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Does zero tillage save or increase production costs? Evidence from smallholders in Kyrgyzstan

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ABSTRACT

Promoting zero tillage has been recognized as an important strategy for smallholders from an agronomic perspective. However, the economic effects of adopting zero tillage are still a matter of debate. Employing an endogenous switching regression model on the plot-level panel data of 878 Kyrgyzstan's smallholders, we investigate the determinants of decision to adopt zero tillage and its effect on smallholders' production costs. We find that the probability of zero tillage adoption is associated with employment in agriculture, assets, agricultural shocks, fertilizer use, number of plots and average distances from dwelling to household fields and to main road. Furthermore, the results indicate that zero tillage adoption decreases land preparation costs by 23%, but increases hired labour and herbicide costs by 13% and 15%, respectively compared to conventional tillage method. Nevertheless, zero tillage can reduce total production costs by 15%. Our findings suggest that zero tillage can be promoted as an option for resource-scarce smallholders, especially to those in remote areas with poor access to inputs and machinery services. Promoting zero tillage adoption as a labour-saving or herbicide reducing practice can create false expectations among smallholders.

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Zero tillage; resource saving; production costs; endogenous switching regression; Central Asia

1. Introduction

Continuous application of conventional practices of tillage-based agriculture leads to soil degradation, soil erosion, and reduces organic matter and crop production capacity of soils (Farooq et al., 2011). Conservation tillage practices can prevent soil erosion (Baker & Saxton, 2007) and result in long-term factor productivity increases in agriculture (FAO, 2023). Reducing production costs while maintaining land fertility in agriculture remains another important feature of conservation tillage (e.g. Hashimi et al., 2023; Jaleta et al., 2016). The resource-saving property of reduced tillage practices can be particularly attractive for resource-poor smallholders in developing countries. Zero tillage, namely when crops are planted directly into a seedbed not tilled after harvesting previous crop, is one such practice (FAO, 2023). Among its benefits is that zero tillage accumulates soil carbon and increases soil nitrogen, thus promoting soil, moisture and nutrients conservation for increasing crop productivity (Baker & Saxton, 2007; Ofstehage & Nehring, 2021). Zero tillage is also proved to be a solution to target low financial and resource capacity of smallholders in developing countries (Jaleta et al., 2016; Jaleta et al., 2019; Montt & Luu, 2020; Musafiri et al., 2022). Since its first adoption in the United States in the 1960s, zero tillage has spread globally from 244.4 million ha in 2009 to 507.6 million ha in 2019, accounting for almost 15% of the global cropland.[1] In Central Asia,

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Kazakhstan has the largest crop area under zero tillage, followed by Kyrgyzstan (Kassam et al., 2019).

Beyond the agronomic benefits, zero tillage offers socio-economic benefits for smallholders such as through reduction of costs related to land tillage, namely costs related to machinery services and inputs such as labour, fuel and fertilizers (Chatterjee & Acharya, 2021). As a result of input savings, zero tillage increases net benefits for smallholders (Jaleta et al., 2016; Keil et al., 2020). Montt and Luu (2020) find that adopting minimum tillage reduces working time for land preparation, weed control and threshing. El-Shater et al. (2016) found that zero tillage can reduce fuel, labour and machinery costs. Within the structure of workers, the adoption of minimum tillage in maize production reduced the use of male and female labour (Jaleta et al., 2016). The findings of Erenstein et al. (2008) show that adopting zero tillage on wheat fields in India reduces the duration of tillage operations by 6–7 tractor hours and 35 l of diesel consumption. Krishna and Veettil (2014) found a similar effect of zero tillage adoption on machinery costs.

However, there is an ongoing debate whether zero tillage affects smallholders' production costs one way or it can change the production cost structure. A summary of findings from nine empirical studies on the impact of conservation tillage methods, including zero tillage, is presented in Table A in Supplementary Materials. For instance, some findings suggest that zero tillage can increase monetary herbicide expenditure and total labour costs (Teklewold et al., 2013). While arguing that zero tillage reduces fuel and labour cost, Yigezu and El-Shater (2021) found that its effect on the labour requirement and expenses are not necessarily straightforward as zero tillage can increase manual work requirements for weeding. Furthermore, while lowering female and male labour requirements, reduced and zero-tillage methods lead to higher application doses of chemical fertilizers and herbicides (Tessema et al., 2018). Our study aims at contributing to the ongoing debate on whether zero tillage saves or increases production costs in smallholder settings.

Furthermore, our investigation is prompted by the growing interest in sustainable agricultural practices in Central Asia and the lack of empirical research on their economic effects in the region. Thus, our study is the first to investigate determinants of zero tillage adoption and its impact on production costs of Central Asia's smallholders using a unique panel dataset from the Life in Kyrgyzstan (LiK) survey. The decades of unsustainable land management have caused land degradation in many agricultural areas of Central Asia (Mirzabaev et al., 2016; Nurbekov et al., 2016). The long-lasting monoculture of cotton and grain cultivation under intensive tillage has negatively affected soil fertility. For instance, more than 40% of agricultural land in Kyrgyzstan is severely degraded, while over 85% of all land is vulnerable to erosion (Polo et al., 2022). In 2010, one-third of rural population of Kyrgyzstan, approximately 1.2 million people, was living on degrading agricultural land (Global Mechanism of the UNCCD, 2018). The total annual cost of land degradation in Kyrgyzstan is estimated at US$ 601 million, or equivalent to 16% of GDP (Mirzabaev et al., 2016).

To combat land degradation, in the mid-1990s, the concept of conservation agriculture was presented by international agencies (Wolfgramm et al., 2015) and several practices including zero tillage have been successfully tested in Central Asia. Notwithstanding the advantages of zero tillage, most Central Asian farmers are reluctant to adopt it (Nurbekov et al., 2016). The conversion to sustainable intensification of crop cultivation in Central Asia, such as zero tillage, is challenged by the lack of agronomic knowledge about sustainable tillage methods among farmers and extension service providers, lack of seed varieties suitable for reduced tillage cultivation, as well as the absence of government incentives for adopting such practices (Kienzler et al., 2012; Nurbekov et al., 2016).

The paper is organized as follows. In the next section, we provide a review of Kyrgyzstan's smallholder farming system and its challenges in adopting conservation agriculture. Following this, we present the conceptual framework and describe our data and summarize selected variables. This is followed by the section that presents a two-stage analytical approach and discusses the estimation results. The final section draws conclusion and proposes policy messages.

