Institute of Economic Growth
University Enclave, University of Delhi
Delhi 110007, India
Tel: 27667101/288/424; Fax: 27667410
Website: www.iegindia.org

Productivity and Efficiency Impacts of Zero Tillage Wheat in Northwest Indo-Gangetic Plains

Prakashan Chellattan Veettil
Vijesh V. Krishna

IEG Working Paper No. 321

2013

RECENT WORKING PAPERS

Title	Author (s) Name	Paper No.
Policies for Increasing Non-farm Employment for Farm Households in India	Brajesh Jha	E/310/2011
Nagaland's Demographic Somersault	Ankush Agrawal Vikas Kumar	E/311/2012
Does Access to Secondary Education Affect Primary Schooling? Evidence from India	Abhiroop Mukhopadhyay Soham Sahoo	E/312/2012
Reexamining the Finance–Growth Relationship for a Developing Economy: A time series analysis of post–reform India	Sabyasachi Kar Kumarjit Mandal	E/313/2012
Fiscal Consolidation in India	Sanhita Sucharita	E/314/2012
The Impact of Carbon Taxes on Growth Emissions and Welfare in India: A CGE analysis	Basanta K. Pradhan Joydeep Ghosh	E/315/2012
An Investigation into Changes in Nagaland's Population between 1971 and 2011	Ankush Agrawal Vikas Kumar	E/316/2012
Carbon Taxes vs Productivity Shocks: A comparative analysis of the costs in a CGE framework for India	Basanta K. Pradhan Joydeep Ghosh	E/317/2012
Food Price Inflation in India: Causes and Cures	Pradeep Agrawal Durairaj Kumarasamy	E/318/2012
India's Petroleum Demand: Empirical Estimations and Projections for the Future	Pradeep Agrawal	E/319/2012
Food Security, Productivity, and Gender Inequality	Bina Agarwal	E/320/2012

Productivity and Efficiency Impacts of Zero Tillage Wheat in Northwest Indo-Gangetic Plains

Prakashan Chellattan Veettil
Vijesh V. Krishna

सत्यमेव परमो धर्मः IEG Working Paper No. 321 2012

ACKNOWLEDGEMENTS

This study was conducted as part of the Cereal Systems Initiative for South Asia (CSISA) project, funded jointly by the United States Agency for International Development (USAID) and the Bill and Melinda Gates Foundation (BMGF), when the first author was a TTI fellow at the Institute of Economic Growth, New Delhi and the second author was employed at the International Maize and Wheat Improvement Center (CIMMYT), New Delhi. We would like to thank Mukesh Meena (research intern, University of Agricultural Sciences, Bangalore) for conducting the household surveys and ML Jat (Senior Scientist, CIMMYT, New Delhi) for providing insights into conservation agricultural technology. We gratefully acknowledge and thank Surit Das for carefully editing this manuscript. The views expressed in this report are of the authors and do not necessarily reflect the views of the USAID, BMGF, CIMMYT, or the CSISA project.

Prakashan Chellattan Veettil is Assistant Professor, Centre for Development Studies, Thiruvananthapuram, India
email: prakashan@cds.ac.in

Vijesh V. Krishna is Senior Research Fellow, Department of Agricultural Economics and Rural Development, Georg-August University of Goettingen, Germany
email: vijesh.krishna@agr.uni-goettingen.de

Productivity and Efficiency Impacts of Zero Tillage Wheat in Northwest Indo-Gangetic Plains

ABSTRACT

Conservation agriculture (CA) technologies are being developed for the cereal production systems of South Asia to address the multifaceted problems of decelerating agricultural productivity, resource scarcity, climate change, and negative environmental externalities generated by the conventional production system. This study is a detailed investigation on one of the prominent CA technologies, namely zero tillage (ZT) wheat, where we quantify productivity and efficiency impacts using stochastic non-smooth envelopment of data approach. An economic analysis of ZT adoption revealed a significant gain with respect to input use, and consequently on the cost of cultivation and profitability. The results showed a yield gain of 7–8 per cent due to adoption of ZT wheat over conventional wheat. Early sown ZT plots are found associated with a substantial efficiency gain (16 per cent) compared to the late sown CT wheat ones. The scale of cultivation and remoteness of the village are found determining factors of efficiency gain apart from ZT technology adoption.

Keywords: Conservation agriculture, convex nonparametric least squares, Haryana, instrumental variables, smallholder farmers

JEL codes: Q12, D24, C14

1. INTRODUCTION

This paper analyses the adoption pattern and productivity impacts of a resource-conserving technology (RCT) in wheat cultivation using semi-parametric frontier production approach. The rice–wheat production system of the Indo-Gangetic Plains (IGP) of India has registered only sluggish productivity growth during the past two decades (GoI 2009). Degradation of the natural resource-base resulting from inappropriate land and input use is widely documented as one of the root causes (along with other factors) of this situation (Ali & Byerlee 2000; Erenstein et al. 2008b), which has compelled many agricultural scientists and policy makers to look toward a more sustainable path of cereal production, viz. conservation agriculture (CA) and RCTs (Erenstein & Laxmi 2008; Gupta & Sayre 2007). While the CA technology ensemble is based on the principles of minimal soil disturbance, residue retention, rational crop rotation, and controlled traffic, RCTs cover all farming practices/ technologies that facilitate the conservation and enhancement of resource use efficiency in farming (Erenstein 2009; FAO 2010; Gupta & Sayre 2007; Harrington & Erenstein 2005). These sustainable agriculture practices, which herald a paradigm shift in tillage and land preparation options, aid farmers in cost-saving and yield enhancement by shifting from conventional tillage wheat to minimal/zero tillage wheat, moving from puddled transplanted rice to ZT direct seeding in rice, and engaging in other resource-saving practices (Hobbs, 2007). Most prominent among such CA-based RCTs in the cereal system of South Asia is the minimal/zero tillage of wheat (Erenstein & Laxmi 2008; Gupta & Sayre 2007; Laxmi et al. 2007).

Research in India on zero tillage (ZT) wheat started in the 1970s but was soon abandoned due to technical constraints (Ekboir 2002). However, with the involvement of the Consultative Group for International Agricultural Development (CGIAR) in the South Asia region under the Rice-Wheat Consortium (RWC) programme of the IGP, ZT technology gained momentum in the late 1990s in NW Indian states. Here, after the initial spread, the area under the technology stabilised at 20–25 per cent (Erenstein 2009). A tractor-drawn ZT seed drill forms the machinery component of the technology, which allows wheat seed to be sown directly into unploughed fields with a single pass of the tractor, often with simultaneous basal fertiliser application. Despite having a relatively short history of adoption, the technology is reported to have helped wheat farmers overcome the constraint of late sowing of the crop after harvesting late-maturing basmati rice and of the widespread incidence of the weed *Phalaris minor* (Mehla et al. 2000; Erenstein & Laxmi 2008).

The positive farm profitability effects of ZT technology adoption in India is estimated at USD 96 per hectare (Erenstein & Laxmi 2008), which can be decomposed into (1) production cost savings and (2) yield increase. While the cost-saving effect of the technology (through reduced energy costs for tillage) is 'robust enough to make adoption worthwhile' (Erenstein et al. 2008a) and relatively straightforward, the productivity gain in fields is often insignificant. According to agronomists, the productivity advantages of ZT wheat originate from earlier planting (and thus evading terminal heat during the grain filling stage), control of obnoxious weeds, better nutrient management, and water savings. Mehla et al. (2000) estimated from on-farm trials a yield gain of 15.4 per cent and apportioned it into timeliness of planting (9.4 per cent) and enhanced input use efficiency (6 per cent). Nevertheless, many farmers are found dis-adopting the technology, even in the north-western plains, citing the absence of productivity enhancement (cf. supplementary material). The fact that CA practices are not continuous over cropping seasons in the IGP—as ZT wheat is followed by puddled, transplanted rice in most of the region (Erenstein et al. 2008a)—also reduces the possibility of deriving intuition from the years of experience in other cereal systems of the world where ZT has been practised successfully.

