also supported by policy; for example, Switzerland has established agri-environmental schemes compensating farmers for adoption (e.g., Mack et al., 2023). However, herbicide-free agricultural systems often require the use of a combination of mechanical, agronomic, and biological control strategies for weed management. Mechanical weed control (e.g., comb harrows, chisel plows, rotary hoes, and finger weeders) is most relevant and consists of physically removing or burying weeds, suppressing weed growth (Ziehmann et al., 2024).

2.2 | Policies to support conservation tillage and herbicide-free production in Swiss agriculture

Like many other European countries, Switzerland has a well-established legal framework that recognizes the multifaceted role of agriculture in providing food, fertile soil, clean drinking water, and preserving landscapes and rural areas (FOAG, 1999). Consistent with these goals, the government has implemented policies aimed at conserving soil and water resources and reducing pesticide use (Federal Council, 2021). The Proof for Ecological Performance is a cross-compliance standard that makes farmers eligible to receive additional direct payments for adopting specific farming practices. The standard comprises biodiversity measures (e.g., buffer strips), integrated pest management practices, regulated crop rotations (at least four arable crops per year), and soil protection (Mack et al., 2023; BLW, 2024).[2] Soil protection measures under the cross-compliance standards require farmers to ensure soil cover with winter crops, cover crops, or green manure. In addition to these practices, farmers can adopt voluntary agri-environmental schemes for conservation tillage (i.e., mulch tillage, direct seeding, and strip tillage) and for not using herbicides (since 2019) (Huber, El Benni, & Finger, 2024). This provides the unique opportunity to analyze farmers' (joint) adoption decisions on a large scale.

Table 1 describes each of the agri-environmental schemes with the corresponding direct payment. Conservation tillage payments aim at improving the quality of the soil including humus content in the topsoil, soil structure, and biological activity, and consist of three main schemes: direct seeding (or no-till), strip sowing, and mulch tillage. Note that in contrast to mulch tillage—where the soil is allowed to be tilled entirely although covered with plant residues—in the more stringent direct seeding, the soil is expected to remain undisturbed (i.e., minimum 75% of the surface), posing more managerial challenges for farmers in weed control, especially when herbicides are not used. The payments differ across systems depending on the complexity of implementation. For example, the highest direct payment in conservation tillage is given by direct seeding with Fr 250 per hectare, whereas mulch tillage receives Fr 150 per hectare. As the scheme acknowledges a potential increase in herbicide use due to participation in conservation tillage measures, accompanying measures to conservation tillage include a limit in the use of herbicides, where farmers receive a direct payment of Fr 200 per hectare in addition to the payments for conservation tillage. The conditions for participation apply from the harvest of the preceding main crop to the harvest of the eligible crop. Thus, applications of herbicides in previous years have no effect on eligibility for subsequent years (Finger & Möhring, 2024).

Since the growing season 2019/2020 and independently from the conservation tillage schemes, farmers can renounce the use of herbicides and receive a direct payment of Fr 250 per hectare. This payment scheme is crop specific, per hectare and year so that herbicides cannot be applied from the harvest of the preceding main crop until the harvest of the eligible crop. In this setting of multiple

TABLE 1 Conservation tillage and herbicide reduction (voluntary) agri-environmental schemes.

Scheme	Requirement	Direct payment
Conservation tillage[a]		
a. Direct seeding	No more than 25% of the soil surface is moved during sowing and the seed is placed in a single operation directly in the unprocessed soil, which is covered with plant residues.	Direct payment: Fr 250/ha and year
b. Mulch tillage	Area is tilled over the entire surface of the grown soil, which is covered with plant remains	Direct payment: Fr 150/ha and year
c. Conservation tillage with renunciation of herbicides (+ a or b)	Renunciation of herbicides on top of conservation tillage measures- direct seeding or mulch tillage.	Fr 200/ha and year
Herbicide-free wheat production	Renunciation of herbicides (without conservation tillage)	Direct payment: Fr 250/ha

[a]Direct seeding and mulch tillage are the most common practices and account for 88% of the area under conservation tillage as per the Swiss agricultural census.

Source: FOAG (2019), Möhring and Finger (2022b), and Mack et al. (2023). Exchange rate: one Swiss Franc is equivalent to approximately 1.14 United States dollars.

[2]A crop is counted if it covers at least 10% of the arable land. Crops that cover less than 10% can be added together and count as one crop for each tranche of 10% that they exceed together (Huber et al. 2024b).

direct payments, farmers can adopt one, both, or neither of the agri-environmental schemes. Next, we explore the determinants for the decision to adopt each system in the literature.

2.3 | Determinants of adoption of herbicide-free and conservation tillage systems

There is a growing interest in understanding the drivers and barriers for the adoption of voluntary agri-environmental schemes and practices (Schaub et al., 2023; Thompson et al., 2020).[3] In our context, opportunity costs are a crucial aspect in decision making. They refer to the forgone utility (i.e., benefits and costs) from the adoption of conservation tillage and herbicide-free systems compared to alternative production systems. For example, compared to alternative systems, the choice of adopting conservation tillage in conjunction with herbicide free can have both benefits and costs such as gains in productivity due to improved soil properties and increased managerial costs, respectively. Similarly, whether a farmer jointly adopts the two systems or not also largely depends on their inner preferences for the systems. For example, risk preferences can determine how much utility the farmer loses or gains when facing a prospect of adopting a production system that compared to alternative systems, has higher production risks. Differences in farmer's utility of alternative production systems, therefore, determine farmers' optimal choice among alternative production systems. We here differentiate between behavioral factors, farm structural, and agronomic factors as determinants of the utility from adoption of the different production systems. Table 2 summarizes the main factors associated with the adoption of agri-environmental schemes.

We are interested in behavioral factors that explain the adoption of two different agricultural systems and thus focus on dispositional behavioral factors that are likely relevant for different production systems (i.e., that are not system specific). In the context of conservation and low input agriculture, these factors include risk aversion, noncognitive skills (self-efficacy and locus of control), farming goals (biodiversity vs. production), and innovativeness (Pannell, et al., 2006; Wauters & Mathijs, 2014).[4]

In the context of joint adoption of conservation tillage and herbicide-free agriculture, noncognitive skills (e.g., locus of control) may decrease the perceived costs of adoption associated to learning and adapting the new production system in the existing one. Farming goals, that is, nonpecuniary benefits or costs of adoption, may make some choices more attractive, for example, by increasing or decreasing the utility farmers perceive from the adoption of sustainable farming systems (Giovanopoulou et al., 2011; Howley, 2015). Although farmers driven by environment conservation are more willing to adopt conservation tillage and herbicide-free systems (Wauters & Mathijs, 2014; McGuire et al., 2015; Finger & Möhring, 2022), farmers oriented toward productivism and economic benefits weight more the potential yields and economic losses of adoption (Kabii & Horwitz, 2006; Yasué & Kirkpatrick, 2020). The adoption of conservation tillage and herbicide-free systems can be seen in the light of the innovations necessary to make the systems succeed. Thus, farmers' innovativeness likely plays a role in the joint adoption of soil conservation and herbicide-free agriculture (Kreft et al., 2021; Mueller & Thomas, 2001).

Structural factors refer to the operational-related aspects of the farm that can enable or restrict adoption such as farm size and tenure. Agronomical factors refer to the production conditions such as soil type and pest pressure (Böcker et al., 2019; Gailhard & Bojnec, 2015). Based on the aforementioned literature, first, we explore the behavioral factors that play a role in the joint adoption of the

[3]See Pannell et al. (2006), Knowler and Bradshaw (2007), Dessart et al. (2019), Schaub et al. (2023), and Thompson et al. (2020) for reviews.