2. Smallholders' challenges in adoption of conservation agriculture

Kyrgyzstan is a land-locked low-income food-deficit country with population of about 6 million, of which almost two-third live in rural areas (FAO, 2020). In 2021, GDP per capita was US$ 1,123 (in constant 2015 US$). Despite the progress in poverty reduction, one-fourth of the population lives below the poverty

line (World Bank, 2023). Rural areas, where two-third of the population is poor, are still lagging behind these figures (FAO, 2020). Although agriculture's contribution to the country's gross domestic products (GDP) has been steadily declining, it still plays a central role in rural economy. In 2021, agriculture accounted for almost 15% of GDP (World Bank, 2023). As of 2019, about 20% of employment was in agriculture (World Bank, 2023).

Kyrgyzstan's late-1990s land reform drove the switch from planned socialist agriculture to smallholder market-oriented agriculture (Lerman & Sedik, 2018). Through the private land ownership recognition in 1996–1999 the government redistributed over 80% of arable land among rural families creating smallholder-based farming system (FAO, 2020). The majority of smallholders are characterized by intercropped and mixed crop-livestock systems with production mostly for their own consumption (Jalilova et al., 2019). In 2016 the official statistics reported about 1,150,000 rural households and peasant farms with an average size of about 0.87 ha (FAO, 2020). This includes 727,000 rural households with an average land size of about 0.1 ha, and 415,000 peasant farms with an average size of 2.2 ha (FAO, 2020).

Although the smallholders have been important in food security and poverty alleviation, the fragmented nature of the farming system is prone to the problems of 'smallness'. For instance, in fragmented agricultural settings of Kyrgyzstan, limited physical, financial and human resources raise concerns about future of agricultural food production and sustainability of arable lands (Wolfgramm et al., 2010). Among the reasons is that rural households have to cope with the increasing costs of agricultural inputs. Most public finance and agricultural subsidies do not reach rural households and are captured by large commercial farms (Lerman & Sedik, 2018). The government does not have a sufficient budget to provide adequate support to smallholders to cover field operation costs. The scarcity of agricultural machinery has been imposing high machinery service costs for land preparation among smallholders, being 55% more expensive than in neighbouring southern Kazakhstan, and hindered agricultural productivity in Kyrgyzstan (Guadagni & Fileccia, 2009). Farmers might be facing a mix of price, risk and quantity rationing as the number of credits at affordable rates is limited (Kuhn & Bobojonov, 2021). The high rates and transaction costs of commercial credits may be unacceptable for smallholders the majority of whom cannot access limited subsidized credits.

The lack of access to new technologies and to the knowledge about conservation tillage practices limits the wider adoption of zero tillage among smallholders in Kyrgyzstan. Kyrgyzstan's irrigated agriculture is among the most vulnerable in Eastern Europe and Central Asia to climate change (Fay et al., 2010). A modelling study by Bobojonov and Aw-Hassan (2014) suggests that under a water shortage scenario, predicted farm incomes in semiarid parts of Kyrgyzstan might decline by 15% harming smallholders' profits and long-term sustainability. In light of the importance of agriculture in rural incomes and food security, the intensity and spread of land degradation and increasing pressure from water scarcity may affect agricultural productivity and threaten agricultural livelihoods.

Cost-saving practices like zero tillage can be an option for smallholders who suffer from low credit access, underinvestment and are prone to water stress. In 2016, the full technical potential adoption level of conservation agriculture in Kyrgyzstan, including reduced and zero-tillage and crop rotation, has been estimated at 1.2 million ha of cultivated area under cereals, oil and leguminous crops (Polo et al., 2022). The results of the financial analysis presented by Polo et al. (2022) show that conservation agriculture scores moderately with an investment return rate of 13% and a payback period of seven years. It was estimated that conservation agriculture can increase agricultural production via long-term improved soil nutrient management and water retention. For instance, raised-bed and no-tillage planting can increase wheat yield by 25–38% compared to the conventional cultivation method (Nurbekov et al., 2016). The economic value of the annual additional production due to adoption of conservation agriculture in Kyrgyzstan was estimated at over US$ 35 million or 9% of gross agricultural value (Polo et al., 2022). However, despite these advantages, the gap between present and potential uptake has remained substantial with little change (Polo et al., 2022).

3. Conceptual framework

Numerous studies have noted three paradigms such as 'the innovation-diffusion', 'the adoption perception' and 'economic constraints' to define farmers' adoption of conservation practices (Chatterjee & Acharya, 2021; Ruzzante et al., 2021). Each paradigm assumes several factors influencing the adoption decision (Figure 1). For example, to illustrate adoption

behaviour, the economic paradigm assumes the maximization of farmer's profit and considers economic constraints such as access to natural resources, access to capital, investment costs and risk attitude. The innovation-diffusion paradigm assumes that access to information is the main parameter to improve adoption decisions. The adoption perception paradigm postulates that a farmer's adoption behaviour depends on perceived attributes of innovation, access to information and individual factors such as farmer's experience and education, as well as institutional factors that can affect the perceptions (Ruzzante et al., 2021).

We conceptualize that a household faces the decision to adopt zero tillage on a specific plot against conventional tillage methods in crop cultivation. From this perspective, the economic paradigm stipulates that adoption decision occurs under farmer's objective of profit maximization. Thus, we can assume that a farmer will adopt zero tillage method if the expected net returns from the adoption are maximized given crop yields and output prices. In this regard, adoption decision is related with farmer's perception whether adoption reduces production costs or not, i.e. production costs under adoption (C_a) are lower than the ones under nonadoption (C_{na}), thus, ($C_{na} - C_a > 0$)

The adoption of zero tillage can, thus, be considered as farmer's binary choice that is influenced by various factors related to individual characteristics of household head, household farm characteristics, institutional and location settings. Along with the adoption of zero tillage, these factors can change the structure of production costs and reduce the total production costs. Household head and farm characteristics include gender, ethnicity, education, experience, occupation and age of household head, as well as household size, wealth, number and size of operated plots and livestock.