As a first step toward accelerating ZT technology diffusion and reaping significant societal and environmental benefits (Gupta & Sayre 2007), the associated yield effects are to be analysed and documented properly. The few attempts to examine the productivity impacts of ZT wheat either do not systematically delineate the different determinants of production or are based mostly on on-farm trials. Nevertheless, certain cultural practices and input uses in wheat production are found endogenous and strongly associated with ZT practice, the adoption of which again is endogenous; for example, ZT wheat is found to increase yield through timely crop establishment, and both ZT technology adoption and the time of sowing are endogenous variables. Therefore, ordinary least squares estimation of production functions on wheat would not conclusively provide quantified results on productivity impacts. In addition, to the best of our knowledge, there are no studies examining the efficiency impact of ZT technology in the rice-wheat production systems of the IGP.

Against this backdrop, the present paper evaluates the on-farm productivity and efficiency impacts of the adoption of ZT wheat, employing econometric models barring the aforementioned endogeneity bias. As outlined in the subsequent methodology section (Section 2), the primary data source is an empirical farm survey in the rice–wheat belt of Haryana state of northwest India. The characteristics of the study area are also presented in Section 2, alongside the analytical methods employed for econometric estimation. The cost, productivity, and technical efficiencyimpacts of the ZT technology are presented and discussed in Section 3. The final section (Section 4) concludes the paper.

2. MATERIALS AND METHODS

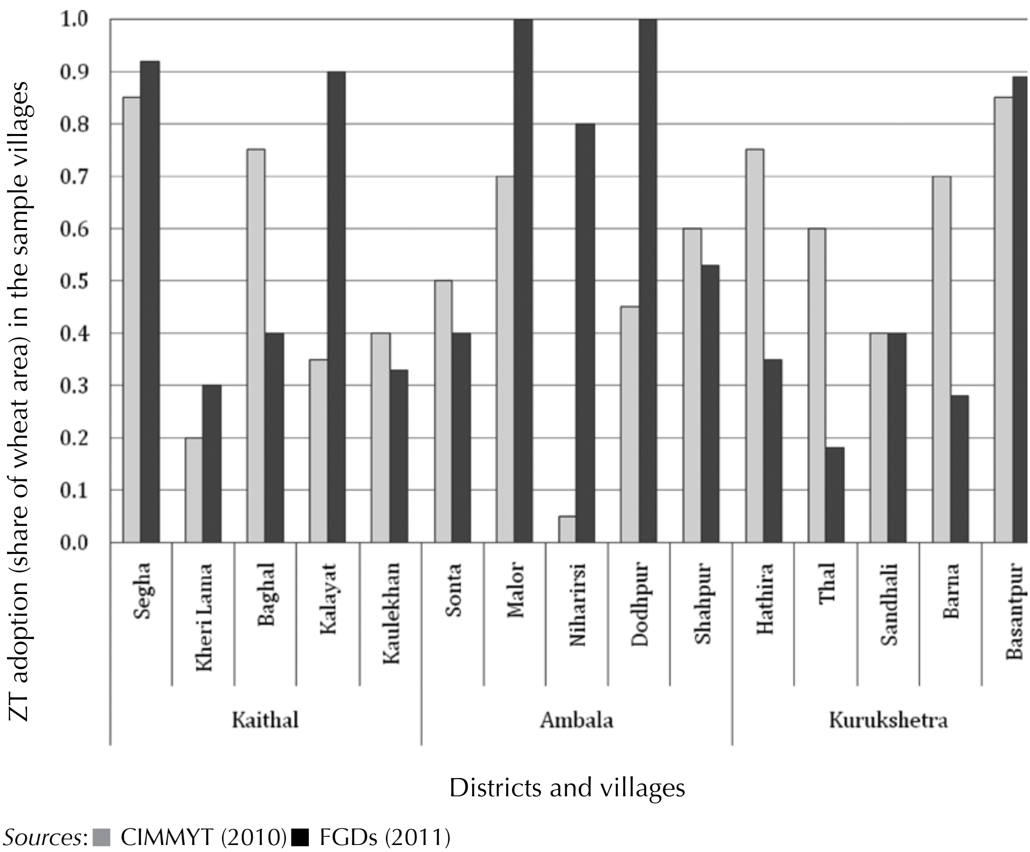
2.1. Study Area and Sampling

Rice–wheat cropping systems occupy about 13.5 million hectares in South Asia (especially in the IGP of India, Pakistan, and Bangladesh), contribute 85 per cent to the region's cereal production, and feed about 20 per cent of the world population (Saharawat et al. 2010; Timsina & Connor 2001). The study area, Haryana, located in the northwest of the Trans-Gangetic Plains, is one of the major producers of both rice and wheat in the country. A semi-arid continental monsoonal climate prevails in this region; 80 per cent of the total precipitation occurs during the monsoon season from June to September (Erenstein & Farooq 2009). Wheat is grown in the cool and dry rabi season (November to March), whereas rice is grown during the warm humid/semi-humid kharif season (June to October) on about 2.5 million ha (Coventry et al., 2011; Krishna et al., 2013). The cereal systems in Haryana, as in the other parts of northwestern IGP, are capital-intensive and commercial and have relatively large farm holdings. Rice and wheat contribute over two-thirds of the overall household income in this region (Erenstein & Farooq 2009).

The soils in the study areas are mostly alluvial, weakly structured, and low in organic carbon with light to medium texture (Jehangir et al. 2007). Cereal production is largely mechanised. Traditionally, four-wheel tractors with attached tine cultivators and disc harrows are used to prepare the land for rice and wheat cultivation (Krishna et al. 2013). However, the adoption of ZT technology is also reported to be the highest in Haryana among all the states in the IGP—the area under ZT wheat was 0.3 million ha in 2002, up from zero adoption in 1997 (Hobbs & Gupta 2004). Erenstein et al. (2007a) reported that 35 per cent of sample households adopted ZT technology, and in 26 per cent of the wheat area during 2003–04. Information on recent adoption rates is unavailable.

The present study was conducted in 2010–11 in collaboration with the Global Conservation Agricultural Programme (GCAP) of the regional station of Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) at New Delhi (India). The main primary data source for this study was a formal survey of rice and wheat growers of Haryana during 2011. Although ZT was relatively popular in the state, a random selection of villages and households would still not ensure an adequate share of adopters for with-and-without comparison of the technology effect. Hence, only the districts and villages with predominantly ZT wheat were chosen for the study. The ZT promotion activities were extensively undertaken under different GCAP projects. A list of 93 villages of Haryana where ZT was popular was obtained, which included 52 villages of Ambala (with average adoption of ZT at 72 per cent of wheat area), 15 villages of Kurukshetra (67 per cent), 18 villages of Kaithal (46 per cent), and 8 villages of Karnal district (26 per cent)[1]. For the present study, we have selected only the first three districts where the number of villages with ZT technology is the highest. From each of the selected districts, five villages were selected randomly. Prior to the household survey, short focus group discussions (FGDs) were conducted in each of these villages, and ZT adoption was recalculated and compared with the figures obtained from the CIMMYT (Figure 1). Possibly due to the differences in data collection approaches employed and to the lapse of time (2–3 years), there was a certain deviation in adoption figures between the secondary and primary datasets. In one-third of the sample villages, the technology adoption was as high as around 90 per cent or more, limiting the number of non-adopters in the household survey. However, the cropping pattern and soil characteristics of these villages are not radically different from the others, making inter-village comparison possible.