[4]The term of "noncognitive skills" is mostly used in the economic literature to comprise a wide variety of personality traits, goals, motivation, and preferences. We here use this concept to refer to two related psychological treats: locus of control and self-efficacy under the theory of core self-evaluations (Judge, 1997; Kreft et al., 2021). Other behavioral factors might be relevant for the joint adoption of soil conservation and herbicide-free agriculture (e.g., perceived costs and benefits and knowledge) (Kabii & Horwitz, 2006). These factors, however, tend to be system specific and therefore are beyond the scope of this paper.

TABLE 2 Factors related to the adoption of soil conservation and herbicide-free agriculture in the literature.

Category	Expected effect/hypothesis	References
Behavioral factors		
Risk preferences/ willingness to take risks	(+) joint adoption Expected utility theory; Prospect Theory	Garcia et al. (2024), Läpple and Kelley (2013), Knowler and Bradshaw (2007), Upadhyay et al. (2003)
Self-efficacy; locus of control	(+) joint adoption Locus of control: farmer's perception of the degree of control they exercise over the events and outcomes of their farming activities. Self-efficacy: farmer's belief or confidence in their ability to successfully achieve their goals, that is, their perceived control over their own farming abilities.	Bandura (1997), Deci and Ryan (1995)
Farming goals	Environmental conservation goal (+) joint adoption. Productive and economic goals (−) joint adoption.	Wauters and Mathijs (2014), Finger and Möhring (2022), Kabii and Horwitz (2006), Yasué and Kirkpatrick (2020), McGuire et al., 2015
Innovativeness	Entrepreneurial behavior (+) joint adoption	Anderson et al. (2015), Covin and Slevin (1991), Knowler and Bradshaw (2007)
Farm structural		
Access to weeding machinery, workforce	Reduce costs of adopting the system.	Claassen et al. (2018)
Farm size; land tenure; crop intensification	Possibility to spread fixed costs from weeding or no-till equipment and deal with risks. Reduces managerial hurdles for farmers (e.g., economies of scale) but might imply larger susceptibility to certain weeds and pests, increasing the need of pesticide use.	Baumgart-Getz et al. (2012), Salaheen and Biswas (2019), Knowler and Bradshaw (2007), Soule et al. (2000), Soh et al. (2023)
Farmer's age and education	Age (−) joint adoption Knowledge of new practices (+) Education (+) joint adoption	Lambert et al. (2007), Pannell et al. (2006), Kabii and Horwitz (2006), Soule et al. (2000), Soh et al. (2023)
Agronomical		
Soil type and quality, topography	Mixed evidence	Soule et al. (2000), Prokopy et al. (2019), Knowler and Bradshaw (2007)
Weather patterns	Mixed evidence	Knowler and Bradshaw (2007)
Pest pressure, crop types and rotations	Presence of glyphosate resistant weeds increase the need for tillage.	Van Deynze et al. (2022), Knowler and Bradshaw (2007), Soule et al. (2000), Peterson et al. (2018), Carlisle (2016)

Note: See Knowler and Bradshaw (2007), Peterson et al. (2018), and Carlisle (2016) for reviews on the adoption of conservation agriculture.

two systems, and second, explore whether farmers perceive utility losses from the joint adoption of soil conservation and herbicide-free systems.

3 | METHODOLOGY

Farmers participate both in conservation tillage and herbicide-free production. We refer to conservation tillage and herbicide-free production as systems, and their interaction (conservation tillage and herbicide free, only conservation tillage, only herbicide free, and neither) as production alternatives.

We assume that farmers' utility after the adoption of conservation tillage and/or herbicide-free production systems follow an additive random utility model as defined in Equation (1). The (latent) utility of farmer i derived after the adoption of the production alternative j—$U_{ij}{}^{*}$—depends on deterministic and random components. The deterministic component refers to factors that influence the adoption of production alternatives, including behavioral factors ($\boldsymbol{B_i}$) and agronomic and structural factors at the farm level($\boldsymbol{X_i}$), whereas the random component ε_{ij} refers to unobserved factors to researchers, such as the farmer-specific returns and costs of adoption. The coefficient α_j is the alternative-specific intercept that represents the intrinsic propensity of farmers for the production alternative j. Note that direct payments for each system are comprised in this term alongside other factors that differ across alternatives but are constant across farmers. The vector B_i includes farmers' risk preferences, farming goals, noncognitive skills, and innovativeness.

$$U_{ij}{}^{*} = \alpha_j + \boldsymbol{\beta_j B_i} + \boldsymbol{\gamma_j X_i} + \varepsilon_{ij} \tag{1}$$

$$K \equiv \{(\text{Conservation tillage, herbicide} - \text{free}) : (1,1), (1,0), (0,1), (0,0)\}$$

The adoption of the two systems leads to four mutually exclusive production alternatives as specified in Equation (1) where the alternative $j = 1 - \{(\text{Conservation tillage, herbicide free}) : (1,1)\} -$, refers to farmers adopting both conservation tillage and herbicide-free agriculture simultaneously, $j = 2, 3$–{(Conservation tillage, herbicide free): (1,0), (0,1)}, refer to farmers adopting conservation tillage or herbicide free in isolation, respectively, and $j = 4$—{(Conservation tillage, herbicide free): (0,0)}—refers to farmers not adopting any of the two systems. Farmer i adopts the alternative j when its adoption provides a greater utility level compared to the remaining alternatives ($k \neq j$) (Equation 2).

$$\Pr\left(y_{ij} = 1\right) = \Pr\left(U_{ij}^{*} \geq U_{ik}^{*}\right), \forall k \in K \tag{2}$$

To model farmers' adoption decisions in this setting, we estimate a multinomial logit model to represent farmers' decision over all possible alternatives. Note that the underlying assumption in this model is that the decision to participate in both systems is done simultaneously. In our context, this assumption is reasonable, because farmers need to decide whether they will apply to the direct payments for conservation tillage and, in addition, follow the guidelines of herbicide-free wheat production before the preparation of the soil and cropping season.[5]

$$\Pr\left(y_{ij} = 1\right) = \frac{e^{\alpha_j + \boldsymbol{\beta_j B_i} + \boldsymbol{\gamma_j X_i} + \varepsilon_{ij}}}{\sum\limits_{j \in K} e^{\alpha_j + \boldsymbol{\beta_j B_i} + \boldsymbol{\gamma_j X_i} + \varepsilon_{ij}}} \tag{3}$$

The probability of farmer i choosing alternative j is given by the standard logistic probability (Equation 3), where K refers to the choice set of farmers (i.e., the four production alternatives). Given that Equation (3) is not identified for all four alternatives, we normalize the problem based on the alternative $j = 4$ where neither of the systems are implemented, namely, {(Conservation tillage, herbicide-free): (0,0)} (i.e., $\alpha_4 = 0$, $\boldsymbol{\beta_4} = 0$, $\boldsymbol{\gamma_4} = 0$). The model is estimated using maximum likeli-

[5]Because soil conservation practices have a long tradition in Swiss agriculture—whereas the herbicide-free production is rather new—in robustness checks, we estimate recursive bivariate probit model that is able to capture data generation processes with sequential decisions.

hood. To account for correlation between farmers in the same cantonal unit, the random component ε_{ij} is clustered at the canton level.[6]