Farmers with higher level of education, or with long schooling years, are more likely to adopt zero tillage as education increases comprehension about application methods and about benefits of sustainable agricultural practices (El-Shater et al., 2020; Jaleta et al., 2016; Yigezu et al., 2018). Age of household head is negatively related to the likelihood of minimum tillage adoption (Ngoma, 2018). One common explanation to this is that older farmers are more risk-averse than younger farmers and, thus, are less likely to adopt new technologies. The adoption of minimum tillage can be also associated with the occupation of household head in farming and agriculture (Musafiri et al., 2022). Household heads working in agriculture are more likely to be exposed to training and practical application of new methods. Furthermore, the adoption decision can vary with respect to household head's gender. Female farmers can have difficulties in accessing productive resources such as machinery services, agricultural credits and have lower non-farm opportunities (Wainaina et al., 2016). As a result of resource access problems, they are more likely to adopt resource-saving agricultural

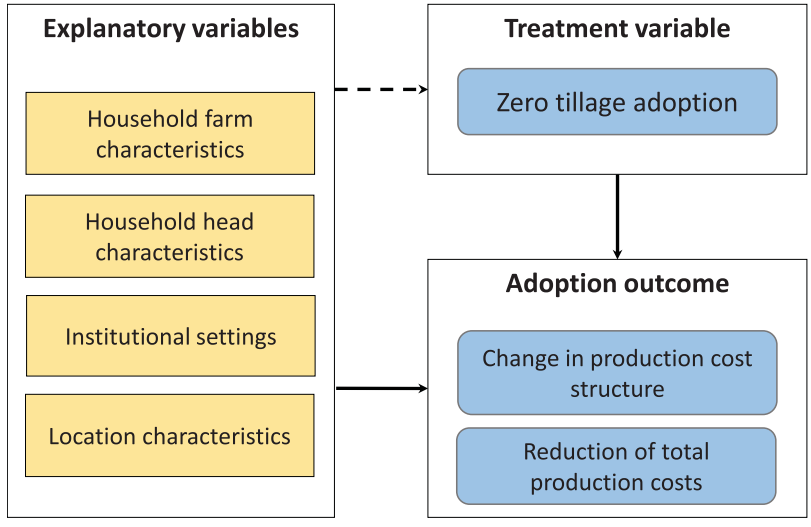

Figure 1. Conceptual framework displaying hypothesized determinants of zero tillage adoption and its economic effects on production costs. Sources: Based on Musafiri et al. (2022).

practices rather than input-intensive ones (Rola-Rubzen et al., 2020). Moreover, the decision to adopt agriculture practices can vary across household ethnicity. Atamanov and Van den Berg (2012) found that Kyrgyz households are more likely to narrowly focus on farming activities rather than other rural nonfarm activities and less likely to mix farm and nonfarm activities.

The adoption of minimum tillage can be determined by the number of household members. For instance, the empirical evidence shows that the likelihood to adopt minimum tillage decreases with the increase in household size (Montt & Luu, 2020). Tambo and Mockshell (2018) found negative and statistically significant relationship between minimum soil disturbance and household size, thus pointing that households with fewer family members are likely to adopt minimum tillage. The size of household plots can also explain the decision to adopt agricultural practices. According to Teklewold et al. (2013) households with larger arable plots are more likely to adopt conservation tillage practices. Similarly, Jaleta et al. (2016) found that households with larger plots tend to adopt minimum tillage. Furthermore, farther distance of household plots from homestead increases the likelihood to minimum tillage use (Jaleta et al., 2016).

Adoption of resource-saving practices is likely to be lower among household who own agricultural machinery and equipment because these tools allow households to receive better control over application of conventional tillage methods (Jansen et al., 2006). Furthermore, Ngoma (2018) found that an increase in household assets reduces the likelihood of minimum tillage adoption. The adoption of minimum tillage can be negatively associated with household's ownership of livestock because such household relies on harvesting of crop residues for animal feeding (Jaleta et al., 2016). Finally, institutional settings are important in supporting adoption decisions of smallholders. They can improve farmer's financial capacity and either promote the adoption of costly tillage practices or improve farmer's ability in taking up resource-saving practices. For instance, according to Musafiri et al. (2022) the adoption of minimum tillage is positively associated with household's access to credits.

4. Data

For our study we use the data from the 'Life in Kyrgyzstan' (LiK) survey. The LiK collects data from all provinces of Kyrgyzstan and two major cities. The LiK is an open access, longitudinal survey and is representative at the national and regional levels (East, West, North, South), as well as for urban and rural areas (Brück et al., 2014). The LiK contains six waves conducted in 2010, 2011, 2012, 2013, 2016 and 2019. Initially, the first wave covered 3000 households and 8160 individuals from these households (Brück et al., 2014). The households for the study were drawn using stratified two-stage random sampling (Brück et al., 2014). As a multi-purpose, socio-economic survey it covers a wide range of topics for economic and sociological research (Brück et al., 2014). An agricultural module that covers plot-level data about crop cultivation and tillage methods was introduced in 2016 wave and repeated in 2019. These two waves cover 2529 and 2316 households, respectively.

We applied several conditions to narrow the dataset to fit our research objectives. Since we focus on rural households, we excluded observations in the cities of Bishkek and Osh as these cover urban households without or with limited agricultural activities. As the agricultural module comprises questions across household plots, we listed all variables at the plot level. The plot-level specification of the dataset also allows us to increase the number of observations in our sample. Furthermore, we kept only observations of rural households that operated plots for crop cultivation. Therefore, our sample does not include households who did not cultivate land or focused only on livestock keeping without land operations.

We assume that household heads are the main decision-maker in agriculture in households and thus accounted for their responses. In our sample, 82% of respondents in 2016 and 75% of respondents in 2019 wave were household heads. We kept rural households who participated in both 2016 and 2019 waves. In the end, our total sample covers 2788 plot-level observations that belong to 878 rural households. We pooled two-year panel data to take advantage of the variability in the dataset. Since some households used a different number of plots across the two years, our panel data are an unbalanced one.

An average size of household lands in our sample is about 1.6 ha, which is close to the national average size of rural households in Kyrgyzstan. An average size of a household plot in our sample is about 0.8 ha. Each household has on average 2 plots. In our 2019 data out of 878 interviewed

households, 149 households were commercial, i.e. cultivating crops for selling. 531 households were subsistence, i.e. cultivated crops purely for home consumption. 101 households were mix of commercial and subsistence. The remaining 97 respondents were either cultivating fodder crops or could not answer the question.

The questionnaire addresses a question to household heads that is 'What types of tillage methods were used in this field?'. This question lists eight answers with an option to choose up to two main tillage methods applied in a particular plot. We treated the responses 'zero tillage' and 'did not till – broadcast seed' as zero tillage method. Other six tillage methods which include hand tillage, ploughing with tractor, ploughing with horses, ridging (before planting), mounding and other tillage methods, we aggregated into a non-zero tillage method. By doing so, we generate a binary choice variable with two expressions such as 0 standing for non-zero tillage and 1 for zero tillage use. Our full sample of 2016 and 2019 of 878 interviewed households has 297 households, or about one-third of respondents, who applied zero tillage on one of the plots.