Figure 1: Zero tillage adoption in sample villages



Sources: ■ CIMMYT (2010) ■ FGDs (2011)

[1] Source: ML Jat, Senior Scientist, GCAP, CIMMYT, New Delhi.

An interview-based survey of 180 wheat farms was carried out in 2011 in collaboration with the CIMMYT training/internship programme, where the student interns were engaged in primary data collection under the supervision of experienced researchers. Most sample households (62 per cent) belonged to the medium-farmer category, owning landholdings of size between 4 ha and 10 ha, followed by marginal (<1 ha; 16 per cent) and small farmers (1-2 ha; 14 per cent). Apart from eliciting general farm and household characteristics, the survey included detailed questions about the history and pattern of adoption of ZT technology and input–output relationships in wheat cultivation for winter (rabi) season 2010–11. The total sample consists of 94 full adopters, 39 partial adopters, and 47 non-adopters of the ZT technology.[2] As the partial adopters were cultivating wheat under both ZT and conventional systems, we have elicited the input data from both plots with tillage (n = 86) and without tillage (n = 133), which allows us to make with-and-without technology comparisons on input use not only across farms but also within them. However, it was observed that the partial adopters often harvest ZT and conventional tillage plots together, mostly using combine harvesters, and precise plot-level data on wheat grain yield was not available. Hence, farm-level average yields were used for analysis instead of plot-level data.

2.2. Analytical Framework

The interdependencies between production rate (productivity) and production level in comparison with resource use (efficiency) are misleading; often, people use these concepts interchangeably. Productivity in agriculture is achieved by maximising production per unit cropped area whereas technical efficiency refers to the economic unit's capacity to produce maximum output for a given bundle of inputs and technology (Färe et al. 1994). Targeting productivity while overlooking efficiency would be very expensive and unaffordable for the production system as a whole. On the other hand, increasing efficiency may not always lead to productivity gain. In this paper, we focus on both efficiency and productivity of the wheat production system from the resource conservation perspective.

2.2.1. Production Function Estimation with Endogeneity Correction

The net yield effect of ZT technology can be estimated econometrically by using a production function approach, in which wheat production is hypothesised as a function of technology adoption (ZT) and time of sowing (S), alongside other farm and household factors (H). We use a Generalised Cobb-Douglas function, which shows a good fit in empirical studies at the micro-level. The core equation of our model is:

$$Y_i = \alpha_0 + \alpha_1 ZT_i + \alpha_2 S_i + \alpha_3 H_{Yi} + \varepsilon_{Yi}, \qquad i = 1,.....n \qquad (1)$$

[2] This study interprets ZT as the planting of wheat with a tractor-drawn ZT seed drill directly into unplowed fields with a single pass of the tractor.

The null hypothesis associated with technology adoption is that neither adoption nor timing of sowing affects productivity (i.e., $\alpha_1=\alpha_2=0$). As indicated in the introductory section, one of the ways ZT technology impacts wheat yield is by facilitating farmers to sow seeds earlier. However, there is a high probability that ZT adoption and timing of wheat sowing are endogenously determined, and hence we employ 2-stage least squares (2SLS) instrumental variable (IV) approach for the production function analysis. The extent of ZT adoption on i^{th} farm, ZT_i, could be affected by the scarcity of seed drills in the village, represented by the village-level adoption of ZT technology, and the ratio of ZT drills to other ploughing machines (e.g., tine cultivators). A Wu-Hausman-Durbin test was employed to compare the IV coefficients with OLS ones. The null hypothesis is that the OLS estimator is indeed an efficient and consistent estimator of the true parameters, and there should be no systematic difference between the two parameters. If there is a systematic difference in estimates, we suspect violation of the OLS assumptions, and hence resort to IV regression.

2.2.2. Frontier Efficiency Estimation

Recently, many researchers have started employing semi-parametric or similar approaches to combine the advantages of two concepts (Fan et al. 1996; Henderson & Simar 2005; Kneip & Simar 1996; Kumbhakar et al. 2007; Kuosmanen & Kortelainen 2012; Park et al. 1998; Park et al. 2003, 2007). Three examples are given below.

1. Combining the axiomatic, nonparametric treatment of frontiers that are free of distributional assumption but impose the general regularity properties (e.g. in DEA) with a stochastic treatment of noise like that of SFA (Kortelainen 2008; Kuosmanen & Kortelainen 2012).

2. Relaxing the a priori assumptions on the production frontier, but imposing distributional assumptions on error components (Fan et al. 1996).

3. Non-parametric stochastic frontier by different techniques such as kernel regression, local linear least squares, or local maximum likelihood (Henderson & Simar 2005; Kneip & Simar 1996; Kumbhakar et al. 2007). Very few empirical works have been reported so far. To our knowledge, this is one of the first attempts to apply the stochastic method in enveloping data using shape constraints in technology adoption (Kortelainen 2008; Kuosmanen & Kortelainen 2012).

The present agricultural production involving CT is in the form of a single output (wheat: $y \in \Re_+$) multiple input (m-dimensional input vector $\mathbf{x} \in \Re_+^m$) case. Let the frontier production technology be $f: \Re_+^m \rightarrow \Re_+$ where f follows classical DEA frontier i.e. continuous, monotonic increasing and globally concave functions that are non-differentiable (denoted by F_2 class of functions). Thus, this specification follows a nonparametric pattern, contrary to SFA where specification of the functional form for f is required a priori. The production function can be formally represented by introducing a composite error term $\varepsilon_i = \upsilon_i - u_i$ which consists of inefficiency (u_i : $u_i > 0$, assuming an asymmetric distribution for u_i with a positive expected value μ_i and a finite variance σ_υ^2) and noise (υ_i: here we assume a symmetric distribution with zero mean and constant, finite variance σ_υ^2) terms. Consequently, the observed output (y_i) may differ from $f(x_i)$. Further, borrowing from the multiplicative formulation from SFA, our production function can be represented as

$$y_i = f(x_i)\exp(\xi Z_i + \varepsilon_i) = f(x_i)\exp(\xi Z_i - u_i + \upsilon_i), \qquad i = 1,\ldots\ldots, n \tag{2}$$

where Z is the environmental or exogenous variable that influences production. Additionally, we assume that u_i and υ_i are statistically independent of each other as well as of inputs x_i. Here, the production function $f(x_i)$ is analogous to DEA, whereas the stochastic part (ε_i) is decomposed into inefficiency (u_i) and noise (υ_i) terms similar to SFA, thus making the model (2) encompassing both classic DEA and SFA models as constrained special cases.

We employed stochastic non-smooth envelopment of data (StoNED) approach proposed by Kuosmanen & Kortelainen (2012) to estimate the model (4). Here, a two- stage estimation strategy is followed.

Stage 1: CNLS estimation

By maintaining the same assumptions of production function f and composite error term as in the model (2) and applying log transformation, we get $y_i = \ln f(x_i) + \xi Z_i + \varepsilon_i$, $i = 1,\ldots\ldots, n$. To preserve the Gauss-Markov properties for error terms without losing generality, the model can be rephrased as follows:

$$\ln y_i = [\ln f(x_i) - \mu]\ \xi Z_i + [\varepsilon_i + \mu] = g(x_i) + \xi Z_i + \upsilon_i, \qquad i = 1,\ldots\ldots, n \tag{3}$$

where $g(x)[=\ln f(x) - \mu]$ is an 'average' practice production function in contrast to the best/frontier production function $f(x)$ and $\upsilon_i \equiv \varepsilon_i + \mu$ where μ is the expected inefficiency. The CNLS estimator for function g can be obtained by a quadratic programming (QP) problem proposed by Kuosmanen (2008):

$$\begin{aligned}
&\min_{\hat{y},\alpha,\beta} \sum_{i=1}^{n} \left(\ln y_i - \ln \hat{y}_i\right) \\
&\hat{y}_i = \alpha_i + \beta_i' x_i + \xi Z_i \\
&\alpha_i + \beta_i' x_i \le \alpha_h + \beta_h' x_i \qquad \forall h, i = 1,\ldots., n \\
&\beta_i \ge 0 \qquad \forall i = 1,\ldots., n
\end{aligned} \tag{4}$$

The first constraint of the problem (4) represents a regression equation which is technically similar to the random parameter SFA model (Greene 2005). For more details about the properties of the CNLS estimator please refer Kuosmanen & Kortelainen (2012).

