

The adoption of cotton combine services and farm technical efficiency: evidence from Kazakhstan and Uzbekistan

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277

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Abstract

Purpose – This study examines the adoption of cotton combine services and its impact on farm technical efficiency in Kazakhstan and Uzbekistan. The research aims to determine whether mechanisation influences productivity and economic output at the farm level.

Design/methodology/approach – Using farm-level data from 511 cotton growers in Kazakhstan and Uzbekistan collected in 2019, this study employs stochastic frontier analysis to measure potential output and technical inefficiency among cotton farmers. The analysis includes a translog functional form to account for the use of cotton combine services and other farming variables.

Findings – The findings indicate that while mechanisation through cotton combines can potentially increase technical efficiency by optimising the harvesting process, the benefits are not uniformly experienced across all farms. Variations in farm characteristics, such as labour availability and existing agricultural practices, influence the efficiency of technology adoption. Institutional factors and historical legacies also play a significant role in the adoption and impact of mechanisation.

Research limitations/implications – The study is based on cross-sectional data from 2019, and the findings may not capture longer-term trends or recent developments in mechanisation policies in the study countries.

Originality/value – This research provides a nuanced understanding of the conditions under which cotton combine services enhance or hinder technical efficiency. It highlights the necessity for carefully tailored

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policies for mechanisation, especially in Uzbekistan, where rural labour is abundant and predominantly female. The study contributes to the broader discourse on agricultural mechanisation in developing countries by focusing on the specific context of Central Asia.

Keywords Central Asia, Cotton harvest mechanisation, Stochastic frontier analysis, Technology adoption

Paper type Research paper

Introduction

The prevailing view in development economics suggests that adopting technologies that enhance agricultural productivity and free up labour to be reallocated to other economic sectors is crucial for economic growth (Gollin *et al.*, 2002; Pardey and Alston, 2021). Mechanisation of various field operations and agricultural processes, in particular, can improve agricultural labour productivity and is a standard feature of modern agriculture in developed countries (Hailu, 2023). However, the impact of mechanisation on farm efficiency in developing countries is still hotly debated. Some studies have shown that mechanisation can positively affect farm technical efficiency (Vortia *et al.*, 2021; Huan *et al.*, 2022). However, other research indicates that mechanisation can have negative effects on production efficiency due to increased costs associated with managing and supervising more complex machinery, particularly in regions with low-wage labour markets (Jayasuriya *et al.*, 1986; Coelli and Battese, 1996).

These debates are also relevant to the application of combine services in mechanised cotton harvesting. While some argue that cotton harvest mechanisation improves labour productivity among cotton farmers, the introduction of the complex technology necessitates new skills and adjustments in farming practices, which in turn can reduce overall technical efficiency of cotton production (Schmitz and Moss, 2015). According to Townsend (2005), approximately one-third of global cotton production has been harvested by cotton combines in 2014. Only in Australia, Brazil, Greece, Israel, South Africa, Spain, and the US, is nearly all of cotton production mechanically harvested. In Argentina, Bulgaria, Colombia, Kazakhstan, Mexico, and Turkey, between 60 and 90% of cotton production was harvested by cotton combines. The slow adoption of mechanisation in cotton harvesting reflects the complex technical and economic requirements of this technology. Its adoption has been particularly gradual due to the need for adapted crop cultivation techniques, appropriate cotton seed varieties, new expensive chemical inputs, and reliable irrigation systems. Furthermore, the institutional arrangements, described by Whatley (1985) as institutional inertia, such as labour supply structures, labour contracting, and the supply of a rural labour force, slowed down the adoption of cotton machine harvesters in the south of the USA.

Central Asia has significantly lagged behind the United States in mechanising cotton harvesting (Pomfret, 2002). The Soviet government made large public investments available for cotton combine technology aimed at improving cotton production efficiency. Despite the policies pushing for mechanisation, manual labour remained more cost-effective due to the abundance of cheap labour, ineffective policy implementations and the relative inefficiency of available machinery (Pomfret, 2002). In the 1980s, the use of cotton combines in Central Asian republics even plummeted, and continued falling after the collapse of the Soviet Union (Pomfret, 2002). Key reasons for this included poor planning, where cotton harvesters were introduced prematurely and hastily without adequate consideration of the economic implications for farmers and rural workers. Additionally, resistance from collective farm managers who relied on abundant and cheap rural labour hindered a wider adoption of cotton harvest mechanisation (Pomfret, 2002). Cotton managers resisted mechanisation, believing that machine-harvested cotton was of lower quality, which resulted in lower prices set up by parastatal ginneries, thereby reducing the net revenue of cotton cultivation. The introduction of a price premium for mechanically harvested cotton in 1970 did little to

incentivise a shift from manual cotton picking to the mechanised harvesting. This inertia in adopting cotton combines was also supported by gender and social hierarchies existing in rural Central Asia that valued the labour of men differently from that of women and children (Keller, 2015).