The survey provides plot-level information on payments for hired labour, machinery costs for land preparation and seeding, weeding, and herbicide costs. We use these responses for outcome variables to estimate the economic effect of zero tillage adoption on production costs. The outcome variables are given in the national currency, Kyrgyz Som (KGS), which we converted to US dollars.[2] If households responded that they did not report about input costs, their values were reported as zero. Households provided information on costs for land preparation, seeding and weeding for each crop at a plot level. These variables include costs for own and hired machinery services. The machinery cost variable in our model comprises two outcome variables, namely 'Machinery costs for land preparation and seeding' and 'Machinery costs for weeding'. About 73% of interviewed household heads, i.e. 640 households out of 878, in our sample reported about machinery costs for land preparation and seeding on at least one plot. About 34% of interviewed household heads in our sample reported about having machinery costs for weeding. We aggregated land preparation and seeding costs for all crops and generate total land preparation costs at a plot level. Similarly, we generated a variable of total weeding costs at a plot level. Finally, we add all mentioned input costs into total production costs.

To understand the use of zero tillage by smallholders in Kyrgyzstan, the first author conducted field research in September 2021 with open-ended interviews of key experts such as farmers, staff of crop research institutes, university researchers and experts from Bishkek office of the UN Food and Agricultural Organization (FAO). These interviews provided additional information to interpret our estimation results.

Table 1 provides information about several control variables used in our study. The variables are divided into 'outcome variables' which are production costs, 'treatment variable' which is a dummy variable of plots with or without zero tillage, and 'explanatory variables'. Explanatory variables comprise 'household characteristics' and 'plot characteristics'. To account for heterogeneity, we use household and plot characteristics such as age, education, gender, ethnicity of household head, number of household members, number of assets, tractor ownership, receiving remittance, plot size, plot distance from dwelling, fertilizer use, etc. We also present the summary statistics across the treatment variable in Table B in Supplementary Materials.

As a proxy for household wealth, we calculated the asset index using the principal component analysis (PCA) as suggested by Filmer and Pritchett (2001). We used binary information regarding ownership of 34 assets based on the standardized PCA scores, as well as min–max normalization (feature scaling) method is used to convert the scaled data into range (0–1).

The number of total livestock units (TLU) is an additional household wealth indicator. We calculated TLU based on livestock unit coefficients.[3] First, we multiplied each type of livestock into LU coefficients, and then summarized the result by households. The summary statistics suggest that the number of livestock units owned by household is average 3 in 2016 and 2 in 2019.

In the study, we also consider the number of plots owned by households. Table 1 indicates that households have on average 2 plots in both years. Remittances and migration have been one of the main income sources in rural areas of many developing countries and particularly of Kyrgyzstan where remittances affect household's decisions in agriculture (Atamanov & Van den Berg, 2012). Following the argument by Montt and Luu (2020) that successful

Table 1. Summary statistics of variables by survey year.

	2016		2019		Full sample	
Variables	Mean	Sd	Mean	Sd	Mean	Sd
Outcome variables						
Total payment for hired labour (US$/ha)	10.217	52.284	6.747	37.924	8.443	45.539
Machinery costs for land preparation and seeding (US$/ha)	35.149	61.600	37.769	81.693	36.488	72.567
Machinery costs for weeding (US$/ha)	7.144	36.072	10.736	48.454	8.980	42.880
Herbicide costs (US$/ha)	7.262	34.853	21.942	77.896	14.690	61.015
Total machinery, labour and herbicide costs (US$/ha)	59.772	121.297	77.076	155.679	68.527	139.997
Treatment variable						
Plots under zero tillage (dummy, 1 = zero tillage)	0.068	0.252	0.204	0.403	0.137	0.344
Household head characteristics						
Age of household head (years)	55.794	12.450	56.189	11.958	55.996	12.201
Education level of household head (categorical, 1 = illiterate … 7 = university degree)	4.333	1.275	4.217	1.185	4.274	1.231
Female household head (dummy, 1 = female)	0.199	0.399	0.253	0.435	0.226	0.419
Household head employment in agriculture (dummy, 1 = occupation in agriculture)	0.340	0.474	0.337	0.473	0.339	0.473
Household head's ethnicity (dummy, 1 = Kyrgyz)	0.786	0.410	0.770	0.421	0.778	0.415
Household farm characteristics						
Number of household members that can work in agriculture (above 10 and under 65 years old)	4.407	1.781	4.570	1.927	4.490	1.859
Asset index	0.400	0.139	0.354	0.168	0.376	0.156
Household owns a tractor (dummy, 1 = yes)	0.049	0.216	0.034	0.182	0.042	0.200
Number of livestock units owned by household	3.364	4.260	2.377	4.268	2.859	4.292
Household received remittances last year (dummy, 1 = yes)	0.145	0.353	0.226	0.418	0.187	0.390
Household applied chemical fertilizers last year (dummy, 1 = applied)	0.252	0.434	0.246	0.431	0.249	0.432
Household experienced a weather shock last year (dummy, 1 = yes)	0.629	0.483	0.161	0.367	0.390	0.488
Household experienced an agricultural shock last year (dummy, 1 = yes)	0.364	0.481	0.088	0.283	0.223	0.416
Plot under grains and legumes (dummy, 1 = yes)	0.318	0.466	0.353	0.478	0.336	0.472
Plot under vegetables (dummy, 1 = yes)	0.400	0.490	0.270	0.444	0.334	0.472
Plot under a mix of crops (grain, legumes and vegetables) (dummy, 1 = yes)	0.073	0.260	0.022	0.146	0.047	0.211
Location characteristics						
Distance to main road from dwelling (km)	0.521	0.738	0.777	0.891	0.652	0.830
Distance from dwelling to plot (km)	1.470	2.840	1.174	2.536	1.319	2.693
Number of land plots owned by household	1.966	0.627	1.980	0.702	1.973	0.666
Plot size (ha)	0.694	1.340	0.794	1.898	0.745	1.649
Institutional settings						
Amount of credit received by household last year (US$)	210.154	775.394	339.183	1387.313	276.103	1131.974
Provinces						
Issyk Kul	0.160	0.367	0.179	0.383	0.170	0.375
Djalal Abad	0.213	0.409	0.201	0.401	0.207	0.405
Naryn	0.073	0.260	0.048	0.213	0.060	0.237
Batken	0.125	0.331	0.122	0.328	0.123	0.329
Osh	0.260	0.439	0.293	0.455	0.277	0.448
Talas	0.079	0.270	0.070	0.256	0.075	0.263
Chuy	0.090	0.287	0.088	0.283	0.089	0.285

Note: $N = 1363$ for 2016, $N = 1425$ for 2019 and $N = 2788$ for the full sample. Because of missing values of herbicide costs, the number of observations for 2016, 2019 and the full sample are 1342, 1396 and 2738, respectively.

conservation agriculture practice requires appropriate management of external inputs such as fertilizers, we add household's application of fertilizers as an explanatory dummy variable in our models.