Stage 2: Efficiency Estimation

By solving the QP, we get CNLS residuals $\hat{\upsilon} \equiv (\hat{\upsilon}_1,....,\hat{\upsilon}_n)$. In the next step, these composite residuals are disentangled into inefficiency and noise by imposing some distributional assumptions i.e. half-normal inefficiency $\left(u_i \underset{iid}{\sim} |N(0,\sigma_u^2)\right)$ and normal noise $\left(\upsilon_i \underset{iid}{\sim} N(0,\sigma_\upsilon^2)\right)$. Using a method of moments approach, the variance parameters are estimated by computing the second $\left[\hat{M}_2 = \sum_{i=1}^{n}\left(\hat{\upsilon}_i - \hat{E}(\upsilon_i)\right)^2 / n\right]$ and third central moments $\left[\hat{M}_3 = \sum_{i=1}^{n}\left(\hat{\upsilon}_i - \hat{E}(\upsilon_i)\right)^3 / n\right]$ of the composite error distribution. Given the estimated $\hat{M}_3$, we can estimate σ_u as the third moment depends only on the standard deviation of inefficiency. Therefore, $\sqrt{\hat{\sigma}_u} = \sqrt[3]{\frac{\hat{M}_3}{(\sqrt{2/\pi})\,[1-\frac{4}{\pi}]}}$ and, $\hat{\sigma}_\upsilon = \sqrt{\hat{M}_2 - [\frac{\pi-2}{\pi}]\,\hat{\sigma}_u^2}$. The frontier production function f can be consistently estimated as $\ln \hat{f}(x) = \hat{g}_{min}(x) + \hat{\sigma}_u\sqrt{2/\pi}$ (shifting the average practice frontier obtained from CNLS upwards by the expected value of the inefficiency term). The point estimator for inefficiency (u_i) can be estimated using the conditional mean, $\sqrt{E}(u_i|\varepsilon_i) = \mu_* + \sigma_*\left[\frac{\phi(-\mu_*/\sigma_*)}{1-\Phi(-\mu_*/\sigma_*)}\right]$

where,

$$\sqrt{\mu_*} = -\varepsilon_i\sigma_u^2/(\sigma_u^2 + \sigma_\upsilon^2),$$

$$\sigma_*^2 = \sigma_u^2\sigma_\upsilon^2/(\sigma_u^2 + \sigma_\upsilon^2),$$

$\sqrt{\Phi}$ is the standard normal density function, and
$\sqrt{\phi}$ is the standard normal cumulative distribution function.
The efficiency is calculated as $eff_i = \exp(-u_i)$.

2.2.3. Determinants of Technical Efficiency

Factors external to production inputs (farmer's education, farm location) influence the technical efficiency of ZT wheat. Here, we applied an instrumental variable Tobit model to analyse the effects of such determinants. Traditional ordinary least squares estimations are inconsistent, as the dependent variable is censored in nature. For example, the upper value of technical efficiency score is truncated to 1. The structural equation in the Tobit model[3] defined below provides us a consistent estimation for the regression coefficients:

[3] Theoretically, the efficiency score lies between [0, 1]. The lower efficiency score is rarely required to be truncated to 0, i.e., the truncation is limited to the upper level of the efficiency score. Hence, we adopted an upper truncated Tobit model in our analysis.

$$eff_i = \text{eff}_i^* = \varphi\, ZT_i + \xi\, DOS_i + \delta\, S_i + \varepsilon_i \tag{5}$$

Following Holden (2004), residuals are assumed to be normally distributed i.e. $\varepsilon_i \sim N(0, \sigma^2)$. eff^* is the latent variable that is observed for efficiency values lower than $\tau(=1)$ and censored otherwise. The observed *eff* is defined by the following equation

$$eff_i = \begin{cases} \text{eff}_i^* \text{ } if \text{ } eff_i^* > \tau \\ 1 \text{ } if \text{ } eff_i^* > \tau \end{cases} \tag{6}$$

where *eff* is the dependent variable (CNLS technical efficiency scores), *S* is a k×1 vector of independent variables relating to ZT.[4] The estimation is carried out by minimising a log likelihood function with a part corresponding to non-censored observations and the other for the values equal to one. Village-level adoption of ZT technology, the ratio of ZT drills to other ploughing machines, and village-level per-household wheat area in the village are used as instruments for ZT and S. As in the case of productivity analysis, a Wu-Hausman-Durbin test was employed to compare the IV coefficients with OLS ones.

3. RESULTS AND DISCUSSION

3.1. Adoption and Economics of ZT Wheat

Table 1 presents the adoption pattern of ZT technology in the sample villages. As the sample includes only those villages where ZT technology is relatively popular in Haryana, very high awareness as well as adoption rate (83 per cent) were observed. This technology take-off stage occurred during the 2004–05 wheat season, coinciding with the time of high extension inputs by Rice-Wheat Consortium of CGIAR that promoted CA in the IGP. Adoption is found slightly higher among the large farmers compared to the small ones, but this difference is statistically insignificant. Dis-adoption rate is much lower than in many other villages in the state: 14 per cent of farmers ever adopted ZT on their farm (cf. supplementary material).

There is significant difference with respect to input use between adopters and non-adopters of ZT technology (Table 2). Unsurprisingly, drill use reduces seed quantity, while there is a marginal increase in chemical fertilisers in the ZT plots. However, the most significant cost changes are observed in labour use. Adopting technology spares about 81 per cent of hired human labour and 21 per cent of machine labour and, as a result, lowers the total paid-out cost of cultivation by 31 per cent over conventional wheat plots and by 25 per cent when the family labour component is imputed. The cost impact is almost the same, even when the partial adopters of the wheat are excluded from the analysis.

[4] Though ZT adoption and date of sowing (DoS) are independent variables related to ZT, we treat them separately to emphasise the importance of those variables in our frontier model.

Table 1: Adoption pattern of ZT wheat technology in Haryana

Farmer class	Number of observations	Familiarity with the ZT technology				Median year of		per cent disadoption
		no information	only heard	heard & seen (but did not adopt)	adopted on-farm	first adoption	last adoption*	
Small (< median)	87	0.0	0.0	20.7	79.3	2005/06	2010/11	17.1
Large (≥ median)	93	0.0	0.0	11.8	88.2	2004/05	2010/11	11.0
Overall	180	0.0	0.0	16.1	83.9	2004/05	2010/11	14.0

Source: Own household survey (2011).

* 2010/11 was the latest wheat season at the time of suvey, on which the present study is based, and most of the sample farmers were found engaged in continual adoption of the ZT technology on farm.