The situation of the low adoption of cotton combines in Central Asia has been persistent following the collapse of the Soviet Union. Among the post-Soviet Central Asian countries, Kazakhstan's cotton-growing farmers, who benefited from the liberalisation of the cotton sector in the mid-1990s, have the highest rate of adopting cotton combines in the region, with approximately 60% of their cotton harvest now mechanised (Townsend, 2005). Compared to Kazakhstan, the Uzbek government maintained stricter control of the cotton sector, and particularly over the decisions of cotton growers, and mobilised labour for cotton picking, leaving less political will to mechanise cotton harvesting. Only recently did agricultural sector reforms announced in 2017 further push the political objective of the rapid mechanisation of cotton harvesting in Uzbekistan (Djanibekov *et al.*, 2024). The mobilisation of cotton pickers has been prohibited, and new cotton combines have been imported or produced locally. Evidence summarised by Pomfret (2002) and reported in Petrick and Djanibekov (2016) and Swinkels *et al.* (2016) show that Uzbek cotton farmers lack experience in mechanised cotton harvesting and expect that such technology can potentially harm their cotton revenue and technical efficiency.

The empirical evidence from Kazakhstan, where cotton sector reforms began in the 1990s leading to significant liberalisation and reduced state intervention, provides important context. By 2018, some 18,000 individual farmers with an average size of 10 hectares were engaged in cotton cultivation. These reforms have tied producer prices to the global market, facilitated by the entry of private investors in the ginning and trading sectors, thus creating a competitive market environment that benefits even small-scale cotton growers (Pomfret, 2008; Petrick *et al.*, 2017). In Kazakhstan, the use of cotton combine services is primarily driven by labour availability and the cost of manual picking. In contrast to Kazakhstan, up until recently the forced mobilisation of cotton pickers from public workers and students from urban areas and rural female workers helped keep the labour costs of manual picking low in Uzbekistan, aligning with Whatley's Institutional Hypothesis. In 2014, this workforce comprised approximately 14–20% of the total workforce in Uzbekistan (Swinkels *et al.*, 2016). Thus, for Uzbekistan, transitioning from manual cotton picking to mechanised harvesting has important meaning for the country's international image, reflecting policies aimed at eliminating forced labour in agriculture.

These concerns present an opportunity to empirically examine the relationship between mechanisation and technical efficiency for understanding the broader impacts of mechanisation on the cotton sector and for informing policy in regions with similar agricultural reforms. While highlighting the difficulties in assessing the true impact of mechanised cotton harvesting, these studies typically applied data aggregated at the regional or national level. There is a notable lack of an evidence using farm-level data. This study aims to address these gaps by examining how cotton harvest mechanisation affects the technical efficiency of cotton-growing farmers in Central Asia. By analysing farm-level survey data from 511 cotton growers in Kazakhstan and Uzbekistan collected in April 2019, this paper seeks to better understand the specific impacts of mechanisation on farm technical efficiency. We use a stochastic frontier analysis (SFA) with a translog functional form, chosen for its flexibility (Skevas, 2024). SFA aims to determine the maximum output possible with a given set of farming inputs and technology (Kumbhakar and Lovell, 2000). The analysis measures the total cotton revenue attainable given a standard set of farming variables. We directly account the variable standing for the use of cotton combine services in our technical inefficiency model to address the debate on the impact of cotton harvest mechanisation on the efficiency of cotton cultivation.

This paper is structured as follows. The second section details the data and methods used in this research. The third section presents the conceptual and empirical frameworks applied in our analysis. The fourth section discusses the results of our models and outlines key considerations for policymakers in Uzbekistan regarding the promotion of cotton harvest mechanisation. The final section concludes the paper, summarising our findings and their implications for agricultural policy and practice in the region.

Data and methods

Survey data

We used data from a farm survey conducted in the AGRICHANGE [1] project in the Turkistan and Samarkand provinces in March–April 2019. In Kazakhstan, Turkistan is the only administrative region (Oblast) [2] that produces cotton. In Uzbekistan we selected the Samarkand region, which also has a long tradition of cotton cultivation. Within each province, two districts were randomly selected based on their specialisation in cotton production: the Maktaaral and Shardara districts in Turkistan, and the Pastdargam and Payarik districts in Samarkand. For the Kazakhstan sample, three villages were chosen in each district, and 50 farm managers were randomly selected from lists for each village. In Samarkand, farm managers were randomly selected from a district-level farm list.

The interviewed farmers provided detailed responses to a questionnaire covering their socio-economic characteristics, as well as the characteristics of their farms, farm fields, crop cultivation practices, and location attributes. Additionally, a separate section of the questionnaire addressed their use of cotton combine services. As this study was confined to the cotton-growing regions, we therefore exclusively used a sample size of $N = 511$ out of full data sample $N = 963$; hence, we did not consider the remaining observations if they did not cultivate cotton crops.

To account the variable of crop diversification, we constructed a Simpson Diversity Index. The index is empirically accepted as a valid representation of crop diversification/specialisation in previous studies dealing with productivity and efficiency analysis (Chen *et al.*, 2009; Conrad *et al.*, 2017). The index ranges from 0 to 1, where a value closer to 0 shows that a farm specialises in cotton monoculture, and a value closer to 1 shows crop diversification, i.e. whether a farmer grows other crops in addition to cotton.