The interrelations between the two systems can be evaluated with the conditional complementarity (conditional on observable factors) and the coexistence of both systems. The concept of complementarity was formalized under the theory of supermodularity (Milgrom & Roberts, 1990, 1995) and applied to contexts of multiple decisions (e.g., Kretschmer et al., 2012; Perry et al., 2016).[7] If the utility function after adoption is supermodular, the adoption of conservation tillage and herbicide free tends to move up or down together. In a strict sense, this means that one system enhances the utility of the other. There is evidence of complementarity between the two systems when the utility of adopting both systems in conjunction or not adopting any at all is larger than the utility of adopting the systems in isolation (see Equation 4).

$$\rho = [U^*(1,1) - U^*(1,0)] - [U^*(0,1) - U^*(0,0)] \geq 0 \tag{4}$$

Coexistence refers to the co-occurrence of both systems in a specific space or point in time and reflects the incentives to jointly adopt the systems. The two systems can coexist when the utility of joint adoption is larger or equal than the utility of other production alternatives, including no adoption. Coexistence, therefore, implies that adoption of both systems is at least as preferable than adoption of each system in isolation. Therefore, whereas complementarity implies coexistence, the opposite is not true (Anna & Eckert, 2016). We measure the conditional complementarity and coexistence with the prediction of the multinomial logit. Miravete and Pernías (2010) outline the challenges of employing dichotomous variables to capture complementarities, particularly concerning unobserved heterogeneity. We here focus on the correlations between systems induced by observable factors. The comprehensive set of explanatory variables we consider, along with the relatively homogenous sample of farmers, can improve the model's identification. However, the presence of unobserved heterogeneity reduces the possibilities of causal inference. For this reason, we here focus on the correlations between systems induced by the large set of observable factors. The normalized coefficients with respect to the base alternative are denoted with tilde (e.g., $\tilde{\alpha}_1 = \alpha_1 - \alpha_4$), and the relative utility gains or losses are derived in reference to the base category $-U^*_{i4}(0,0)$ (Equation 5). Note that Equation (5) correspond to the logarithmic specification of Equation (3), and so, they are farmer specific.

$$\begin{aligned} \widehat{\rho}_{i1} &= U^*_{i1}(1,1) - U^*_{i4}(0,0) = \tilde{\alpha}_1 + \tilde{\boldsymbol{\beta}}_{\mathbf{1}}\boldsymbol{B_i} + \tilde{\boldsymbol{\gamma}}_{\mathbf{1}}\boldsymbol{X_i} \\ \widehat{\rho}_{i2} &= U^*_{i2}(1,0) - U^*_{i4}(0,0) = \tilde{\alpha}_2 + \tilde{\boldsymbol{\beta}}_{\mathbf{2}}\boldsymbol{B_i} + \tilde{\boldsymbol{\gamma}}_{\mathbf{2}}\boldsymbol{X_i} \\ \widehat{\rho}_{i3} &= U^*_{i3}(0,1) - U^*_{i4}(0,0) = \tilde{\alpha}_3 + \tilde{\boldsymbol{\beta}}_{\mathbf{3}}\boldsymbol{B_i} + \tilde{\boldsymbol{\gamma}}_{\mathbf{3}}\boldsymbol{X_i} \end{aligned} \tag{5}$$

The values of $\widehat{\rho}_{i1}$, $\widehat{\rho}_{i2}$, and $\widehat{\rho}_{i3}$ refer to the utility gains and losses compared to nonadoption and allow for the ranking of alternatives that yield the highest utility for farmers and to evaluate whether the two systems can coexist. By construction, these coefficients are proportional to the percentage of farmers adopting each system. If the relative utility of joint adoption—that is, $\widehat{\rho}_{i1}$—is larger or equal than the relative utility of adoption of the two systems in isolation—$\widehat{\rho}_{i2}$ and $\widehat{\rho}_{i3}$—there is evidence for coexistence. The coefficients vary across farmers through the alternative-specific returns—α_j,

[6]The multinomial logit model relies on the assumption of independence of irrelevant alternatives (IIA). The mixed logit model is a common alternative that relaxes this assumption by allowing for correlation between practices through alternative-specific variables. However, in our case, this model is not feasible given that all our variables have the potential of affecting the adoption of both systems.

[7]In Kretschmer et al. (2012), the application of the concept of supermodularity involves a continuous variable representing profit under various investment decisions. Perry et al. (2016) apply this concept to dichotomous decisions, that is, to adopt or not to adopt agricultural practices. We adopt the latter approach.

behavioral—$\boldsymbol{\beta}_j$, and agronomical and structural characteristics–$\boldsymbol{\gamma}_j$. Factors that affect all farmers such as the agro-environmental schemes are mean shifters and can affect the adoption rates and therefore the estimated latent utility but do not offer sources of variation across farmers.

The coefficients of utility gains or losses also help determine whether the two systems are conditionally complementary under the supermodularity property. We rearrange (Equation 4) with the coefficients of utility gains and losses and retrieve the coefficient in Equation (6). We refer to $\widehat{\rho}_i$ as the conditional complementarity coefficient to differentiate from the literature that estimates the effect of the adoption of one system on the utility of the other. We here, as Cassiman and Veugelers (2006), are interested in the characteristics that determine the utility of adoption $U^*(.)$ and are behind the complementarity patterns (see Equation 6).[8] The conditional complementarity coefficient is assumed to be conditional on structural, agronomical, and behavioral factors, implying that whether farmers perceive the two systems as complementary largely depends on idiosyncratic factors, including farmer's preferences. Given that the coefficients include the role of the alternative-specific intercepts, the conditionally complementary coefficient can also capture any mean shifting effect.

$$\widehat{\rho}_i = \widehat{\rho}_{i1} - \widehat{\rho}_{i2} - \widehat{\rho}_{i3} \tag{6}$$

If the two systems are conditionally complementary, the joint adoption should give the farmer a larger utility than the sum of the independent adoption of conservation tillage and herbicide-free systems. For the average farmer, we compute $\widehat{\rho}$, $\overline{\widehat{\rho}_1}$, $\overline{\widehat{\rho}_2}$, and $\overline{\widehat{\rho}_{3,}}$ and test for statistical significance with bootstrapped standard errors. Note that the analysis of the utility gains and losses depend on the set of factors considered in the estimations. Therefore, the extent to which behavioral factors versus agronomic and structural factors contribute to utility gains and losses and adoption decisions becomes important to tackle the sources of noncomplementarities. To assess the relative importance of each of the factors considered, namely, behavioral, farm structural, and agronomical, we perform dominance analysis based on the results of the multinomial logit. The procedure entails (i) the estimation of nested models with all possible combinations of explanatory factors, (ii) retrieval of McFadden pseudo R2 for model fit, and finally, (iii) the estimation of the marginal contribution associated with each explanatory factor.[9] The dominance statistic reflects the marginal contribution of the set of behavioral factors to the model of adoption decisions.

The analysis is conducted for conservation tillage and disaggregated for mulch tillage and direct seeding. We expect joint adoption to vary depending on the type of conservation tillage practiced by farmers. Mulch tillage and direct seeding have different implications in terms of farm and risk management. Whereas mulch tillage allows to mechanically turn the entire production surface, in direct seeding no more than 25% of the soil surface is allowed to be moved. The main challenge of joint adoption of herbicide-free production and conservation tillage is therefore more present in direct seeding compared to mulch tillage. Comparing both in terms of their joint adoption with herbicide-free production will therefore provide useful insights.