Table 2: Cost difference between conventional and zero tillage

Cost (Rs/ha)	Zero tillage, ZT [N = 133]			Conventional tillage, CT [N = 86]			per cent difference between ZT & CT (p-value)
	Mean (Std. dev)	Minimum	Maximum	Mean (Std. dev)	Minimum	Maximum	
Seed	1946.8 (251.5)	1037.4	2470.0	2009.6 (276.7)	1167.1	2964.0	-3.1 (0.08)
Farm yard manure	102.6 (443.5	0.0	2470.0	122.8 (467.2)	0.0	2470.0	-16.4 (0.75)
Chemical fertilisers	3383.0 (583.1)	2568.8	8299.2	3258.1 (249.3)	2568.8	3902.6	3.8 (0.06)
Plant protection chemicals	1118.3 (373.2)	0.0	2531.8	1203.1 (389.4)	395.2	2531.8	-7.1 (0.11)
Hired human labour	984.3 (2549.7)	0.0	19110.7	5119.6 (5995.7)	0.0	27713.4	-80.8 (0.00)
Machine labour cost	4193.5 (1079.2)	494.0	6298.5	5280.3 (1696.5)	666.9	9386.0	-20.6 (0.00)
Total paid-out cost	11728.5 (2706.6)	7722.3	30448.0	16993.6 (5763.1)	7434.7	39161.9	-31.0 (0.00)
Imputed cost of family labour	6725.4 (3430.5)	3430.5	3430.5	7648.0 (5027.2)	0.0	29454.8	-12.1 (0.11)
Total cost including family labour	18453.8 (4192.4)	10942.1	41365.4	24641.6 (7147.9)	15961.1	50276.9	-25.1 (0.00)

Source: Own household survey (2011).

Table 3: Economics of conventional and zero tillage wheat*

	Zero tillage, ZT [N = 94]			Conventional tillage, CT [N = 47]			per cent difference between CT & ZT (p-value)
	Mean (Std. dev)	Minimum	Maximum	Mean (Std. dev)	Minimum	Maximum	
Total paid-out cost (Rs/ha)	11979.2 (3017.4)	8293.9	30448.0	17662.8 (6724.5)	7434.7	39161.9	-32.2 (0.00)
Total cost including family labour (Rs/ha)	18830.9 (4152.6)	11725.4	41365.4	25824.9 (8358.6)	16734.3	50276.9	-27.1 (0.00)
Wheat yield (quintals/ha)	44.6 (4.8)	29.6	54.3	42.0 (4.6)	32.1	52.4	6.2 (0.00)
Gross revenue(Rs/ha)	48123.0 (5161.9)	32011.2	58687.2	45323.4 (4951.7)	34678.8	56553.1	6.2 (0.00)
Net revenue(Rs/ha)							
i. over paid-out cost	36143.9 (5584.9)	20236.4	47988.6	27660.6 (8943.0)	-1815.5	40582.1	30.7 (0.00)
ii. over paid-out and family labour cost	29292.1 (6297.2)	9319.0	42801.6	19498.6 (9542.6)	-10040.6	33505.6	50.2 (0.00)
Benefit-cost ratio							
i. over paid-out cost	4.0			2.6			
ii. over paid-out and family labour cost	2.6			1.8			

* Excluding the partial adopters of ZT technology.

Source: ADF: Own household survey (2011).

Farmers often harvest wheat with combine harvesters, and ZT and CT plots together. Pilot surveys have shown that the farmers have difficulty in computing plot-level productivity. There would be measurement errors in plot-level yield data; hence, whole-farm productivity data is used for functional analysis. Before that, the economics of wheat farming was calculated for ZT plots (52 per cent of the sample) and conventional plots (26 per cent), excluding the plots of partial adopters. Although the results so obtained are slightly biased, they indicate that the technology can be highly profitable to farmers. Adopting ZT is associated with a 6 per cent increase in productivity and 31 per cent increase in profitability when only paid-out costs are included for the analysis (Table 3), and with a change in input use (e.g. chemical fertilisers), which could also contribute to the yield difference (Table 2). The next sub-section presents the results of the production function analysis, conducted to delineate the impact of technology adoption from associated input use.

3.2. Productivity Impact of ZT: Functional Approach

To estimate the individual impacts of ZT adoption and time of sowing, a Generalised Cobb-Douglas model was used, in which all the production inputs and farm size along with the dependent variable (wheat yield) were transformed into natural logarithmic form. Since whole farm productivity was used as the dependent variable, ZT adoption was captured as a share of ZT wheat in the total wheat area in the scale of 0–1. The variable 'date of sowing' (DoS) shows the difference between the date of sowing wheat and 1 November. A value of 1 is given if wheat is sown on or before 31 October. Wheat sown after the second week of November is critically affected by terminal heat, and 1 November is chosen as a cut-off date after keeping a margin of two weeks for weather fluctuations. The variables used in the productivity analysis are shown in Table 4.

Attempts were made to instrument both ZT adoption and DoS using a number of variables, viz., village-level adoption or ZT technology, wheat area per number of drills available in the village, village-level per-household wheat area, etc. The reduced form (yield as a function of IVs) was not statistically significant when DoS was instrumented although these variables fulfil the exclusion restriction (that IVs affect the dependent variable only through the treatment variable) and there were strong indications of a first stage. On the other hand, ZT adoption was more satisfactorily instrumented by different variables. The results of OLS and IV regression are shown in Table 5. Nevertheless, in all the cases, the Wu-Hausman-Durbin test showed that the OLS estimator is an efficient and consistent estimator of the true parameters, and hence the model can be explained better based on OLS parameters.

Table 4: Descriptive statistics

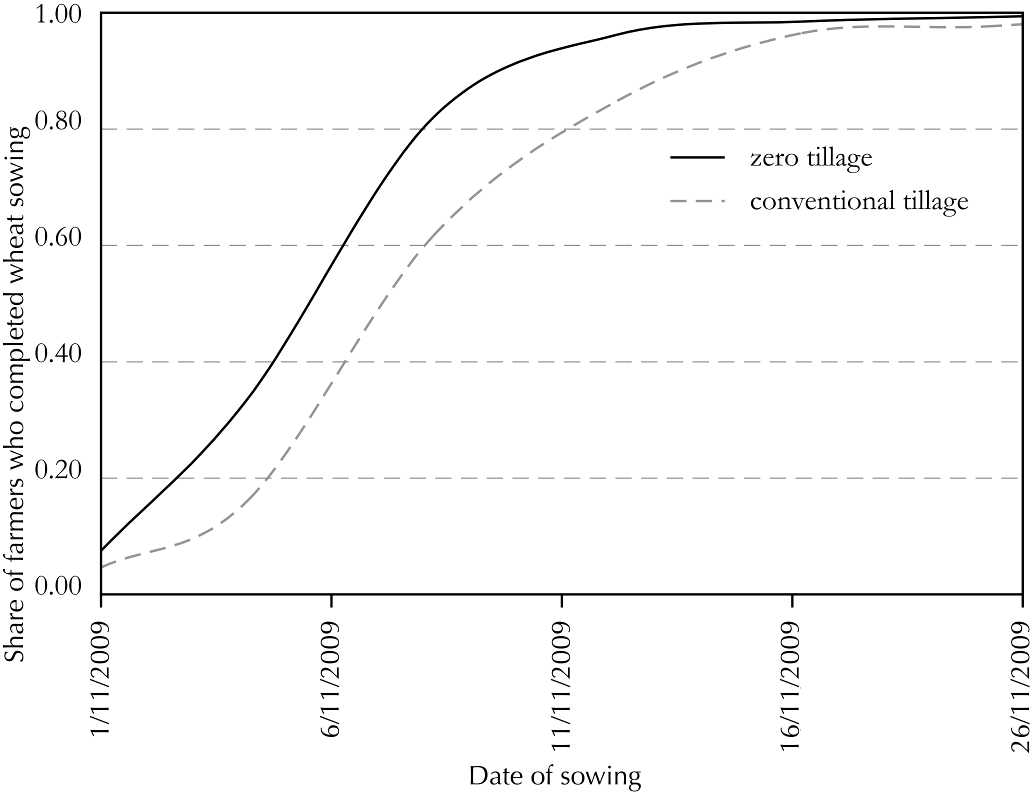
Variable	Description (unit)	Mean (Std. devn)	Minimum	Maximum
Output variable				
Wheat yield	Quantity of wheat grain yield (quintals/ha)	43.5 (4.7)	29.6	54.3
Technology adoption				
Zero tillage	Share of wheat area under ZT technology in a farm (0-1)	0.6 (0.4)	0.0	1.0
Date of sowing	Number of days between the date of wheat sowing and 1 November. Date of sowing is one, if wheat is sown on or before 31 October	7.1 (4.9)	1.0	27.0
Production inputs				
Seed	Cost incurred to purchase wheat seeds (Rs/ha)	1117.7 (353.6)	184.4	2532.6
Chemical fertilisers	Quantity of nitrogen and phosphorous applied for wheat (quintals/ha)	2.5 (0.3)	1.9	5.0
Human labour	Number of days of labour used for wheat cultivation (days/ha)	9.8 (6.5)	3.7	44.9
Herbicides	Cost incurred to purchase herbicides (Rs/ha)	1981.2 (264.3)	1089.0	2963.1
Farm-household characteristics				
Land cultivated	Area under cultivation by the household (ha)	5.4 (5.1)	0.4	30.0
Age of HoH	Age of household head (years)	57.2 (13.1)	28.0	90.0
Education of HoH	Years of schooling obtained by the household head	4.5 (5.3)	0.0	17.0
Remoteness	Distance of the village from the nearest city (km)	11.6 (10.5)	0.0	40.0
Kaithal district	Dummy for the farmer from Kaithal district (=1, 0 otherwise)	0.3	0.0	1.0
Kurukshetra district	Dummy for the farmer from Kurukshetra district (=1, 0 otherwise)	0.3	0.0	1.0
Instruments				
Village-level adoption	Share of ZT adopters in the village (0-1)	0.6 (0.3)	0.2	1.0
Drill/other ratio	Number of ZT drills to number of conventional tillage machineries (ratio)	0.4 (0.2)	0.1	1.0