Econometric model

The present study employed SFA with translog functional form, with the estimation being based on translog functional form due to its flexibility (Skevas, 2024). Following, O'Donnell *et al.* (2008), we assumed farms may adopt a given technology based on different farms and farmer-specific attributes. In addition, due to an ongoing debate on the pros and cons of using a cotton combine during cotton harvesting in Central Asia (Pomfret, 2002), we included the cotton combine variable in the inefficiency model. We measured the total cotton revenue that could be obtained for the standard set of farming variables. Thus, depending on a standard set of farming variables, farms were expected to operate at various points along their production frontier. Kumbhakar and Lovell (2000) state that the distinguishing feature of SFA is to envisage how maximum output could be obtained with a standard set of farming variables and a given technology. Farmers are technically efficient when producing on their production frontier, whilst if producing below their production frontier they are termed as technically inefficient. Following Aigner *et al.* (1977), the classical SFA is defined below:

$$y_i = f(x_i; \beta) \exp(-\mu_i) \quad (\mu_i \geq 0)$$
$$y_i = f(x_i; \beta) \exp(v_i) \cdot \exp(-\mu_i) \quad (v_i \leq 0) \text{ and } (\mu_i \geq 0)$$

$$y_i = f(x_i; \beta) \exp(v_i - \mu_i) \quad (1)$$

Where v_i is the error component of a noise effect on the model output by exogenous shocks out of farmers' control (e.g. extreme weather events, pest outbreaks) and assumed *i.i.d* as $N(0, \sigma_{v_i}^2)$. In addition to noise effect, μ_i is the error term with a non-negative technical inefficiency component and is assumed to be distributed independently of v_i and to satisfy $\mu_i \geq 0$. In addition, μ_i is the attributes related to farms and farmers specifically and assumed to follow half-normal distribution $N(|0, \sigma_{\mu_i}^2|)$.

The models include total cotton revenue/ha and a set of farming variables including country dummy and soil quality index as shifter variables and determinants of technical inefficiency. A comparable model formulated by [Bilal et al. \(2022\)](#) for the cotton producers has been assessed. We merged the Uzbek and Kazakh farms dataset of a single cross-section, and, using the maximum-likelihood method, we specified the following translog functional form, defined as:

$$\ln Y_i = \beta_0 + \sum_{j=1}^5 \beta_j \ln X_{ji} + 0.5 \sum_{j=1}^5 \sum_{k=1}^5 \beta_{jk} \ln X_{ji} \ln X_{ki} + \sum_{j=1}^2 \beta_{sj} S_{ji} + v_i - \mu_i \quad (2)$$

Where Y = total cotton revenue in USD/ha, X = land sown under cotton, total permanent labour (both family and permanently hired), machinery costs/ha, oil costs/ha, fertiliser (NPK) costs/ha and S = soil quality, and country dummy. In addition, following, [Wang and Schmidt \(2002\)](#), we employed the model for technical inefficiency expressed below:

$$\sigma_{\mu_i}^2 = \exp\{T_i \delta_j\} \quad (3)$$

Where term $\sigma_{\mu_i}^2$ is the variance of technical inefficiency for the i th farm and T_i is a vector ($M \times 1$) of technical inefficiency variables (cotton combine dummy, agronomic information received from a farmers' union, farm distance from a water head, the Simpson diversity index, and a country dummy) that could influence the technical inefficiency of farms. δ_j is a ($1 \times M$) vector of parameters estimated that could capture the potential effect of included inefficiency variables associated with farm technical inefficiency and μ_i is non-negative such that $\mu_i(T_i \delta_j) \geq 0$. Hence, our final model is specified below:

$$Y_i = f(X_i s + S_i s) + v_i - \mu_i(T_i \delta_j), (\mu_i(T_i \delta_j) \geq 0) \quad (4)$$

Following, [Battese and Coelli \(1988\)](#), we estimated the i^{th} farm technical efficiency scores as provided below:

$$TE_i = \exp(-\mu_i) \quad (5)$$

Results and discussion

Description of the translog and Cobb-Douglas SFA production model variables

The sampled farmers' distribution with respect to country and mean of cotton revenue/ha [3] in each country is presented in [Table 1](#). It is evident from [Table 1](#) that the mean of the cotton revenue/ha is approximately 10% higher in Kazakhstan than in Uzbekistan. The guidelines for considering production and inefficiency variables were taken from the recent literature regarding productivity and farm mechanisation ([Karimov, 2014](#); [Wu, 2020](#); [Bairagi and Mottaleb, 2021](#)).

Table 2 presents descriptive statistics and two-sample mean-comparison tests between the variables observed in our sample of farmers in Uzbekistan and Kazakhstan used in the SFA production function and the inefficiency model. 27% of respondents reported using combines for harvesting their cotton in 2018, with this practice being exclusively observed among the Kazakhstan respondents. Specifically, 54% of the sampled Kazakh farmers used cotton combines, in contrast to none in Uzbekistan.

The statistics indicate that across the two country settings, cotton growers in our dataset have statistically significant differences in all variables apart from the total number of workers, a farm being located near a water source head, and the distance of a farm from dwellings. These results reveal distinct cotton production practices, economic conditions and socio-demographic characteristics between cotton growers in Kazakhstan and Uzbekistan.

The average age of the respondents is 45.3 years, with a standard deviation of 11.9 years, highlighting a wide range of ages from 21 to 79 years. The respondents in Uzbekistan were slightly younger (43.5 years) compared to those in Kazakhstan (47.2 years), with a significant difference of -3.71 years ($p < 0.01$). The education level of the farmers shows an average of 5.8 years with a relatively narrow spread ($SD = 1.69$), indicating a range from minimal to moderate educational attainment (1–8 years). Uzbekistani farmers have a higher average of 6 years of education compared to 5.5 years in Kazakhstan.