3.1 | Robustness checks

We conduct two additional analyses to identify underlying mechanisms and provide robustness checks. First, we use census instead of survey data. The census data cover the complete population of Swiss farmers (i.e., $N = 12{,}440$) but is less detailed than the survey data ($N = 1073$). For example, the census data contain information on farmers' decisions towards conservation tillage and herbicide use (and non-use) based on their participation in agri-environmental payment schemes, but it does

[8]See Cassiman and Veugelers (2006) for a discussion on the alternatives to measure complementarities in innovation adoption.

[9]We use the community-contributed Stata command domin. See Luchman (2021) and online supplementary Appendix A4 for further details.

not contain information on behavioral factors. Based on farmers' decisions over a period of 4 years, the census data allow us to estimate the utility gains and losses and conditional complementarity parameters that control for (time constant) unobserved heterogeneity. The resulting coefficients, therefore, are conditional on observables that vary across time. We follow an approach drawn from recent developments on conditional fixed effects for multinomial logit models (D'Haultfœuille & Iaria, 2016).[10] As explanatory factors of adoption we include a time trend, number of farm workers, farm size, and number of crops produced, and include fixed effects to account for time-invariant individual heterogeneity. We expect the resulting coefficients of utility gains/losses and conditional complementarity based on census data to preserve the pattern of the main analysis using survey data (see the online supplementary Appendix A2 for details on census data). Second, we estimate a recursive bivariate probit to acknowledge the long tradition of conservation tillage systems in Swiss agriculture compared to the new herbicide-free production systems. In this setting, the adoption of conservation tillage could hinder the adoption of herbicide-free agriculture (See the online supplementary Appendix A6 for details).

4 | DATA

The survey data used in this analysis were introduced by Möhring and Finger (2022b). They consist of a stand-alone, detailed survey of 1073 farmers in Switzerland. The survey is representative of the population of wheat farmers who produce under guidelines that restrict the use of insecticides, fungicides, and growth regulators but are not organic, and that comprise about 50% of total wheat produced in Switzerland (Finger & El Benni, 2013). The survey comprises questions regarding the adoption of no-herbicide use and conservation tillage (i.e., mulch tillage and direct seeding); farm and farmers' characteristics, including structural and agronomic aspects of the farm such as workforce, agricultural land, animal husbandry and share of wheat in production; and behavioral aspects including risk preferences, noncognitive skills, and farm goals.

In addition, we merge our farm-level data with external, environmental and agronomic data. First, this includes the susceptibility of soils to erosion and soil degradation that we proxy with the percentage of the farm in mountainous area, precipitation, temperature, erosion in farm area, slope of farm, root penetration potential, and share of wheat in crop rotation (Gould Brian et al., 1989; Soule et al., 2000).[11] Second, we consider presence of different weed species as proxy for weed pressure and also consider the presence of herbicide resistant weeds detected up to 2014 (i.e., before the herbicide-free production program was introduced) (Böcker et al., 2019; Tschuy & Wirth, 2015). This broad range of environmental and agronomic data enables the characterization of the coefficients of utility gains/losses and reduces concerns about unobserved heterogeneity. The sample represents the population well in terms of important structural characteristics. Compared to the study population, the sample of farmers comprised in the survey have on average 0.95 hectares more of wheat and have 2% more land in mountainous areas. These differences, however, do not pose major inference concerns for the large-scale conversion of wheat surfaces (see Möhring & Finger, 2022b).

Table 3 shows the adoption of conservation tillage and herbicide-free wheat production in Switzerland. Although 35% of farmers adopt both systems, systems also largely exclude each other; for example, 24% are using only conservation tillage without herbicide free, and 28% use herbicide free without conservation tillage, and 13% use neither. Table 4 disaggregates conservation tillage

[10]We use the Stata command xtmlogit (Stata 17).

[11]Erosion and the level of awareness regarding erosion problems are relevant for the adoption of soil conservation practices such as no-tillage (Gould Brian et al., 1989). Aspects related to the risk of erosion include precipitation and the slope of the farmland. For example, farms with slopes are at a higher risk of experiencing soil losses. Root penetration refers to the ability of plant roots to grow through the soil and access nutrients. In fields under long-term tillage and heavy machinery traffic, soils can develop plow pans, dense topsoil, and compaction. These conditions increase soil penetration resistance and ultimately reduce the soil's ability to support plant growth and provide essential services (Colombi et al., 2018).

TABLE 3 Adoption of herbicide-free wheat and conservation tillage.

Production system	**Conservation tillage**	
Herbicide-free production	**Yes**	**No**
Yes	0.35	0.28
No	0.24	0.13

Note: Conservation tillage comprises farmers who produce with mulch tillage or direct seeding.

TABLE 4 Adoption of herbicide-free wheat and conservation tillage disaggregated by type.

Production system	**Share**
(Mulch tillage, herbicide free)	
(0, 0)	0.17
(0, 1)	0.33
(1, 0)	0.20
(1, 1)	0.30
(Direct seeding, herbicide free)	
(0, 0)	0.29
(0, 1)	0.53
(1, 0)	0.08
(1, 1)	0.10
Obs.	$N = 1073$

Note: System (1, 1) refers to joint adoption, whereas (1, 0) and (0, 1) refers to adoption of one system in isolation.

across two types, namely, mulch tillage and direct seeding. Joint adoption is more likely when conservation tillage is implemented with mulch tillage compared to direct seeding (see Table 4). For the latter, only 10% of farmers implement both practices. This descriptive evidence, however, cannot be taken as evidence of the utility gains or losses from joint adoption given the drivers of adoption and the heterogeneity in farm's context such as farm characteristics and farmers' innate preferences that may account for the adoption patterns. This calls for a more systematic way of estimating and comparing the utility of adoption of each of the systems that we approach with a multinomial logit.

We first explore the role of behavioral factors vis-à-vis agronomical and structural factors making use of the detailed survey (Table 5). We capture five behavioral aspects, namely, risk preferences, locus of control, self-efficacy, farming goals, and innovativeness. Given that behavioral aspects are often domain specific (Alkire, 2005), the questions are framed in the domain of agriculture and plant protection.[12] First, we measure farmers' willingness to take risks with a 10-point Likert scale framed in the domain of agricultural activities in general. In the sample, the average farmer is between risk neutral and risk loving.

Second, we identify noncognitive skills with locus of control and self-efficacy, measured using 5-point Likert scale questions (Möhring & Finger, 2022a). Higher scores of locus of control represent a more internal (vs. external) locus of control and higher scores for self-efficacy a higher self-efficacy of farmers (Anger & Schnitzlein, 2017). On average, farmers report a moderate level of internal locus of control with a mean of 3.24 and a moderately high level of self-efficacy with 3.58 in this trait.[13] The survey captures four goals including achieving high yields, high income (including direct payments), clean fields from weeds, and biodiversity. To reduce the dimensionality of these measures,

[12]In the online supplementary appendix, we present the complete phrasing of the questions (see Table A.1).

[13]We opt for considering each of the constructs, self efficacy and locus of control, separately. See Table A.2 in online supplementary appendix for the results on factor analysis to evaluate the reliability of the constructs.

TABLE 5 Behavioral, structural, and agronomic factors.