Table 5: Estimation of impacts of ZT adoption on wheat yield*

	OLS			IV		
	coef.	std. error	p-value	coef.	std. error	p-value
Technology adoption						
Zero tillage#	0.070	0.019	0.00	0.240	0.064	0.00
Date of sowing*	-0.019	0.011	0.10	0.007	0.016	0.68
Production inputs						
Seed*	-0.013	0.058	0.82	0.097	0.080	0.23
Chemical fertilisers*	-0.036	0.079	0.65	-0.102	0.099	0.30
Herbicides*	-0.001	0.029	0.97	0.004	0.035	0.90
Human labour*	-0.005	0.004	0.24	-0.009	0.005	0.07
Farm-household characteristics						
Land cultivated*	0.027	0.009	0.00	0.028	0.011	0.01
Age of HoH	4.E-04	0.001	0.48	0.001	0.001	0.43
Education of HoH	0.001	0.002	0.51	0.001	0.002	0.53
Remoteness	0.003	0.001	0.00	0.004	0.001	0.00
Kaithal district	0.042	0.025	0.09	0.099	0.036	0.01
Kurukshetra district	0.082	0.020	0.00	0.130	0.029	0.00
Model intercept	3.760	0.492	0.00	2.742	0.696	0.00
Adjusted R^2	0.241					
F (12 167)	5.74		0.00	4.30		0.00
Hausman test statistic $\chi^2(12)$				7.81		0.80

* Variables taken in their natural logarithmic terms. # Instrumented in IV regression.

Figure 2 : Cumulative distribution of sample farmers according to date of wheat sowing



Source: Own household survey (2011).

Similar to the mean variance analysis carried out beforehand (excluding the partial adopters; Table 3), the yield effect of ZT was found to be 7 per cent over conventional wheat (Table 5), which is slightly higher than the previously reported estimate (5 per cent; Erenstein 2009, in mean variance analysis). This yield effect is only due to better nutrient management and weed control and not through facilitating early sowing. A delay in sowing wheat reduces yield significantly, and since ZT adoption facilitates early sowing of wheat (Figure 2), the indirect yield benefits could also be substantial. Unlike in the case of the aforementioned variables, usage of the inputs has yielded only insignificant elasticity coefficients, indicating that they are currently used at their agronomic optimum levels. There was a clear economy of scale: the percentage increase in wheat area increased yield by 2 per cent. Farmer age and education yield insignificant coefficients in the production function, whereas remoteness of the village was found associated with higher yield.

Table 6: Estimation of impacts of ZT adoption on efficiency

	non parametric frontier dependent variable: wheat yield*			IV Tobit model# dependent variable: technical efficiency		
	coef.	std. error	p-value	coef.	std. error	p-value
Technology adoption						
Zero tillage#	0.081	0.018	0.00	0.101	0.039	0.01
Date of sowing*	0.651	0.131	0.00	-0.004	0.011	0.72
Production inputs						
Seed*	0.386	0.041	0.00	0.386	0.041	0.00
Chemical fertilisers*	2.646	0.167	0.00	2.646	0.167	0.00
Herbicides*	2.618	0.050	0.00	2.618	0.050	0.00
Human labour*	1.132	0.144	0.00	1.132	0.144	0.00
Farm-household characteristics						
Land cultivated*				0.025	0.007	0.00
Age of HoH				0.001	0.001	0.28
Education of HoH				0.001	0.001	0.38
Remoteness				0.003	0.001	0.00
Kaithal district				0.049	0.018	0.01
Kurukshetra district				0.090	0.019	0.00
Model intercept				0.683	0.064	0.00
Log likelihood	0.241			114.62		
Wald χ^2 (8)	5.74		0.00	61.69		
Wald test of exogeneity χ^2(1)				8.00		0.00

Notes: * Variables taken in their natural logarithmic terms.# Instrumented variable in IV Tobit.

3.3. Productivity Impact of ZT: Frontier Analysis

The parameter estimates in SFA usually have an interpretation of marginal product/cost or elasticities, but in DEA and StoNED the shadow price can be interpreted as marginal product/cost. The marginal product of inputs in StoNED—contrary to SFA—varies across firms. The variables in the CNLS production function described in equation (4) comprised inputs (labour, seed, fertiliser and herbicides, DoS), ZT (as external variable influencing the frontier), and output (wheat yield). The effects of these inputs on production frontier are estimated and reported in the first columns of Table 6.

The DoS and the production inputs (seed, chemical fertilisers, herbicides, and human labour) influence the frontier significantly; the DoS also determines its shape. Further, the marginal product is calculated by multiplying the shadow prices obtained as the optimal solution for the CNLS problem by the expected value of inefficiency (Kuosmanen 2012). For every unit increase in input use, wheat production is increased by 0.35 units (seed), 0.02 units (chemical fertilisers), 0.23 units (herbicides), and 1.02 (human labour) units. Thus, the input use of the present production system showed a positive but decreasing marginal productivity except for the human labour input. The study region is one of the highly mechanised states in India and we do expect a labour shortage in these region. The optimal use of inputs could be achieved by adopting ZT technology. For example, the number of tillage operations, as reported by Sharma et al. (2002) and Erenstein et al. (2007b), decreases from 7–8 in conventional tillage to zero in ZT wheat. Zero tillage saves irrigation water use (Gupta et al. 2002; Hobbs and Gupta 2003; Mehla et al. 2000); improves soil quality and structure (Chauhan et al. 2002; Mohanty et al. 2007) and reduces the incidence of weeds and pests (Chauhan et al. 2002; Dabur et al. 2002; Franke et al. 2007; Malik et al. 2004; S. Singh 2002).