The size of cotton cultivation areas varies significantly, with an average of 15.9 hectares and a standard deviation of 14.6 hectares, spanning from as small as 1 hectare to as large as 100 hectares. Uzbekistan farmers operate larger areas (mean = 20.6 hectares) than their Kazakhstan counterparts (mean = 11.1 hectares). The labour force involved in cotton farming comprises, on average, 0.77 female labourers ($SD = 3.46$) and an overall average total labour force of 6.57 workers per farm ($SD = 9.03$), indicating a broad spectrum of labour use ranging from 1 to 150 workers. Despite the farm size differences, Uzbekistan farmers employ fewer female workers (mean = 0.24) than farmers in Kazakhstan (mean = 1.3). However, the total labour used does not significantly differ between the two countries.

The financial costs of cotton production detailed by the average costs per hectare for nitrogen fertiliser (84.8 USD), phosphorus (26.91 USD), potassium (3.6 USD), and the aggregate costs for NPK (115.3 USD) suggest substantial variability in fertiliser expenditure among farmers. These input costs show a significant difference, with Uzbekistani farmers having two times higher fertiliser costs (mean = 105.2 USD for nitrogen and 44.3 USD for phosphorus) than their Kazakhstan counterparts (mean = 64.3 USD for nitrogen and 9.4 USD for phosphorus).

Furthermore, machinery and oil costs per hectare average 191.7 USD and 47.5 USD, respectively, with machinery costs per hectare found to be much higher in Kazakhstan (mean = 312 USD) compared to Uzbekistan (mean = 71.9 USD). In contrast, oil costs from the use of farmers' own machinery was found to be higher among Uzbekistan farmers. These two variables come from our observation that cotton-growing farmers in Kazakhstan are much smaller than in Uzbekistan. Thus, they rely on hired machinery more, whereas cotton-growing farmers in Uzbekistan use more of their own machinery for which they purchase fuel.

Table 1.
Frequency distribution
of the sampled farmers

Country	Frequency	Percent	Cumulative	Mean of cotton revenue/ha (USD)
Uzbekistan	256	50.10	50.10	925.86
Kazakhstan	255	49.90	100.00	1025.12
Total	511	100.00		

Source(s): Table created by authors

Table 2.
Descriptive statistics
and two-sample mean
comparison test
between Kazakhstan
and Uzbekistan sub-
samples

Variables	Full sample (N = 511)				Uzbekistan (N = 256)		Kazakhstan (N = 255)		Diff
	Mean	SD	Min	Max	Mean	SD	Mean	SD	
<i>SFA production function</i>									
Age of the respondents (years)	45.37	11.86	21	79	43.51	10.17	47.23	13.10	−3.71***
Education of the farmers (years)	5.76	1.69	1	8	6.02	1.58	5.50	1.76	0.52***
Cotton area in hectares (ha)	15.87	14.65	1	100	20.64	15.14	11.08	12.45	9.55***
Female labour (number)	0.77	3.46	0	50	0.24	1.42	1.30	4.64	−1.06***
Total labour (number)	6.57	9.03	1	150	6.81	3.51	6.33	12.30	0.47
Nitrogen fertiliser costs/ha (USD)	84.80	104.79	0	976.34	105.17	134.42	64.34	55.42	40.82***
Phosphorus costs/ha (USD)	26.91	37.38	0	367.31	44.32	36.87	9.42	28.78	34.89***
Potassium costs/ha (USD)	3.57	11.22	0	138.37	4.93	8.60	2.19	13.23	2.73**
Total NPK costs/ha (USD) ^a	115.28	113.11	1.02	976.34	154.43	134.67	75.97	66.23	78.45***
Machinery costs/ha (USD)	191.70	363.73	0.04	2702.70	71.85	70.33	312.01	481.32	−240.16***
Oil costs/ha (USD)	47.51	36.07	1.37	405.40	50.34	19.33	44.68	47.12	5.66*
Cotton revenue/ha (USD)	975.39	388.86	21.87	4,000	925.86	295.93	1025.13	459.06	−99.25**
<i>Inefficiency model</i>									
Farm distance from dwelling (km)	5.76	5.80	0	40	5.48	6.23	6.04	5.32	−0.56
Simpson diversity index	0.32	0.22	0	0.66	0.46	0.08	0.18	0.22	0.28***
Soil quality (fertile = 1; otherwise = 0)	0.48	0.44	0	1	0.57	0.41	0.39	0.45	0.18***
Agronomic information received from farmers' union (yes = 1; no = 0)	0.49	0.50	0	1	0.72	0.44	0.25	0.43	0.47***
Farm location to water source head (close = 1; otherwise = 0)	0.24	0.42	0	1	0.24	0.43	0.23	0.42	0.006
Farmer used cotton combine (yes = 1; no = 0)	0.27	0.44	0	1	n.a.	n.a.	0.54	0.49	n.a.
Note(s): The level of significance is *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$									
^a Aggregate costs of nitrogen, phosphorus, and potassium fertilisers									
Source(s): Table created by authors									

The revenue from cotton per hectare averages out at 975.4 USD (SD = 388.9), with a wide range of profitability from 21.87 to 4,000 USD, underscoring the economic variability within the sample. The Simpson diversity index averages at 0.3 (SD = 0.2) with a range from 0 (a farmer cultivating only cotton) to 0.66, reflecting small crop diversity within the sample. About half of the interviewed farmers had fertile farmland. Uzbekistan farmers have a higher crop diversity index (mean = 0.5) and better soil quality (mean = 0.6) compared to Kazakhstan farmers (mean = 0.2 for diversity and 0.4 for soil quality), indicating significant variances in the cropping portfolio and environmental conditions in the two country settings.