Variables	Mean	Std.	Description	Source
Behavioral variables				
Willingness to take risks	5.59	2.30	Likert scale 0–10, domain of agriculture in general. (0 = very risk averse, 10 = very risk loving)	Survey
Locus of control	3.24	0.81	Mean Likert scale 1–5, 1 = external locus of control, 5 = internal locus of control	Survey
Self-efficacy	3.58	0.75	Mean Likert scale 1–5, 1 = low self-efficacy, 5 = high self-efficacy	Survey
Goal: production	3.67	0.81	Mean Likert scale 1–5, 1 = not important to achieve high income, yields, clean fields, 5 = very important	Survey
Goal: biodiversity	3.75	1.00	Likert scale 1–5, 1 = not important to have high biodiversity, 5 = very important.	Survey
Innovativeness	3.34	1.11	Likert scale 1–5, 1 = not open to agricultural innovations, 5 = very open to agricultural innovations.	Survey
Structural factors				
Work force in farm	1.68	1.19	Units of labor force	Survey
Age of farmer	47.08	9.35	Age of farmer in years	Survey
Agricultural land	34.63	21.65	Hectares of agricultural land	Survey
Share of leased land	0.35	0.29	Share of leased land	Survey
Share of off-farm income	0.29	0.25	Share of income coming from off-farm activities	Survey
Arranged succession	0.67	–	Dummy variable (1/0)	Survey
Education of farmer	0.64	–	Has higher degree, that is, “Meister” degree (1/0)	Survey
Western Switzerland	0.22	–	Survey in French (1/0)	Survey
Weeding machinery[a]	0.86	–	Share of farmers with access to weeding machinery (1/0)	Survey
Animal husbandry	0.79	–	Share of farmers with animal husbandry	Survey
Agronomic factors				
Share of mountainous area	0.05	0.20	Share of land	
Yearly average of temperature	9	0.63	Mean 1971–2018, in°C. Precision 1-km grid.	MeteoSwiss
Historical mean of precipitation	7.04	0.74	Mean 2008–2018, per 100 mm. Precision 1-km grid.	Meteosuisse
Land suitable for grain cultivation	0.63	–	Dummy variable (1/0)	FOAG (2009)
Herbicide resistance	0.11	0.33	Number of herbicide resistant variety in municipality of farmer.	Agroscope
Share of wheat	0.16	0.11	Percentage of wheat in agricultural land.	IP-SUISSE
Presence of weed species	0.48	0.29	Percentage of weed species in municipality (out of 21 types).	Info Flora (2019)
Erosion measure	1.81	0.75	Erosion measure ranging from 1 to 9[b]. Scale 1:500	FOAG (2021)

(Continues)

TABLE 5 (Continued)

Variables	Mean	Std.	Description	Source
Slope	1.48	0.53	Slope category ranging from 1 to 4[c] Scale 1: 500	FOAG (2013)
Root penetration depth	3.57	0.42	Root penetration category from 1 to 5[d]. Scale 1:200,000	FOAG (2022)
$N = 1073$			Number of observations in survey data	

[a]Weeding machinery refers to cultivators, harrows (curry comb) or any equipment required for mechanical weed control. Farmers are assumed to be homogeneous regarding machinery use for other types of machinery. For the population of arable and wheat farmers, 78% of farms have a field sprayer, 88% of farms a plow, 84% a rotary harrow (Groher et al., 2020).
[b]Erosion measure ranges from 1 (=soil loss of 0 to 10 in t/(ha × a)) to 9 (=soil loss of more 200 t/(ha × a)).
[c]Slope is measured across four categories from 1 (= slope < 18%) to 4 (= slope > 50%).
[d]Root penetration depth ranges from 1(= very superficial ∼ up to 30 cm) to 5(= very deep ∼ over 100 cm).

we perform factor analysis and identify two main goals: production and biodiversity (see Table A.3 in the online supplementary appendix). Accordingly, the biodiversity goal is measured with one question, whereas the production goal is measured with three questions (i.e., over yields, farm income, and clean yields). On average, farmers consider both production and biodiversity goals as relatively important with a mean of 4.67 and 3.75 respectively. Finally, we measure innovativeness with a 5-point Likert scale question referring to the openness to adoption of agricultural innovations. The variable is a compound measure of the attitude toward innovations and the actions taken based on that attitude.[14] Larger values refer to farmers who report being open to innovations or early adopters of innovations.

Although innovativeness and risk aversion may be correlated, they are distinct constructs. Risk aversion pertains to farmers' preference to avoid risks, whereas innovativeness denotes their willingness to embrace innovation. Given that the adoption of innovations inherently involves some degree of risk, both constructs can influence adoption similarly. However, it is feasible for farmers to be innovative yet risk averse.[15]

Regarding structural factors, our survey captures farmer characteristics such as age of farmer, education, and cultural/geographical background (accounting for the cultural gradient along the language region, French and German, see Wang et al., 2023) and aspects related to the productive inputs in the farm including workforce, size of agricultural land, share of off-farm income, succession arrangements, and access to weeding machinery.

To better account for unobserved heterogeneity, we complement our analysis with the Swiss agricultural census that consists of a panel of all Swiss wheat producers spanning the years 2019–2022 ($N = 12{,}440$). The panel records whether the farmer received direct payments for the adoption of conservation tillage and herbicide-free production system. In addition, the data comprise farm characteristics including the number of farm workers, farm size, and number of crops. In the census we identify as adopters farmers who receive a compensation for their practices. This approach is justified, as 98% of Swiss farmers receive direct payments for biodiversity conservation, sustainable production systems, landscape maintenance, and animal welfare (Huber, El Benni, & Finger, 2024). Consequently, if they adopt any of the two systems, they have the incentive to apply for the corresponding direct payment. The temporal variation in the census data allows us to identify the utility gain or losses from joint adoption and account for unobserved heterogeneity but, unlike the survey data, does not allow us to identify the role of behavioral factors as the survey and the census

[14]See online supplementary Appendix A1 for a description of this measure.
[15]Risk aversion and innovativeness can similarly influence the adoption of risk-increasing innovations and practices. Risk-averse farmers are less likely to adopt these practices due to the inherent risks. Conversely, non-innovative farmers are less likely to adopt these practices because of inertia and resistance to change.

cannot be matched. A description of census data is provided in the online supplementary Appendix A2.

5 | RESULTS

Table 6 shows the results from the analysis that explores the adoption of both systems—conservation tillage and herbicide-free wheat. Panel A presents the results for conservation tillage, whereas Panels B and C present the results for the disaggregation of conservation tillage into mulch tillage and direct seeding. First, we explore what are the behavioral factors that potentially enable joint adoption. The table reports the logit coefficients and standard errors in reference to the base alternative of adopting neither of the systems (i.e., {(conservation tillage, herbicide free): (0,0)}). The estimations control for structural and agronomic factors.[16] We find that farmers with a larger willingness to take risks are more likely to adopt conservation tillage and herbicide-free production jointly, and conservation tillage and herbicide-free production in isolation, and this result holds for both types of conservation tillage. We evaluate the marginal effects at the mean and find that in terms of magnitude, an increase in one standard deviation in the measure of willingness to take risks over the mean is associated to an increase of 0.04% points in the probability of joint adoption (see Table A.8 in the online supplementary appendix).

Farmers with larger valuations of biodiversity in their farming activities are more likely to adopt jointly herbicide-free and conservation tillage, and herbicide free in isolation compared to non-adoption. On the contrary, farmers oriented toward production goals (including income, yield, and weed management) are less likely to adopt herbicide-free production and less likely to jointly adopt direct seeding and herbicide free jointly (see Panel C. Direct seeding). An increase of one standard deviation over the mean in the biodiversity goal and production goal imply an increase of 0.03percentage points and decrease of 0.02 percentage points in the probability of adopting herbicide-free agriculture in isolation, respectively (see Panel A. Conservation tillage).