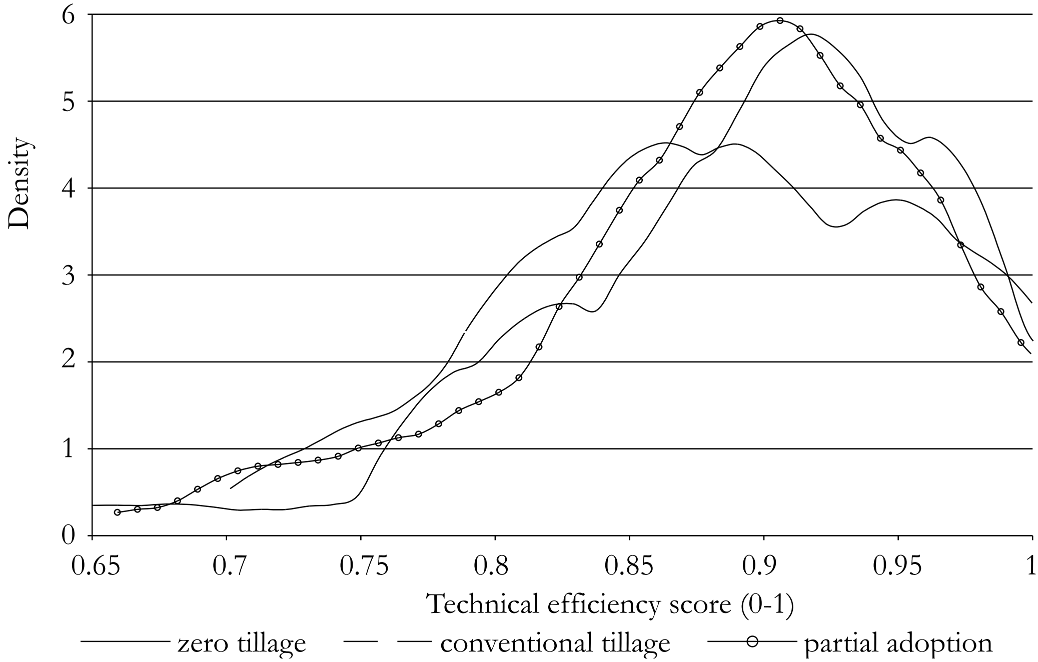
The ZT variable determines the production frontier level but does not influence its shape. The model specification in equation (4), the ZT variable, explains the differences in efficiency across farms with different levels of ZT adoption. Alternatively, this technology variable represents farm heterogeneity and their production environment. In contrast to conventional DEA, the StoNED approach provides a clear advantage as the z variable is incorporated in the model directly and estimates the parametric part involving the z variable jointly with the non-parametric frontier (Johnson & Kuosmanen 2011; Johnson & Kuosmanen 2012; Kuosmanen 2012). The coefficient of the ZT variable, thus, follows the conventional properties of an estimate for statistical inferences. The coefficient of z variable (ZT) reported in Table 6 influences wheat yield significantly and positively. Adopting ZT increases wheat production by 8 per cent on average over conventional wheat production. Erenstein and Laxmi (2008) also reported similar yield effects (6 per cent on average) in rice–wheat systems in the IGP. Mehla et al. (2000) reported a higher ZT yield gain of 15.4 per cent in on-farm trials in Haryana. Many of these studies are based on on-station or on-farm trials and very few field studies have been conducted (Erenstein & Laxmi 2008). Moreover, ZT technology will also influence crop production activities such as date of sowing, input use, etc. Thus, in addition to tillage technology, ZT captures the part of the production environment that influences the wheat production process.

3.4. Technical Efficiency of ZT: Moments Approach

Following the method of moments approach, CNLS Technical Efficiency (TE) scores are estimated and represented using Kernal density estimates in Figure 3. The average input-oriented efficiency score is 0.89, which denotes that 11 per cent of the current resource use could be saved by increasing farm performance to the highest level. In other words, the same level of output can be produced with 11 per cent less resources if all farms produce at the frontier level. Out of the total 180 farms, 17 (9 per cent) are efficient (with TE score of 1.00). This is in contrast with the standard DEA where the percentage of dominant farms is high (18 per cent in our sample) due to the absence of noise terms in model formulation. Density distribution of farmers with respect to TE shows a clearly distinctive pattern: a steady increase in share of farms at the lower efficiency level (TE scores from 0.61 to 0.75) followed by a sharp increase at the average efficiency score (TE from 0.75 to 0.95) and finally a steady increase at the high efficiency region (TE: 0.95 to 1.00). Previous studies have reported a similar TE distribution: Huang and Bagi (1984) estimated an average TE of 0.90 for high yielding wheat in this region using translog production model whereas Malana & Malano (2006) estimated an average TE of 0.85 in the DEA framework.

The full adopters of ZT technology are found performing better than other farmers (including the partial adopters and non-adopters), providing an efficiency gain of approximately 1 per cent (Figure 3). However, it should be remembered that in the CNLS frontier model, ZT is treated as an environmental (external) variable influencing the frontier. The Kernal density graph (Figure 3) did not show any substantial differences in average efficiency between ZT adopters and non-adopters. Nevertheless, the pace of achieving high efficiency levels (TE score above 0.90) is comparatively faster for ZT partial/full adopters than non-adopters. As stated before, the major influence of this RCT is captured by DoS in the frontier model: as DoS is delayed, the TE reduces. There is very substantial efficiency gain (16 per cent) for early growers compared to late growers. Kamruzzaman & Islam (2008) also reported a similar trend in technical efficiency gain for early sowing of wheat compared to late sowing.

Figure 3: Kernal density estimates of technical efficiency scores with respect to ZT adoption



3.5. Determinants of ZT efficiency

The results of the Tobit model (Table 6) suggests that the technical efficiency of wheat production is positively associated with ZT, land cultivated, farm remoteness, and the district they belong to. No significant associations between technical efficiency and household characteristics (such as age and education of head of household) are observed. Further, the date of sowing does not show any significant influence over technical efficiency. Note that the effect of DoS is shown as decreasing marginal productivity and the variable ZT captures a significant part of the efficiency gain attributed to timely sowing. In this model, DoS explains only the remaining effect of the delay in the date of sowing on technical efficiency given the adoption of ZT technology.

Subsequently, further analysis is conducted to examine the marginal effect of these determinants to understand to what degree these farm-household characteristics and technology adoption influence the efficiency of wheat production. The efficiency gain from adopting ZT technology is estimated as 14 per cent. As stated above, the timely sowing of wheat plays a vital role in ZT technology and hence this efficiency gain is attributed partly to

DoS as well. If we examine the effect of DoS, it shows a negative but insignificant effect on technical efficiency. Thus, by proper adoption of ZT, the expected efficiency gain would be more than 14 per cent. The insignificance of this variable can also be attributed to the fact that most farms sow seeds by the second week of November and none of them delay cultivation until after November (Table 4).

The remoteness of the farm from the city influences the efficiency positively, i.e., farms situated 1 km away from the city showed a marginal efficiency gain of 0.25 per cent. Here, our focus is on ZT farming where inputs are used at low intensity. Hence, the remoteness influences such a farming system positively as the input access is no more a limiting factor in the production process (usually, the input access of remote farms is lower compared to those farms close to the city; in conventional farming, this can reduce crop productivity). For every unit increase in land, technical efficiency increases by 2 per cent. Some studies showed that ZT benefits are scale-neutral in terms of yield gain (Malik et al. 2005; Thakur et al. 2005) but none analysed the efficiency gain associated. Our study departs from the above and shows that the scale of operation influences the technical efficiency of ZT wheat. Further, compared to the reference district (Ambala), the districts Kaithal and Kurukshetra are found 4 per cent and 9 per cent more efficient, respectively, in wheat production.