About half of the respondents received agronomic information from state farmers' unions, with the majority of responses coming from farmers in Uzbekistan where the government pays high attention to cotton cultivation. In Uzbekistan, about three quarters of farmers reported being informed via a farmers' union, whereas this is three times lower in Kazakhstan. The presence of farmers' unions as a source of agricultural information is notably higher in Uzbekistan (mean = 0.72) than in Kazakhstan (mean = 0.25), highlighting

a difference of 0.47 ($p < 0.01$), which suggests varying degrees of institutional engagement and support for farmers in the two countries. The distance from the farm to a farmer's home averages 5.8 km (SD = 5.8), with distances ranging up to 40 km and being almost equal on average in the two settings.

Estimates of the inefficiency models

The determining factors of technical inefficiency are presented in Table 3. The signs of estimated coefficients are crucial for constructing a meaningful economic interpretation and the determinants of technical inefficiency have exhibited the expected signs.

The country dummy variable in the inefficiency model exhibited a positive sign with +0.73 magnitude, indicating that farmers in Uzbekistan were generally more efficient in cultivating cotton than those in Kazakhstan. This could be attributed to the strategic importance of cotton in Uzbekistan compared to Kazakhstan, where cotton has more local meaning and is cultivated at a smaller scale only in one administrative region. The cotton sector in Uzbekistan, where the government has made it a priority, is supported by public cotton research infrastructure and extension services tailored for cotton growers, and the government's support and prioritisation of cotton growers through subsidies and agricultural inputs (Lombardozi, 2019).

The use of cotton combines (−0.34) and the crop diversification index (−1.51) show negative signs, meaning that farmers can decrease their inefficiency if they practice a crop diversification strategy and employ mechanised cotton harvesting. Specifically, the negative coefficient for cotton combines indicates that their use is associated with reduced inefficiency, aligning with the hypothesis that mechanisation, such as the use of cotton combines, enhances farm productivity and technical efficiency. Consistent with the findings of Faulkner *et al.* (2011) and Fite (1980), the adoption of mechanisation, including the use of cotton combines, is associated with reduced inefficiency and enhanced productivity in cotton farming by a more efficiently organised harvesting process compared to conventional manual cotton picking. Likewise, cotton combines may aid the farms deprived of excessive labour. The sign of interaction terms of labour and farm machinery costs/ha is positive, suggesting a complementary but insignificant effect between these inputs. Similarly, Chen *et al.* (2009) found a significant complementary effect between the capital and labour if farms were located in the regions characterised by low labour input use in China.

The negative sign associated with crop diversification means that cotton growers diversifying their cropping portfolio exhibit relatively higher efficiency levels. This supports the idea that diversification strategies can mitigate inefficiency, which is in line with findings from Coelli and Fleming (2004), Rahman (2009), Manjunatha *et al.* (2013), and Mzyece and Ng'ombe (2021), who also found efficiency gains from crop diversification. Although farm specialisation, such as in cotton monoculture, may offer cotton growers increased technical efficiency in the short term

Inefficiency variables	Coefficient	Std. err
Country dummy (Kazakhstan = 1, Uzbekistan = 0)	0.735***	0.258
Use of cotton combine (1/0)	−0.344*	0.192
Agronomic information from farmers' union (1/0)	0.367**	0.189
Farm location to water source (1/0)	−0.226	0.158
Simpson diversity index	−1.513***	0.431
Constant	−0.795***	0.279

Table 3.

Estimates of the
inefficiency model

Note(s): The level of significance is *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source(s): Table created by authors

(Chavas, 2008), it degrades land quality in the long run via water depletion, diminished soil fertility, and issues related to waterlogging and salinity (Toderich *et al.*, 2007).

Receiving agronomic information from local farmers' union increases farmers' inefficiency, indicating that the quality of existing public infrastructure specialised in cotton research and extension in Kazakhstan and Uzbekistan is of low quality and harms cotton growers' performance. The role of private and public institutions, for example, membership in a cooperative and/or private and public extension services, is often related with improved technological adoption and enhancing farm technical efficiency (Dinar *et al.*, 2007; Tipi *et al.*, 2009; Biswas *et al.*, 2021); however, in the present case, there is a hint of farmers' unions being deprived of mandatory training from agricultural extension perspectives (Takeshima *et al.*, 2024). Akouwerabou (2023) highlight how skilled agricultural technical advisers affect technical efficiency positively. Likewise, Djuraeva *et al.* (2023) found that, due to its poor current conditions, the public extension services inversely affect the technical efficiency of Uzbekistan farmers. Alternative channels of information dissemination, such as peer-to-peer knowledge exchange among farmers or interactions with neighbouring agricultural practitioners and specified training in agronomy, can mitigate this inefficiency (Bilal *et al.*, 2022; Takeshima *et al.*, 2024).

The mean of technical efficiency for the entire sample of cotton growers is 0.65 (also reported in the last row of Table 6). This means that 35% of the sampled farmers can enhance their efficiency through the use of a cotton combine and practicing crop diversification. Our average sample of technical efficiency is much lower than the one estimated by Karimov (2014), who found that Uzbekistan cotton-growing farmers had a technical efficiency of 0.84. However, a separate model for exclusive Uzbek [4] farmers revealed a TE of 0.71. In addition, we conducted a separate analysis using data from Kazakhstan sample of farmers ($N = 255$). The technical efficiency value was 0.63, indicating slightly lower efficiency scores compared to the pooled estimates (see Appendix Table A1).