We find that self-efficacy and locus of control regarding wheat production and pest management are not related to the joint adoption of mulch tillage and herbicide-free agriculture. However, farmers who perceive greater control over their own farming abilities are less likely to adopt jointly direct seeding and herbicide-free production. Innovativeness emerges as a critical aspect for the joint adoption of conservation tillage and herbicide-free agriculture. More innovative farmers are more likely to adopt conservation tillage in conjunction with herbicide-free production, and herbicide-free production in isolation, and this relation is detected for both types of conservation tillage. An increase of one standard deviation over the mean in the innovativeness factor is associated with an increase of 0.08percentage points in the probability of joint adoption (see Panel A. Conservation tillage). The finding that both risk aversion and innovativeness are significantly associated to adoption behavior reinforces the initial intuition that these constructs are distinct, despite their conceptual interactions.

Altogether, behavioral factors explain to an important extent the adoption behavior of farmers. Dominance analysis based on the multinomial logit model reveal that behavioral factors explain 26% of the variation in joint adoption behavior. This implies that farmer behavior plays an important role in alleviating the conflict between the two systems and not, for example, only agronomical factors. Moreover, the individual contribution of behavioral factors is comparable to the contribution of agronomical and structural factors such as the share of wheat in crop rotation, access to weeding machinery, and size of agricultural land, supporting the notion that, despite the challenges in measurement of behavioral factors, they are important to understand adoption behavior (Table A.9 in the online supplementary appendix).

[16]Table A.7 in online supplementary appendix reports the coefficients for the agronomical and structural factors.

TABLE 6 Joint adoption of herbicide-free agriculture and soil conservation (logit coefficients).

Dependent variable: adopt	Both	Only conservation tillage	Only herbicide-free agriculture
A. Conservation tillage (B + C)[a]	(1)	(2)	(3)
Willingness to take risk	0.17***	0.10**	0.13***
	(0.04)	(0.04)	(0.03)
Self-efficacy	−0.18	0.09	−0.07
	(0.18)	(0.16)	(0.18)
Locus of control	−0.06	−0.14	−0.10
	(0.17)	(0.11)	(0.16)
Goal: biodiversity	0.17*	0.09	0.28**
	(0.10)	(0.13)	(0.12)
Goal: production	−0.19	0.06	−0.22**
	(0.19)	(0.16)	(0.10)
Innovativeness	0.43***	0.10	0.16*
	(0.06)	(0.09)	(0.09)
Constant	4.81	4.70	0.36
	(4.09)	(3.26)	(3.80)
Type of conservation tillage			
B. Mulch tillage[b]	(4)	(5)	(6)
Willingness to take risk	0.16***	0.07*	0.09***
	(0.03)	(0.04)	(0.03)
Self-efficacy	−0.17	0.03	−0.13
	(0.20)	(0.11)	(0.11)
Locus of control	0.03	−0.08	−0.10
	(0.19)	(0.13)	(0.14)
Goal: biodiversity	0.17**	0.05	0.21**
	(0.07)	(0.11)	(0.10)
Goal: production	−0.19	−0.01	−0.29***
	(0.21)	(0.20)	(0.11)
Innovativeness	0.35***	0.03	0.18**
	(0.06)	(0.08)	(0.09)
Constant	3.40	3.61	0.03
	(3.50)	(2.74)	(3.49)
C. Direct seeding[c]	(7)	(8)	(9)
Willingness to take risk	0.09***	0.08	0.11***
	(0.03)	(0.05)	(0.03)
Self-efficacy	−0.38***	−0.08	−0.16
	(0.14)	(0.21)	(0.14)
Locus of control	−0.05	0.09	0.04
	(0.09)	(0.19)	(0.14)
Goal: biodiversity	0.04	0.04	0.19**
	(0.10)	(0.13)	(0.09)

TABLE 6 (Continued)

C. Direct seeding[c]	(7)	(8)	(9)
Goal: production	−0.25*	0.05	−0.22***
	(0.14)	(0.14)	(0.07)
Innovativeness	0.51***	0.23***	0.26***
	(0.10)	(0.09)	(0.06)
Constant	−0.97	−3.06	−0.71
	(4.37)	(3.99)	(2.51)
Structural and agronomical controls	Yes	Yes	Yes
Pseudo R2	0.11[a]	0.11[b]	0.08[c]
Dominance statistic	0.26[a]	0.26[b]	0.37[c]

Note: Results refer to Equation (1). Clustered standard errors in parenthesis $*p < 0.1$; $**p < 0.05$; $***p < 0.1$. Log coefficients are reported. Agronomical and structural controls include all factors presented in Table 5.

Table 7 shows the coefficients for utility gains or losses as specified in Equation (5) and the conditional complementarity coefficient as specified in Equation (6). The estimated coefficients $\overline{\widehat{\rho}_1}$-$\overline{\widehat{\rho}_3}$ allow us to rank an average farmers' utility across different production alternatives given the current agri-environmental payments in place in Switzerland. This implies that the utility derived from adoption of each of the systems comprise farmers' underlying utility and the net benefits from direct payments. The positive coefficients we find for joint adoption, adoption of conservation tillage only, and adoption of herbicide-free only can be interpreted as utility gains in the respective production alternative compared to adopting neither of the systems (see Panel A, Table 7). Most important, we document utility gains of joint adoption compared to adoption of the two systems in isolation (i.e., $\overline{\widehat{\rho}_1} > \overline{\widehat{\rho}_2}$ and $\overline{\widehat{\rho}_1} > \overline{\widehat{\rho}_3}$). This means that farmers are on average better off adopting any system individually compared to nonadoption but would perceive a higher utility after joint adoption. In terms of ranking, for the average farmer, jointly adopting the system is preferred to adopting herbicide free in isolation, and this in turn is preferred over adopting conservation tillage in isolation (i.e., $\overline{\widehat{\rho}_1} > \overline{\widehat{\rho}_3} > \overline{\widehat{\rho}_2}$). This result, however, varies according to the type of conservation tillage implemented (i.e., mulch tillage and direct seeding). The challenges of direct seeding compared to mulch tillage are reflected in the estimated coefficients for utility gains and losses. Although the conditional complementarity remains negative for both systems, a key difference emerges. Joint adoption is a preferred system over the remaining systems when conservation tillage is enacted with mulch tillage, whereas nonadoption is preferred to joint adoption when conservation tillage is enacted with direct seeding (see Panel B and C, Table 7). This implies that the utility loss for farmers with joint adoption of direct seeding and herbicide-free production arise from the higher managerial challenges, potential opportunity costs, and complexity of implementation associated with no tillage.

Despite the estimated utility gains of joint adoption, the conditional complementarity coefficient $\overline{\widehat{\rho}}$ is negative and significant at 1%. This indicates that the utility of adoption of conservation tillage and herbicide-free agriculture under the current agri-environmental payments is not (conditionally) supermodular for the average farmer and conditional on the observed farmer's characteristics, the two systems are not complementary (see Panel A, Table 7). Note that two systems are complementary, when the benefit of joint adoption is more than proportional to the sum of the adoption of the individual systems in isolation. In our case, there are utility gains of joint adoption for mulch tillage, but they are not large enough to imply conditional complementarity (see Panel B, Table 7). In addition, there are on average, utility losses of joint adoption when direct seeding is implemented jointly with herbicide-free systems (see Panel C, Table 6). Furthermore, the coefficients of utility gains and losses, as well as conditional complementarity for the average farmer, do not accurately reflect the adoption incentives for all farmers. As demonstrated in online supplementary Appendix A5, there

TABLE 7 Conditional complementarity and utility gains or losses.