Furthermore, we consider the opinion of household heads about whether their households experienced agricultural shocks over the last year such as pest infestations, crop and livestock diseases, insufficient irrigation water supply, theft of livestock, or inability to sell agricultural products as well as weather shocks such as drought, flood, heavy rain or extremely cold winter temperatures. We assume that such agricultural and weather shocks can affect household's decision to adopt zero tillage practices by harming household's agricultural outputs and assets.

Smallholders often cultivate a mix of crops on a single plot. We aggregated all costs for various crop types to control their effect on zero tillage adoption decision. We generated three dummy variables which explain that plot was cultivated (1) purely by grain and legume crops, (2) by vegetables and (3) a mix of grains, legumes and vegetables.

5. Analytical framework and estimation procedure

We explain the empirical models in the following subsections and motivate the selection of our methodology. The assessment of economic effects of the technology adoption from non-experimental survey data requires the correction of self-selection bias, identification of proper counterfactuals and controlling for non-observable farm characteristics (Asfaw et al., 2012; Jaleta et al., 2016). We base the identification of farmer's decision to adopt zero tillage on the measurement of profitability through its production cost reducing effects. To estimate the impact of zero tillage on production costs, we follow existing literature such as Abdulai and Huffman (2014), Jaleta et al. (2016), Keil et al. (2020), Khonje et al. (2018), Montt and Luu (2020) and employ a two-stage estimation approach. We assess different models to investigate the relationships between zero tillage adoption and payments for hired labour, machinery costs for land preparation and seeding, weeding, and herbicide costs as well as total costs. We employ the Mundlak device (Mundlak, 1978) to estimate time-invariant endogeneity. Furthermore, we use the endogenous switching regression (ESR) model to account for selection bias. To estimate the association between zero tillage adoption and each production cost considered above, we use the counterfactual framework that measures average treatment effects on the treated (ATT).

5.1. Zero tillage adoption decision and production costs

The decision to adopt zero tillage and the selection of plots under this method is made by a household head and other household members, and thus not random. Such self-selection problem implies a potential bias in the effect of zero-tillage adoption on production costs. In reality, households might apply zero tillage on plots with higher production costs. As a result, the effect of zero tillage on production costs can be overestimated. As commonly done in other studies (e.g. Jaleta et al., 2016; Keil et al., 2020; Khonje et al., 2018; Montt & Luu, 2020), to correct for selection bias, we employ two stage ESR model. In the first stage, we estimate the main determinants of zero tillage adoption. The probability of zero tillage adoption for an individual can be written as follows:

$$Pr(zt_{jit}) = f(X_{jit}) \tag{1}$$

where $Pr(zt_{jit})$ is the probability of zero tillage adoption of i's household in j's plot at time t. X is a vector of explanatory variables describing household and plot characteristics, personal characteristics, location settings, etc.

We use the Mundlak approach where the means of observable time-variant variables are added in the model. The Mundlak approach is applied to panel fixed-effects in cases of variation within units over time and when time-invariant observables affect both adoption decision and outcomes (Khonje et al., 2018; Montt & Luu, 2020; Mundlak, 1978). This approach also reduces the problem of unobserved heterogeneity. The fundamental assumption of using Mundlak approach is to consider unobserved time-invariant components by calculating and employing the mean of time-variant variables as proxy (Montt & Luu, 2020; Mundlak, 1978). We computed the means of all time-variant variables ($\bar{x}_i$) and added a probit regression model to measure the probability of zero tillage adoption. Furthermore, we included province dummies (R_p, here, Issyk Kul is the reference province) and a time dummy (Y_t, here, 2016 is the reference year) for all models to account for the province-level and year differences. The regional dummies allow us to account for other cross-regional differences that can be associated with adoption decisions such as costs of machinery, labour and other inputs. Thus, from Equation (1), a household i's likelihood of adopting zero tillage in their j's plot at time t can be formulated as:

$$\begin{aligned} Pr(zt_{jit} = 1 | X_i,\ R_p,\ \overline{X_i},\ Y_t) \\ = \Phi(a_i + \beta' x_{jit} + \delta' x_{it} + R_p + Y_t) \end{aligned} \tag{2}$$

where β, δ and γ are the parameters to be estimated. x_{jit} contains observables at the plot level. x_{it} contains observables at the household level. $\bar{x}_i$ mean of time-varying variables that follow the Mundlak approach.

In the second stage, we apply an OLS model under two regimes, namely, under non-adoption and adoption of zero tillage. Here, our model estimates the relationship of outcome variables for zero tillage adopters and non-adopters.

$$\begin{cases} y_{1jit} = K_{jit1}\beta_1 + \bar{k}_{i1}\nu_1 + R_p + Y_t + \eta_{1jit}\,, & if\ \ ZT = 1 \\ y_{0jit} = K_{jit0}\beta_0 + \bar{k}_{i0}\nu_0 + R_p + Y_t + \eta_{0jit}\,, & if\ \ ZT = 0 \end{cases} \tag{3}$$

where y_{jit} is outcome variables such as machinery costs for land preparation, machinery costs for

weeding, payment for hired labour and herbicide costs, on plot j of i's household at time t. K_{jit} is a set of explanatory variables that relate to outcomes. $\bar{k}_i$ is a mean of time-varying variables. As mentioned before, R_p and Y_t are the province and time dummies. Some households report relatively high costs per plot and high amounts of credit. Therefore, natural logarithm is used for these variables. However, there are some observation with '0' values. Hence, to avoid missing values, we add '+1' for these variables before transforming natural logarithm.

The probit model supplies essential information to examine and correct the potentially resulting bias (Maddala, 1983, p. 223; Petrick, 2004, p. 151). To test selection bias, we follow Heckman (1979) and use the Inverse Mills Ratio (IMR) calculated from the results of a probit estimation as follows:

$$\begin{aligned}\lambda_{1jit} &= \varphi(\delta x_{jit})/\phi(\delta x_{jit});\ \lambda_{0jit} \\ &= -\varphi(\delta x_{jit})/[1-\phi(\delta x_{jit})]\end{aligned} \tag{4}$$

where $\varphi(.)$ and $\Phi(.)$ indicate density and cumulative density function of the standard normal distribution, respectively. λ_{0jit} and λ_{1jit} represent IMR. After calculating IMR, we add it to the second stage model to correct selection bias and have the following equation:

$$\begin{cases} y_{1jit} = K_{jit1}\beta_1 + \bar{k}_{i1}\nu_1 + R_p + Y_t + \lambda_{1jit}\sigma_1 \\ \quad + Y_t{*}\lambda_{1jit}\tau_1 + \eta_{1jit} \quad , \ if \ \ ZT = 1 \\ y_{0jit} = K_{jit0}\beta_0 + \bar{k}_{i0}\nu_0 + R_p + Y_t + \lambda_{0jit}\sigma_0 \\ \quad + Y_t{*}\lambda_{0jit}\tau_0 + \eta_{0jit} \quad , \ if \ \ ZT = 0 \end{cases} \tag{5}$$

Furthermore, to consider changes in selection effect over time, we interact the IMR with the time dummy ($Y_t{*}\lambda_{jit}$) following Montt and Luu (2020).