The technical efficiency interval reported in Table 4 indicates that almost 5% of the sampled farmers have a technical efficiency of less than 30% and generated an average cotton revenue of 317 USD/ha. The highest technical efficiency score above 90% is observed for 33 farmers (6.5% of observations). Their average cotton revenue was 1,693 USD/ha, which is five times higher than the cotton revenue of farmers with technical efficiency scores below 30%. The majority of respondents have technical efficiency within an interval between 60–90% and an average revenue of 1,120 USD/ha. Table 4 shows a clear trend that the mean cotton revenue per hectare increases with the increase in technical efficiency. This suggests that improvements in technical efficiency in cotton farming can lead to significantly higher revenues, underscoring the economic benefits of investing in practices and technologies that enhance technical efficiency.

Tests of the null hypothesis of the translog versus Cobb-Douglas functional form

Table 5 presents a few relevant tests of the null hypothesis. The first row in Table 5 rejects the null hypothesis of employing the Cobb-Douglas functional form over the translog at a 5%

Technical efficiency interval	Frequency	Percent	Cumulative	Mean of cotton revenue/ha (USD)
>0 < 30	25	4.89	4.89	317.10
>30 < 60	166	32.49	37.38	680.43
>60 < 90	287	56.16	93.54	1120.74
>90 < 100	33	6.46	100.00	1693.72
Total	511	100.00		975.39

Source(s): Table created by authors

Table 4.
Tabulation of technical
efficiency and the
means of cotton
revenue/ha with
respect to technical
efficiency interval

level of significance. Therefore, the translog functional form is a valid representation for estimating the productivity and inefficiency to yield unbiased estimates of the included parameters. This rejection translates to second-order coefficients being statistically different than zero. The third row of Table 5 presents how the null hypothesis of the coefficients of the cotton combine is zero in the inefficiency model, strongly rejecting a 1 % level of significance. Hence, the unrestricted model with a cotton combine in the inefficiency model displays significant importance in explaining the inefficiency of the sampled farmers. The fourth row of Table 5 presents the null hypothesis so that no effects of the determinants of inefficiencies were present and rejected at a 1 % significance level. Hence, simultaneously approximating the estimates of production and inefficiency variables by translog functional form was justified.

The estimated parameters of the translog and Cobb-Douglas SFA production models are reported in Table 6. We present here the production elasticities of the main model (TLi). Input elasticities of fertiliser costs NPK/ha (+0.34) and the square term of fertiliser costs NPK/ha (−0.076) were highly significant compared with other input elasticities. The negative sign of the square term of fertiliser costs/ha implies that fertiliser costs/ha have decreasing marginal returns. This implies that with the significantly high application rates of chemical fertilisers, soil quality can be harmed, resulting in a reduction in farm revenue. Table 2 presents an apparent difference among the sample farmers' trends towards fertiliser costs (an average of 115 USD/ha with a maximum standing at 976 USD/ha).

The partial production elasticity of the area sown under cotton was insignificant and the square term of the cotton area was significant and positive, implying that the farm revenue increasing effect rises with more area sown under cotton. Such a relationship can be true for cotton cultivation, which has the production technology available to support larger farm sizes. Furthermore, larger farms have better access to production inputs such as irrigation water and fertilisers.

Similarly, the square term of oil costs/ha was significant and positive, indicating that the farm revenue-increasing effect increases with increasing oil costs/ha. Noticeably, the interaction term of oil costs/ha with machinery costs/ha were significant and negative, indicating a substitution effect between oil costs/ha and machinery costs/ha. This effect indicates how farmers spend less on oil with each additional USD incurred on machinery costs/ha. The soil quality dummy and country dummy as a shifter variable appears to be highly significant, pointing towards how good quality soil supports higher farm revenues. In contrast to the estimated country inefficiency variable, the SFA findings show that farmers originating from Kazakhstan exhibit higher levels of productivity. This can be explained by the cotton sector in Kazakhstan being more market-oriented compared to Uzbekistan and farmers receiving higher economic incentives, such as cotton prices from private ginneries, to increase physical outputs (Pomfret, 2021; Petrick *et al.*, 2017).

Table 5.
Tests of the null
hypothesis of the SFA
translog production
function

Null hypothesis	Log likelihood	Test statistics	C.V.	d.f.	Decision
H0: Cobb – Douglas (CD vs TL)	−256.69	26.29**	24.38	15	Rejected
H0: Cobb – Douglas (CDi vs TLi)	−235.47	24.21*	21.71	15	Rejected
H0: No effects of cotton combine	−235.47	55.35***	9.50	1	Rejected
H0: No effects of determinants of inefficiencies	−235.47	42.44***		5	Rejected
H0: No inefficiency component	−247.93	−17.09***			Rejected

Note(s): C.V. is a critical value for the specified degrees of freedom (d.f.), taken from Kodde and Palm (1986).
The level of significance is *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$
Source(s): Table created by authors