Supermodularity/average utility gains or losses	Coefficient
A. Conservation tillage (B + C)	
Utility gain of joint adoption $\overline{\widehat{\rho}_1}$	1.16***
	(0.04)
Utility gain of conservation tillage adoption $\overline{\widehat{\rho}_2}$	0.69***
	(0.03)
Utility gain of herbicide-free adoption $\overline{\widehat{\rho}_3}$	0.85***
	(0.03)
Conditional complementarity $\overline{\widehat{\rho}}$	−0.38***
	(0.02)
B. Mulch tillage	
Utility gain of joint adoption $\overline{\widehat{\rho}_1}$	0.68***
	(0.03)
Utility gain of Mulch tillage adoption $\overline{\widehat{\rho}_2}$	0.12***
	(0.03)
Utility gain of herbicide-free adoption $\overline{\widehat{\rho}_3}$	0.74***
	(0.02)
Perceived complementarity $\overline{\widehat{\rho}}$	−0.18***
	(0.02)
C. Direct seeding	
Utility gain of joint adoption $\overline{\widehat{\rho}_1}$	−1.19***
	(0.04)
Utility gain of direct seeding adoption $\overline{\widehat{\rho}_2}$	−1.42***
	(0.03)
Utility gain of herbicide-free adoption $\overline{\widehat{\rho}_3}$	0.71***
	(0.03)
Perceived complementarity $\overline{\widehat{\rho}}$	−0.49***
	(0.02)

Note: Bootstrapped standard errors based on 1000 replications in parenthesis ***p : Infoflora <0.1, **p <0.05, *p <0.1. Coefficient $\overline{\widehat{\rho}}$ refers to Equation (6) and $\overline{\widehat{\rho}} < 0$ implies conditional noncomplementarity. Coefficients $\overline{\widehat{\rho}_1}, \overline{\widehat{\rho}_2}, \overline{\widehat{\rho}_3}$ refer to Equation (5). A positive estimate indicates utility gain in the respective production alternative compared to adopting neither of the systems, and a negative estimate indicates utility loss. The empirical distribution of the coefficients is shown in online supplementary Appendix A5.

is significant heterogeneity in the empirical distribution of these coefficients. For instance, the distribution of the coefficient for utility gains from the joint adoption of conservation tillage and herbicide-free agriculture is negatively skewed. This indicates that while farmers generally perceive utility gains, a subset of farmers experiences utility losses from joint adoption.

5.1 | Robustness checks

First, we estimate a fixed effects multinomial logit model with panel data with the Swiss agricultural census ($N = 12{,}440$ farmers) (see Table A.10 in online supplementary appendix) and provide estimates of the coefficients of utility gains or losses (Table A.11). The patterns presented in the main analysis remain highly consistent. For example, we estimate that the conditional complementarity coefficient is negative and significant at 1% level, supporting the result that the adoption of conservation tillage and herbicide-free production are, on average, conditionally noncomplementary. Furthermore, consistent with the main analysis, the findings indicate that farmers on average, derive the highest utility from the joint adoption of the two production systems, followed by herbicide-free production in isolation, and then conservation tillage implemented in isolation. Nonadoption of any of the systems is the least preferred alternative for farmers. This suggests that although on average joint adoption yields the highest utility, it does not enhance farmers' utility more than proportionally compared to adopting each system independently. Second, the recursive bivariate probit suggest that the main model specification is preferred to a recursive data generation process (see online supplementary Appendix A6).

All in all, we find that the patterns delineated by the coefficients of utility gains and losses and the conditional complementarity are robust to the estimation of alternative models and the use of census data. The behavioral factors are robust in explaining the adoption decisions of both systems under different specifications, comprising the disaggregation across conservation tillage types and the estimation of alternative econometric models for decisions with interdependencies.

6 | DISCUSSION

Recent developments of pesticide policies and regulations to reduce pesticide use and associated risks have raised concerns about the future of conservation tillage systems (Kudsk & Mathiassen, 2020; Melander et al., 2013). To date, however, it remains unclear whether conservation tillage and herbicide-free production systems can coexist, the characteristics of farms and farmers adopting them jointly and to what extent adoption decisions are influenced solely by agronomic and farm structural factors or if behavioral factors also play a role. Our analysis examines the joint implementation of conservation tillage and herbicide-free agriculture in Swiss agriculture. First, by investigating the behavioral factors of farmers' decision making, we provide important insights of why, despite implementation challenges, farmers are willing to implement both systems. We find that behavioral factors explain 26% of the variation of the joint adoption of the two systems, with the remaining share explained by structural and agronomical factors. The significant role of farmer's willingness to take risks suggests that farmers expect higher risks after the joint adoption of conservation tillage and herbicide-free agriculture. This evidence is consistent with previous literature addressing the technological uncertainty of the adoption of low input agriculture and conservation tillage (see e.g., Garcia et al., 2024; Knowler & Bradshaw, 2007). Adopting herbicide-free agriculture jointly with conservation tillage raises additional sources of production uncertainty, including the weed pressure of the next crop season when tillage is reduced or remains of the previous crop or cover crops stay on the soil.

Farmers with large valuations of biodiversity and lower valuations of production goals in their farming activities are more likely to adopt an herbicide-free system in isolation. Moreover, one of the determinants for adopting mulch tillage and herbicide free is larger biodiversity valuations, whereas a determinant for *not* adopting direct seeding and herbicide free is larger production valuations. This indicates that farmers recognize the biodiversity benefits of mulch tillage in conjunction with herbicide-free production. However, the production challenges linked to the adoption of direct seeding and herbicide-free practices deter production-oriented farmers from adopting these systems jointly. Previous literature suggests a positive correlation between environmental and production valuations for the adoption of sustainable agricultural practices such as crop diversity, reduced tillage, and no herbicide use (e.g., Isbell et al., 2021; Mann, 2018). This raises considerations regarding the production challenges farmers face by enacting both measures simultaneously, especially with systems of minimum soil disturbance, as well as the economic reward for biodiversity.

Self-efficacy and locus of control regarding wheat production and pest management are not related to the joint adoption of herbicide-free agriculture and mulch tillage. This result is aligned with literature finding no differences in self-efficacy between adopters and nonadopters of agri-environmental schemes (Beetstra et al., 2022; McGinty et al., 2008) but contrasts with literature finding that perceived agency in terms of knowledge, skills, and time are correlated with farmer's adoption of practices such as low-input agriculture, organic agriculture, and grassland conservation (e.g., Defrancesco et al., 2008; Läpple & Kelley, 2013; Wu & Mweemba, 2010). Moreover, we observe that farmers high in self-efficacy are less likely to adopt jointly direct seeding and herbicide-free production. This suggests that farmers with high confidence in wheat production and plant protection, as indicated by their self-efficacy, are less inclined to adopt a production system that is likely to amplify the managerial demands for successful production, such as in weed management. These mixed results reflect that self-efficacy, if related to adoption of sustainable practices, does not always enable adoption as the characteristics of the systems likely play a crucial role. Moreover, the mixed results could reflect differences in the phrasing and the elicitation of a context dependent construct such as the one we implemented here, compared to a technology/agricultural practice specific construct (see Thompson et al., 2020).[17]

Innovativeness emerged as a crucial determinant of adoption of both agri-environmental schemes, that is, conservation tillage and herbicide-free agriculture, compared to nonadoption. Nonadoption can be regarded as a status-quo production system. A transition out of this status quo can be enabled through positive attitudes towards new practices and innovations.