Several studies emphasize the selection of valid instruments that influence adoption decisions but do not affect outcome variables. We assume households near the main road will have more convenience in using conventional tillage methods by easy access to machinery services and, thus, less likely to adopt zero tillage than households located further away from the road. A falsification test shows that 'distance to the main road' relates to zero tillage adoption decision but does not affect the outcome variables (see Table C in Supplementary materials).

5.2. Estimation of average treatment effect on the treated

The average treatment effect is estimated in the framework ESR method to test the impact of zero tillage adoption on outcome variables. First, we compared the expected outcomes of zero tillage adopters and non-adopters in actual and counterfactual situations. The expected (actual) outcome for zero-tillage adopters can be expressed as follows:

$$\begin{aligned}E(y_{1jit}|zero\ tillage = 1) = K_{jit1}\beta_1 + \bar{k}_{i1}\nu_1 + R_p \\ + Y_t + \lambda_{1jit}\sigma_1 \\ + \ Y_t{*}\lambda_{1jit}\tau_1\end{aligned} \tag{6}$$

The expected outcome for adopters had they not adopted zero tillage (counterfactual) can, thus, be expressed as follows:

$$\begin{aligned}E(y_{0jit}|zero\ tillage = 1) = K_{jit1}\beta_0 + \bar{k}_{i1}\nu_0 + R_p \\ + Y_t + \lambda_{1jit}\sigma_0 \\ + \ Y_t{*}\lambda_{1jit}\tau_0\end{aligned} \tag{7}$$

Second, the differences between the actual and counterfactual expected outcomes, which explain ATT are estimated as follows:

$$\begin{aligned}ATT = E(y_{1jit}|zero\ tillage = 1) \\ - E(y_{0jit}|zero\ tillage = 1)\end{aligned} \tag{8}$$

We estimate the econometric models in STATA 17 software. Before accomplishing the endogenous switching regression, we employ a falsification test to check the data for the instrumental variables.

6. Results and discussion

6.1. Determinants of zero tillage adoption

We only briefly discuss results from a probit adoption model since our primary interest is to study the resource-saving impact of zero tillage. We assess the average marginal effect from the probit model (Equation (2)). The model results are given in the first column of Table 2. The statistical significance of Wald-test shows that all coefficients for explanatory variables are not simultaneously equal to zero. The falsification test shows a significant correlation between the instrumental variable and zero tillage adoption decision, but not with production costs (Table C in Supplementary Materials). Hence, our selected instrument is plausible.

Table 2. Determinants of zero tillage adoption decision.

	Marginal effect (Probit model)	Standard error
Age of household head (years)	0.0003	0.002
Education level of household head (categorical, 1 = illiterate … 7 = university)	0.002	0.005
Female household head (dummy, 1 = female)	−0.008	0.016
Household head employed in agriculture (dummy, 1 = occupation as agriculture)	0.048*	0.025
Number of household members that can work in agriculture (above 10 and under 65 years old)	−0.003	0.009
Household head's ethnicity (dummy, 1 = Kyrgyz)	0.022	0.017
Asset index	−0.245***	0.068
Household owns a tractor (dummy, 1 = yes)	0.083	0.051
Household received remittances last year (dummy, 1 = yes)	−0.042	0.028
Household experienced a weather shock last year (dummy, 1 = yes)	0.034	0.022
Household experienced an agricultural shock last year (dummy, 1 = yes)	−0.043*	0.024
Amount of credits received by household last year (logarithm, US$)	0.002	0.003
Number of land plots owned by household	−0.021**	0.010
Number of livestock units owned by households	0.002	0.003
Distance from dwelling to plot (km)	0.004*	0.002
Household applied chemical fertilizers last year (dummy, 1 = applied)	−0.051***	0.019
Plot size (ha)	0.001	0.004
Plot under grains and legumes (dummy, 1 = yes)	0.009	0.017
Plot under vegetables (dummy, 1 = yes)	−0.062***	0.017
Plot under a mix of crops (grain, legumes and vegetables) (dummy, 1 = yes)	−0.026	0.034
Djalal Abad	−0.096***	0.022
Naryn	−0.042	0.028
Batken	0.012	0.022
Osh	−0.127***	0.024
Talas	−0.221***	0.040
Chuy	0.048**	0.023
Survey year (2019 = 1)	0.133***	0.015
Distance from dwelling to the main road (km)	0.019***	0.007
Joint significance of instrument: χ^2 (1)	7.68***	
Joint significance of time-varying covariates: χ^2 (11)	30.90***	
Wald χ^2 (38)	329.88***	
Pseudo R^2	0.168	
N	**2788**	

Note: ***, ** and * are significant at 1%, 5% and 10% level, respectively.

In summary, our results show that zero tillage is favoured by poorer households whose heads are employed in agriculture, have less plots, located in remote areas and do not apply chemical fertilizers. More specifically, household heads with agricultural employment are more likely to use zero tillage because they are exposed to knowledge about sustainable practices. Secondly, agricultural wages are lower than in other sectors (Atamanov & Van den Berg, 2012) and thus such households are more likely to opt for zero tillage rather than apply conventional tillage.

The relationship between the asset index of households and the adoption of zero tillage practices is significantly negative. This indicates that households with more assets, i.e. wealthier households, are likely to adopt conventional agricultural practices that depend on mechanized tractor services. This result is consistent with Ngoma (2018), who found that household assets reduce the likelihood of minimum tillage adoption. Furthermore, the model results show that households with more plots are less likely to adopt zero tillage. Applying chemical fertilizer can be also related to smallholders' wealth status, where poor smallholders have more challenges accessing this input and often cannot afford it. The model result shows that households who apply chemical fertilizers are less likely to adopt zero tillage.