Frontier	Coef. TLi		Coef. TL		Coef. CDi		Coef. CD	
Ln cotton area	-0.174	(0.224)	-0.1889	(0.214)	-0.016	(0.017)	-0.007	(0.018)
Ln labours	0.030	(0.208)	0.102	(0.190)	-0.059**	(0.024)	-0.063***	(0.023)
Ln oil costs/ha	-0.221	(0.170)	-0.302*	(0.163)	0.058***	(0.021)	0.047**	(0.021)
Ln machine costs/ha	0.096	(0.111)	0.124	(0.105)	-0.023*	(0.013)	-0.022*	(0.013)
Ln fertiliser costs NPK/ha	0.374***	(0.147)	0.499***	(0.147)	0.120***	(0.029)	0.137***	(0.029)
Soil quality (fertility)	0.077**	(0.036)	0.117***	(0.037)	0.088**	(0.037)	0.126***	(0.037)
Country dummy	0.336***	(0.056)	0.268***	(0.052)	0.351***	(0.048)	0.264***	(0.044)
Ln area sq	0.050*	(0.030)	0.050	(0.033)				
Ln labour sq	0.015	(0.046)	0.010	(0.043)				
Ln oil costs/ha sq	0.074**	(0.035)	0.066**	(0.034)				
Ln machine costs/ha sq	0.001	(0.007)	-0.004	(0.007)				
Ln fertiliser costs NPK/ha sq	-0.076**	(0.034)	-0.100***	(0.034)				
Ln area*lab	0.000	(0.026)	-0.001	(0.026)				
Ln area*oil	0.048	(0.033)	0.060*	(0.032)				
Ln area*mach	-0.018	(0.017)	-0.017	(0.016)				
Ln area*ferti	-0.013	(0.031)	-0.017	(0.030)				
Ln lab*oil	-0.035	(0.029)	-0.039	(0.028)				
Ln lab*mach	0.004	(0.018)	0.003	(0.016)				
Ln lab*ferti	0.001	(0.041)	-0.009	(0.039)				
Ln oil*mach	-0.031**	(0.015)	-0.026*	(0.014)				
Ln oil*ferti	0.018	(0.034)	0.032	(0.034)				
Ln mach*ferti	0.008	(0.021)	0.001	(0.020)				
Constant	6.366***	(0.543)	6.127***	(0.524)	6.574***	(0.154)	6.534***	(0.155)
N = 511								
Wald χ^2 (22) of TLi/TL	133.11***		110.63***					
Wald χ^2 (7) of CDi/CD					93.16***		72.05***	
Log likelihood	-235.472		-256.694		-247.578		-269.84	
Gamma	0.82		0.82		0.81		0.80	
Mean technical efficiency	0.65		0.64		0.65		0.64	

Note(s): Translog (TL) TLi was preferred over Cobb-Douglas (CD) CDi. The TLi final model simultaneously estimates production and inefficiency variables; inefficiency estimates of TLi presented in [Table 3](#). TL and CD are restricted models, without inefficiency variables. Standard errors are in parenthesis. The level of significance is *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source(s): Table created by authors

The second last row of [Table 6](#) reports the value of the gamma parameter. The value of the gamma parameter calculated by a single-step estimation as proposed by [Battese and Corra \(1977\)](#) in terms of the parameterisation and value of the gamma parameter lies between 0 and 1. The observed value of the gamma parameter was 0.82, indicating a strong influence of technical inefficiency effects; in contrast, a value closer to 0 shows that the deviances from the frontier are due to noise effects, meaning perfect efficiency in a production system. The last row of [Table 6](#) indicates that the mean of technical efficiency was an average of 0.65 for both the translog and Cobb-Douglas SFA production models.

Conclusion

Globally, the use of mechanisation is associated with increasing the technical efficiency of farms. However, the historical experience of Kazakhstan and Uzbekistan shows that using cotton combines to mechanise cotton harvesting remains a major concern for policymakers. The slow uptake of cotton combine adoption in Soviet times made scholars question whether it is a technically efficient approach. Following the collapse of the Soviet Union, the use of cotton combine services in Kazakhstan has mainly been induced by labour availability and labour picking costs. More recently, for Uzbekistan, the switch from manual cotton picking to mechanised cotton harvesting has been essential for improving its international image of zero forced labour in agriculture ([Djanibekov et al., 2024](#)).

Based on the technical inefficiency model and using a cross-sectional data of 511 farmers in Kazakhstan and Uzbekistan, we found that cotton combines improve the technical efficiency of cotton-growing farmers. Interestingly, cotton growers in Uzbekistan are more efficient but less productive than their peers in Kazakhstan. This difference could be explained by the focus of the Uzbek government on the cotton sector, which has a strategic importance for the economy, while in Kazakhstan, the cotton sector has only local relevance. Furthermore, cotton farmers face better economic incentives due to the cotton sector liberalisation about 3 decades ago, while Uzbekistan farmers still have to face stricter regulations surrounding farm-gate prices for their cotton.

Likewise, practicing diversified farming could accelerate technical efficiency and further agronomic advantage, as the use of cotton combines and practicing diversified farming could improve mean technical efficiency. The mean technical efficiency was 0.65, indicating that farms were substantially technically inefficient, which is a striking finding of our study. The results also reveal that being a member of a farmers' union to acquire agronomic information positively influenced technical inefficiency, which could be because of a lack in agronomic training, or farmers being deprived of accessing extension services is another factor accelerating technical inefficiency.