Second, we explore the coexistence of both systems at the farm level and find that when direct seeding—a system that implies minimum tillage—is implemented, the average farmer faces utility losses after joint adoption, whereas he gains utility when mulch tillage, a less strict soil conservation practice, is implemented. Additionally, we note that although the average farmer may experience utility gains from joint adoption, it is not necessarily optimal for all farmers. This reflects differences in the interaction of two types of conservation tillage and herbicide-free systems, and confirms results from agronomic literature in which conservation tillage and herbicide-free systems are not fully compatible (e.g., Casagrande et al., 2016; Kudsk & Mathiassen, 2020).

The findings emerge in a context where each of the systems are economically incentivized via agri-environmental schemes, meaning that under the current incentive schemes, and depending on the type of conservation tillage, the two systems can coexist. This coexistence, however, does not imply complementarity meaning that the utility gains from joint adoption are insufficient to surpass the sum of utilities of adopting each system individually. The pattern persists when examining the entire wheat producer population over a 4-year period. The identification of the conditional non-complementarity aligns with prior findings by Perry et al. (2016) and Van Deynze et al. (2022) on conservation tillage practices and low-input agriculture.

The implementation of rigorous production standards, which offer significant environmental benefits but also pose substantial adoption challenges, requires finding a middle ground during the transition to overcome these barriers and facilitate broader adoption. This study underscores the importance of a nuanced understanding of the perceived total and marginal benefits of various combinations of conservation tillage and low-input agriculture to ensure optimal adoption levels. Our findings suggest that, given structural, agronomic, and behavioral factors, a combination of mulch tillage and herbicide-free production provides greater utility for farmers compared to a combination of direct seeding and herbicide-free production. Furthermore, the heterogeneity of gains and losses among farmers calls for combinations of practices that enhance synergies and minimize tradeoffs in agricultural systems at the farm level. This approach can serve as an entry point for farmers into strategic mixes of sustainable practices.

The generalizability of our results to other settings strongly depends on the institutional arrangements for agri-environmental schemes. The Swiss policy environment has a high degree of tailoring and coordination of direct payments (Huber, El Benni, & Finger, 2024). The results, therefore, can

[17]We contextualize our questions in terms of wheat production and plant protection but do not refer specifically to the adoption of herbicide free and soil conservation. Schaub et al. (2023) report that case specific and less general questions could improve prediction power of environmental attitudes.

be similar for policy settings such as the agri-environmental schemes of the CAP for the European Union (Guyomard et al., 2023).

There are important limitations in our analysis. We mainly analyzed the interactions between the systems in a cross-sectional setting. However, adoption choices and interactions between systems are dynamic. For example, adopting soil conservation in one period may either hinder or promote subsequent adoption of herbicide-free agriculture (Power, 2010). Furthermore, long-term adoption and adoption dynamics are crucial for three reasons. First, farmers can make short-term decisions for trialing purposes, but full adoption is only seen in the long term, which emphasizes the need to understand the processes behind sustained adoption over time (e.g., Wade & Claassen, 2017). Second, the benefits and costs from adopting more sustainable practices, for example, in terms of better soil productivity or ecosystem services or changes in weed seedbanks, might only materialize in the long-term; and third, farmers can experiment the different practices and adopt them step by step so that production and managerial decisions of farmers in longer term matter (e.g., increasing use of herbicides or tillage in other crops/seasons). Analyses of farmers' behavior over various years and at the crop-rotation level are thus likely to reveal the path dependencies in the substitution of pesticides with more complex agricultural systems.

7 | CONCLUSION

Global challenges related to soil erosion, the emergence of herbicide-resistant weeds, and pesticide risks underscore the need for the widespread adoption of practices that strike a balance between food production and the reduction of environmental impacts. Research on the coexistence between different agri-environmental schemes is, however, limited. For instance, it is unclear how to assess conflicting sustainable goals and assessments of the role of behavioral factors to ease or mitigate potential tradeoffs. Our study speaks to this gap and delves into the coexistence of conservation tillage and herbicide-free agriculture production systems. Previous studies have recognized the technical, agronomic challenges that arise after the joint adoption of these systems. However, this is not enough because farmers' behavior and the utility they perceive after adoption of different production alternatives go beyond the monetary benefits and costs associated with adoption. Our focus here is on assessing conflicting sustainability goals in agriculture by understanding the adoption behavior pertaining to these two systems and the key behavioral factors that facilitate their implementation. Our case study is given by Swiss wheat farmers and is understood within the existing policy framework of agri-environmental schemes supporting conservation tillage and herbicide-free production. Our findings reveal that although 35% of farmers adopt both systems, schemes also largely exclude each other; for example, 24% are using only soil conservation without herbicide free, 28% use herbicide free without soil conservation, 13% use neither of the strategies. Given the current agri-environmental payments, the systems coexist with utility gains from the joint adoption of the two systems, but they are on average and conditionally on observed factors noncomplementary. The coexistence, however, is only identified for mulch tillage unlike direct seeding. We find that behavioral factors explain 26% of the variation in farmers' adoption behavior. Farmers with more willingness to take risks, more openness to innovative practices, and larger valuations of biodiversity in their farming activities are more likely to jointly adopt herbicide-free and conservation tillage schemes. This shows that despite the challenges in measurement of behavioral factors, they are crucial to understand farmers' behavior and can facilitate joint adoption.

The identified relation between conservation tillage and herbicide-free systems and the behavioral factors behind adoption decisions present key entry points for agri-environmental policies and programs. These include efforts oriented toward the expansion of conservation practices, the exploitation of synergies between production, and the tackling of emerging challenges such as the prevalence of glyphosate-resistant weeds (Canales et al., 2020; Van Deynze et al., 2022). The identified utility gains from joint adoption of the two systems, together with the conditional noncomplementarity, imply that agri-environmental schemes can acknowledge the agronomical challenges of joint adoption of noncomplementary production systems with economic incentives, thereby overcoming the opportunity costs. These policies can also account for behavioral factors to mitigate tradeoffs in the implementation of complex production systems. Risk preferences, biodiversity and production goals, and innovativeness are all relevant to enable adoption. A wide range and mix of policy instruments, for example, comprising economic incentives and information or advisory services as well as nudges, may potentially encourage adoption from farmers who have a productive orientation and farmers who expect larger risks after adoption. Policy makers can aim at expanding the range of tools available to farmers to reduce the risks associated to the adoption of conservation tillage and herbicide-free production and actively assess new technologies and adapting regulations (Vanclay et al., 2013). The crucial role of innovativeness among all the other behavioral factors suggest that policies can introduce the trait of innovativeness into farm typologies to target policies (e.g., Huber, Bartkowski, et al., 2024), so that innovative solutions arise from successful implementations as a bottom-up approach (e.g., from local levels with farmers, to larger implementations at national levels) to ease the adoption of seemingly conflicting production systems. The tradeoffs we explored between conservation tillage and herbicide free agriculture apply to other production systems and levels of economic incentives in agri-environmental schemes. As more agri-environmental schemes are expected in the policy arena to incentivize adoption of sustainable agricultural practices, more research is needed regarding the extent to which these payments can cover farm-specific costs of implementation. Although in our setting, all farmers are exposed to the same agri-environmental schemes, future work can estimate the utility gains of joint adoption in settings with varying degrees of compensation for yield losses and managerial costs, and so reveal further the role of agri-environmental schemes in the adoption of noncomplementary systems. Future research can expand the here developed framework to investigate other management choices that potentially reveal tradeoffs, for example, between environmental and economic domains. More specifically, the estimation of utility gains or losses can prove useful to understand complex relationships between agricultural practices and be applied to multiple agri-environmental schemes. Furthermore, additional empirical work is needed to better understand farmer's decision making across time periods as well as interactions between different agricultural practices that farmers can implement for sustainable farming.

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SUPPORTING INFORMATION

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

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