Households located further away from their land plots and main roads are likely to adopt zero tillage. This is not surprising since it is expected that households located further away from their lands and roads are likely to have higher costs for accessing production inputs and machinery services and, thus, likely to switch to input-saving zero tillage. This result is in line with the findings of Jaleta et al. (2016) and Tessema et al. (2018), who found a positive relationship between plot distance and minimum tillage adoption. Remote location in rural area can be associated with lower wealth status.

Table 3. Impact of zero tillage adoption on production costs.

Outcome variable	Zero tillage (actual)	Conventional (counterfactual)	ATT (average treatment effect on the treated)
Total payment for hired labour (US$/ha) (ln)	0.380	0.255	0.125***
Machinery costs for land preparation and seeding (US$/ha) (ln)	1.264	1.524	−0.260***
Machinery costs for weeding (US$/ha) (ln)	0.542	0.529	0.013
Herbicide cost (US$/ha) (ln)	0.898	0.760	0.138**
Total cost (US$/ha) (ln)	2.049	2.217	−0.168*

Note: ***, ** and * are significant at 1%, 5% and 10% level, respectively.

Households that experienced agricultural shocks are less likely to adopt zero tillage. Other studies that considered agricultural shocks, e.g. waterlogging stress by Teklewold et al. (2013), droughts and floods frequencies by Wainaina et al. (2016), did not find its association with adoption of conservation tillage.

Finally, our result shows that the dummy variable of 'grain and legume production' is positive but statistically insignificant in relation to zero-tillage adoption. In contrast, there is a negative and statistically significant relationship between vegetable production and zero tillage adoption decision. It can be explained that some vegetable crops may not be planted in zero-tillage method.

The significant negative values of regional dummy variables show that the adoption of zero tillage among smallholders in Dlalal Abad, Osh and Talas regions is less likely than among smallholders in the Issyk Kul province. At the same time, there is no significant difference in likelihood of zero-tillage adoption between smallholders in the Issyk Kul province and in its neighbouring Naryn and Chuy regions and the Batken province. Various unobserved region-specific characteristics can explain these cross-regional differences in adoption of zero-tillage. For instance, higher population density and limited availability of land in Osh and Djalal Abad provinces (Zhunusova & Herrmann, 2018) can reduce smallholders' costs for hired labour in tillage operations and as a result lower the adoption rate of zero-tillage in these two provinces. Furthermore, agro-ecological zoning of the regions of Kyrgyzstan can stand for difference in crop portfolio, production specialization and tillage methods (Jalilova et al., 2019). Chuy, Talas and Issyk Kul regions are closer agro-ecologically to each other representing the northern regions. Djalal Abad, Osh and Batken represent southern agro-ecological regions encompassing the Fergana valley. Naryn region represents the central zone with vast alpine areas of mountains and valleys suitable for winter grazing and crop cultivation.

6.2. Resource-saving effects of zero tillage

Table 3 and Figure 2 present ESR-based average treatment effects of the adoption of zero tillage on the costs of labour, machinery and herbicide under actual and counterfactual conditions. The second-stage regression estimates (Equation (5)) are not discussed due to space limitation (Table D in Supplementary materials).

The result of the average treatment effect shows that per ha costs of machinery land preparation and seeding are lower for plots under zero tillage. According to Figure 2, adopting zero tillage will decrease land preparation and seeding costs by almost 23%. In other words, if households who applied zero tillage method would have decided not to use it, their per-hectare land preparation cost would be higher by 23%. This result is in line with the findings of Erenstein et al. (2008) who found negative effect of zero tillage on land preparation costs. Montt and Luu (2020) showed that the adoption of zero tillage reduces per ha costs for land preparation and threshing. Although per ha cost for mechanized weeding is higher for zero tillage plots, this difference is not statistically significant.

The adoption of zero tillage increases hired labour requirements. This is visible in the estimation results which show that payment for hired labour is higher for zero tillage plots than for plots under conventional tillage. The treatment effect of adoption of zero tillage on the hired labour costs per ha is 0.125. This means that households who used zero tillage spent 13% more for hired labour than their counterfactual. This result is consistent with findings by Montt & Luu (2020) and Teklewold et al. (2013) who found that conservation tillage increases household labour demand and associated labour costs.

The results of average treatment effect show a positive effect of zero tillage adoption on herbicide costs (Figure 2). Households spent 15% more on herbicides under zero tillage than under conventional

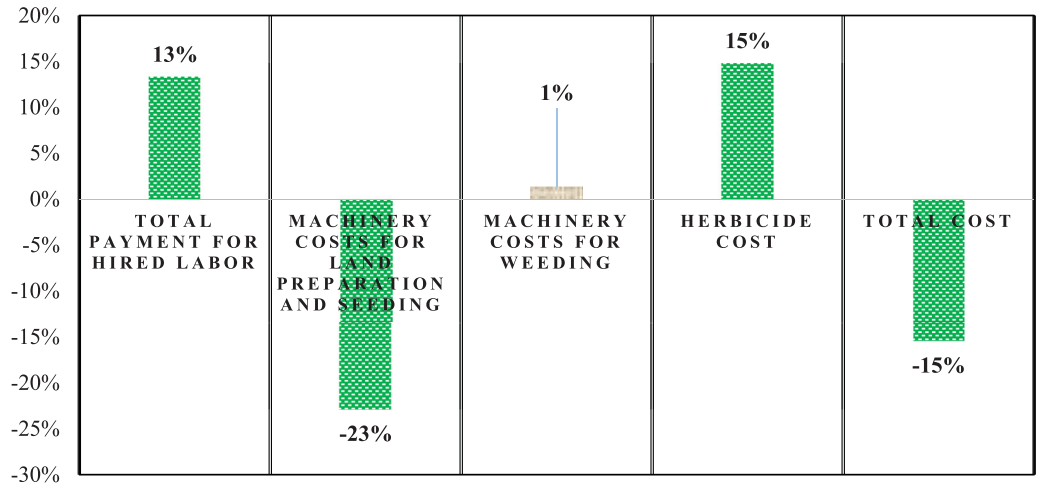

Figure 2. Average treatment effect of zero tillage adoption on production costs. Note: The effect of zero tillage on weeding costs is insignificant. For calculating the percentage difference of treatment effects from Table 3 we followed Asfaw et al. (2012) and used $100*(e^{ATT}-1)$ equation.

tillage. This is in line with findings by Teklewold et al. (2013) found that zero tillage adopters use more chemical pesticides and herbicides than nonadopters. Furthermore, Polo et al. (2022) showed that during first years, conservation practices in Kyrgyzstan can reduce fuel consumption and field operations, but can increase herbicide costs.