Although using cotton combines is an effective and efficient measure, considering the scale of manual cotton picking and existing policies regarding cotton combines in Kazakhstan and Uzbekistan, policies towards cotton harvest mechanisation should be handled delicately. For instance, promoting mechanised cotton harvesting will result in a large discharge of seasonal workers who previously benefited from voluntary participation in cotton picking. This will, in turn, impact rural incomes, especially of those who are most vulnerable and without many employment options apart from cotton picking. Thus, cotton harvest mechanisation policies, particularly in Uzbekistan which has an abundance of rural labour, most of whom are women, should direct rural labour employment to other agricultural activities, such as, for example manual weeding and pest scouting in cotton fields, other crop cultivation, and be accompanied by policies targeting new jobs along agricultural value chains, e.g. in the cotton textile industry.

Second, diversified farming systems should be promoted to mitigate risks associated with monoculture, enhance soil fertility, and provide farmers with multiple revenue streams, to improve both technical efficiency and economic resilience. Third, the role of farmers' unions

should be strengthened to provide technical training, agronomic guidance, and advocacy for farmers, bridging the information gap and ensuring access to extension services and market insights related to cotton combine services. In this regard, agronomic training programs around cultivating cotton for mechanised harvesting should be institutionalised to ensure farmers have access to education on sustainable farming practices, including integrated pest management, soil health, and crop rotation. Mechanisation incentives such as subsidies or being a member of machinery circles or farmers' groups for investing in machinery could be useful for adopting cotton combines to boost productivity and efficiency (Müller, 2020). Finally, international partnerships with agricultural organisations and research institutions should be encouraged to facilitate knowledge transfer, technology exchange, and the implementation of best practices in cotton harvest mechanisation.

Notes

1. Institutional change in land and labour relations of Central Asia's irrigated agriculture (AGRICHANGE), www.iamo.de/en/agrichange.
2. This region is the highest administrative unit at a country level.
3. Kazakhstani Tenge (KZT) and Uzbek Som (UZS) converted into USD: 1 USD = 8700 UZS and 1 USD = 370 KZT at the time of data collection, presently (April 2024) 1 USD = 12,600 UZS and 1 USD = 442 KZT.
4. We performed a separate analysis using Uzbekistan farmers' data ($N = 256$). The value of technical efficiency was 0.71, showing relatively improved efficiency scores compared to pooled estimates (TE 0.65, see Table 6). The TE scores were for the case of Uzbek farms exclusively calculated without cotton combine services in the inefficiency model. The complete results are not reported here but can be made available upon request.

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Frontier	Coef.TLi	Std.Err.	Coef.TL	Std.Err.	Coef.CDi	Std.Err.	Coef.CD	Std.Err.
Ln cotton area	-0.298	0.289	-0.410	0.317	0.029	0.034	0.022	0.035
Ln labour	-0.018	0.211	0.050	0.226	-0.082***	0.028	-0.077***	0.029
Ln oil costs/ha	-0.265	0.204	-0.435**	0.214	0.037	0.026	0.028	0.028
Ln machine costs/ha	0.079	0.145	0.169	0.143	-0.019	0.016	-0.016	0.017
Ln fertiliser costs NPK/ha	0.332	0.226	0.435**	0.227	0.150***	0.037	0.163***	0.039
Soil quality (fertility)	0.255***	0.059	0.223***	0.061	0.257***	0.058	0.232***	0.060
Ln area sq	0.008	0.063	0.051	0.068				
Ln labour sq	0.001	0.047	-0.018	0.049				
Ln oil costs/ha sq	0.013	0.037	0.034	0.042				
Ln machine costs/ha sq	0.001	0.012	-0.008	0.011				
Ln fertiliser costs NPK/ha sq	-0.104*	0.061	-0.128**	0.062				
Ln area*lab	0.014	0.033	0.008	0.035				
Ln area*oil	0.093**	0.037	0.106**	0.044				
Ln area*mach	-0.043*	0.024	-0.046*	0.026				
Ln area*ferti	0.049	0.049	0.044	0.050				
Ln lab*oil	-0.028	0.032	-0.027	0.035				
Ln lab*mach	0.021	0.019	0.014	0.018				
Ln lab*ferti	-0.023	0.046	-0.019	0.048				
Ln oil*mach	-0.020	0.016	-0.019	0.017				
Ln oil*ferti	0.039	0.043	0.054	0.046				
Ln mach*ferti	0.010	0.026	0.002	0.025				
Constant	6.882***	0.677	6.842***	0.709	6.644***	0.172	6.661***	0.179
<i>Inefficiency variables</i>								
Cotton combines	-0.399**	0.201			-0.333*	0.204		
Farmers' union	-0.532**	0.244			-0.635**	0.255		
Farm location to water source	-0.524**	0.238			-0.524**	0.244		
Simpson diversity index	-1.560***	0.489			-1.725***	0.489		
N = 255								
Wald χ^2 (21) of TL	79.87***		74.50***					
Wald χ^2 (6) of CD					54.74***		46.59***	
Log likelihood	-147.4454		-159.0154		-154.9054		-168.5954	
Gamma	0.80		0.81		0.77		0.78	
Mean technical efficiency	0.63		0.62		0.64		0.62	

Note(s): Translog (TL) TLi was preferred over Cobb-Douglas (CD) CDi. The TLi final model simultaneously estimates production and inefficiency variables. TL and CD are restricted models, without inefficiency variables. The level of significance is *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source(s): Table created by authors

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