The above-mentioned positive effects of zero tillage adoption on labour and herbicide costs are related to the property of zero tillage demanding more labour resources and herbicides for weed management in the short term. This finding can be a sign that smallholders are lacking access to technologies specialized for conservation tillage and thus have to rely on family and hired labour. Merely implementing zero tillage practices is insufficient to reduce production costs. Its wider adoption requires a whole set of adjustments and specialized equipment such as seeding equipment modified to local conditions to manage and cut through crop residues, planting and weed control (Jaleta et al., 2019). Often adapting existing equipment for zero tillage purposes can be unfeasible and small size of farms impedes smallholders' investment in a specialized machine. The absence or high cost of adequate machines poses a significant obstacle to the widespread adoption of zero tillage practices among smallholders, hence limiting its future diffusion in Central Asia. Yigezu et al. (2018) showed that the provision of new technologies to smallholders via free trials and field days increases the speed and rate of adoption. Brazil's 'zero-tillage revolution' is an example that a variety of relatively low-cost zero-tillage equipment can be made available for resource-poor farmers (Ofstehage & Nehring, 2021). Furthermore, weeds are problematic particularly in the initial years after switching from conventional to zero tillage (Nichols et al., 2015). In fact, weed infestation and associated management costs are among major constraints for the widespread adoption of conservation tillage (Lee & Thierfelder, 2017).

In summary, zero tillage changes the agricultural practices on household plots by reducing demand for mechanized services for land preparation, seeding and weeding, but increasing demand for labour and herbicides. Despite the labour costs requirements in our case cannot be distinguished across season and field operations, the increased demand in herbicide use indicates the increasing demand for labour for weed control, e.g. for manual weeding or herbicide application, as well as for sowing period as a response to decline on machinery costs.

Finally, when considering the three cost components, the adoption of zero tillage has a negative and statistically significant effect on the aggregated input costs. The treatment effect of zero tillage adoption on the input costs is −0.168, which suggests that adopting zero tillage reduces households' production costs by almost 15% (Figure 2). Thus, the additional resource-saving benefits under zero tillage can compensate the increase in labour and herbicide costs.

6.3. Robustness check

We also performed propensity score matching (PSM) approach as a means of robustness check of the estimated average treatment effect results from the ESR model. Table E in Supplementary Materials shows the results of treatment effects based on PSM approach. The PSM approach shows that the impact of zero tillage on labour cost is positive, and for land preparation and for total costs are negative and statistically significant, as well as positive and statistically insignificant for weeding cost. Hence, the PSM results are consistent with the results discussed above in Table 3 and Figure 2. Compared to ESR approach, the PSM estimator showed positive but statistically not significant effect of zero tillage adoption on herbicide costs. This difference can be due to the better control of unobserved factors by the ESR estimation than by the PSM approach (Abdulai & Huffman, 2014; Khonje et al., 2018).

7. Conclusions

Using parametric and nonparametric empirical methods on two waves of longitudinal LiK data, we measured the adoption determinants and resource-saving effects of zero tillage among smallholders in Kyrgyzstan. Our findings suggest that zero tillage can be an attractive option for resource-poor smallholders located in remote areas. The probability of zero tillage adoption is positively associated with household head's employment in agriculture, and distance of household dwellings to household fields and main road. Furthermore, the probability of zero tillage adoption is negatively related to household wealth measured in asset index and number of household plots as well as fertilizer application. The findings suggest that zero tillage can generate tangible benefits to smallholders in terms of reducing input costs by 15%. However, zero tillage also affects the structure of production costs. As expected it reduces machinery costs for land preparation and seeding by almost 23%. As a result, of substituting the machinery services with external workers, zero tillage can increase hired labour costs by 13%. Zero tillage also increases herbicide costs by 15%.

Our findings produce several policy messages for promoting conservation tillage among smallholders in Central Asia. Policymakers and development community should promote zero tillage among smallholders as a cost-reducing option, particularly for machinery services. Zero tillage practice can be attractive for resource-poor smallholders located in remote rural areas and who lack access to inputs and machinery services. However, zero tillage adoption should not be promoted as a labour-saving or herbicide-reducing practice. Doing so will create false expectations among its potential adopters.

The observed labour-increasing property of zero tillage is particularly important for Central Asia where increasing shortage of agricultural labour might have adverse effects if zero tillage comes with higher labour demand. A solution should come by identifying and developing specialized machinery and implements suitable for smallholder that would substitute labour. Wider adoption of zero tillage requires government initiatives to make conservation tillage machinery available to smallholders. Promoting hiring services of zero tillage machinery and supplying zero tillage implements on subsidized rates through soft loans for smallholders would swiftly expedite its adoption in Kyrgyzstan.

Our findings show that policymakers should also be aware that zero tillage expansion can increase herbicide use by smallholders, thus producing additional environmental damage and resulting in higher health costs. The trade-off between farm-level suitability and benefits from a societal perspective requires that the government and research organization take more actions to introduce effective alternatives for weed control.

Finally, our findings suggest that zero-tillage expansion can be suppressed when labour and herbicides become more expensive or prices for machinery services and fuel go down. Thus, expanding the adoption of zero tillage practices among smallholders in Central Asia will require supporting policy instruments such as greater knowledge dissemination, pilots with lead farmers, demonstration and free trials, and further tailoring inputs and machines to local conditions.

Our study has several limitations related to the dataset. First, our data does not tell us how long farmers have been applying zero-tillage. Thus, the determinants we estimated should be interpreted as underlying factors for current or short-term adoption of zero-tillage rather than its continuous use. For instance, the production cost effects can be different if farmers practice rotational tillage which we cannot observe from our data. As the LiK plot-level data allows recording multiple crops of different species and one tillage method, we cannot distinguish the

production effects and adoption decisions across crop species. Another limitation of our dataset is that it does not distinguish labour efforts between household members and hired workers, but only records hired labour costs. The LiK survey does not inquire information about actual reasons of (non)adopting zero-tillage beyond pure cost-benefits, but also related to agronomy and soil quality. Finally, our study does not capture the entire long-term impact of zero tillage adoption on production costs. Thus, the results reported here should be interpreted with a caution.

Notes

1. https://www.no-tillfarmer.com/articles/10906-worldwide-no-till-acres-increase-93-in-10-years
2. According to the National Bank of Kyrgyzstan, an average exchange rate in 2016 was 1$ = 69.90 KGS and in 2019 1 US$ = 69.79 KGS.
3. Total livestock units (TLU) is calculated based on livestock unit (LU) coefficients according to the following sources: (1) https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Livestock_unit_(LSU) and (2) http://adlib.everysite.co.uk/adlib/defra/content.aspx?id=000il3890w.198awldohj69f3#nix.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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