4. CONCLUSION

Prosperity and food and nutritional security are heavily dependent on increasing food crop productivity, given the fixity of land. Reportedly, productivity must grow at 2 per cent every year to meet the future wheat demand imposed by the increasing population and economic growth in India and other South Asian countries (Reynolds et al. 2008). Unfortunately, the challenges are compounded by the sluggish productivity growth after the green revolution (Rejesus et al. 1999); impediments due to second-generation problems such as climate change (Fischer et al. 2002); water scarcity (Shiklomanov & Rodda 2003); inappropriate and under-developed agricultural production (both inputs and output oriented) institutions, etc. In this context, feeding the continually growing population without further sacrificing environmental integrity is a great challenge for the coming decades. Understanding the productivity and efficiency of different types of farming is essential to producing sufficient food and fibre at minimal environmental cost. This paper is the first attempt to compare the productivity and efficiency of a promising wheat production technology with that of traditional wheat cultivation using farm-level data. The productivity gain is verified by different approaches (parametric and semi-parametric). Our study showed a promising result of 7–8 per cent yield gain for ZT wheat over conventional wheat. The early ZT growers showed a substantial efficiency gain (16 per cent) compared to the conventional late growers. Indian agriculture is facing serious productivity gaps at various levels with low average yields. The silver lining to the cloud is that the productivity gaps are bridgeable, for example by using appropriate technology such as ZT.

The agrarian crisis and consequent decelerating agricultural productivity growth induced an agrarian transformation in India. An environmentally friendly, productive, and efficient production technology is essential to tackle the growing challenges in Indian agriculture. Zero tillage is one such promising CA technology that can be integrated with low chemical input use. In our study, this technology's productivity and efficiency is significantly higher than that of the conventional cultivation method. Input use is also minimal. But the factors of no/low adoption of this promising technology need to be investigated in detail considering the existing low rate of ZT diffusion. Further, agricultural policies promoting such types of technology are central to achieving the objective of environmentally sustainable, efficient, and productive wheat cultivation in realising the 'evergreen revolution' visualised by the Indian government.

References

Ali, M., Byerlee, D., 2000. Productivity growth and resource degradation in Pakistan's Punjab: a decomposition analysis, Policy Research Working Paper No. 2480. World Bank, Washington DC.

Chauhan, B.S., Yadav, A., Malik, R.K., 2002. Zero tillage and its impact on soil properties: a brief review, in: Malik, R.K., Balyan, R.S., Yadav, A., Pahwa, S.K. (Eds.), Herbicide Resistance Management and Zero Tillage in Rice-Wheat Cropping System. CCSHAU, Hisar, India, pp. 109-114.

Coventry, D.R., Poswal, R.S., Yadav, A., Gupta, R.K., Gill, S.C., Chhokar, R.S., Kumar, V., Sharma, R.K., Kumar, A., Mehta, A., Kleemann, S.G.L., Cummins, J.A., 2011. Effect of tillage and nutrient management on wheat productivity and quality in Haryana, India. Field Crops Research 123, 234-240.

Dabur, K.R., Malik, R.K., Singh, S., Yadav, A., Banga, R.S., 2002. Impact of zero tillage in wheat on nematodes population under rice–wheat cropping system, in: Malik, R.K., Balyan, R.S., Yadav, A., Pahwa, S.K. (Eds.), Herbicide Resistance Management and Zero Tillage in Rice–Wheat Cropping System. CCSHAU, Hisar, India, pp. 162-165.

Ekboir, J., 2002. Developing no-tillage packages for small-scale farmers, in: Ekboir, J. (Ed.), World wheat overview and outlook. CIMMYT, Mexico, DF, pp. 1-38.

Erenstein, O., 2009. Adoption and Impact of Conservation Agriculture –Based Resource Conserving Technologies in South Asia, 4th World Congress on Conservation Agriculture, New Delhi, India.

Erenstein, O., Farooq, U., 2009. A survey of factors associated with the adoption of zero tillage wheat in the irrigated plains of South Asia. Experimental Agriculture 45, 133-147.

Erenstein, O., Farooq, U., Malik, R.K., Sharif, M., 2007a. Adoption and impacts of zero tillage as a resource conserving technology in the irrigated plains of South Asia, Comprehensive Assessment of Water Management in Agriculture - Research Report 19. International Water Management Institute, Colombo, Sri Lanka.

Erenstein, O., Farooq, U., Malik, R.K., Sharif, M., 2008a. On-farm impacts of zero tillage wheat in South Asia's rice-wheat systems. Field Crops Research 105, 240-252.

Erenstein, O., Laxmi, V., 2008. Zero tillage impacts in India's rice-wheat systems: A review. Soil & Tillage Research 100, 1-14.

Erenstein, O., Malik, R.K., Singh, S., 2007b. Adoption and Impacts of zerotillage in the irrigated Rice–Wheat systems of Haryana, India, Research Report. CIMMYT India & RWC, New Delhi, India.

Erenstein, O., Sayre, K., Wall, P., Dixon, J., Hellin, J., 2008b. Adapting no-tillage agriculture to the conditions of smallholder maize and wheat farmers in the tropics and sub-tropics, in: Goddard, T., Zoebisch, M.A., Gan, Y.T., Ellis, W., Watson, A., Sombatpanit, S. (Eds.), No-till farming systems. Special publication NO.3. World Association of Soil and Water Conservation, Bangkok, pp. 253-277.

Fan, Y., Li, Q., Weersink, A., 1996. Semiparametric Estimation of Stochastic Production Frontier Models. Journal of Business & Economic Statistics 14, 460-468.

FAO, 2010. Conservation Agriculture. Website: http://www.fao.org/ag/ca/.

Färe, R., Grosskopf, S., Lovell, C.A.K., 1994. Production Frontiers. Cambridge University Press, London.

Franke, A.C., Singh, S., McRoberts, N., Nehra, A.S., Godara, S., Malik, R.K., Marshall, G., 2007. Phalaris minor seedbank studies: longevity, seedling emergence and seed production as affected by tillage regime. Weed Research 47, 73-83.

GoI, 2009. Agricultural statistics at a glance 2009. Ministry of Agriculture, Government of India, New Delhi,India.

Gupta, R.K., Naresh, R.K., Hobbs, P.R., Ladha, J.K., 2002. Adopting conservation agriculture in the rice–wheat system of the Indo-Gangetic Plains: new opportunities for saving water, in: Bouman, B.A.M., Hengsdijk, H., Hardy, B., Bindraban, P.S., Tuong, T.P., Ladha, J.K. (Eds.), Water wise rice production. Proceedings of the international workshop on water wise rice production. nternational Rice Research Institute, Los Banos, Philippines, pp. 207-222.

Gupta, R.K., Sayre, K., 2007. Conservation agriculture in South Asia. Journal of Agricultural Science 145, 207-214.

Harrington, L., Erenstein, O., 2005. Conservation Agriculture and Resource Conserving Technologies- A global perspective. Agromeridian 1, 32-43.

Henderson, D.J., Simar, L., 2005. A fully nonparametric stochastic frontier model for panel data, Discussion Paper 0417. Institut de Statistique, Universite Catholique de Louvain, Belgium.

Hobbs, P.R., 2007. Conservation agriculture: what is it and why is it important for future sustainable food production? Journal of Agricultural Science 145, 127-137.

Hobbs, P.R., Gupta, R.K., 2003. Resource-conserving technologies for wheat in the rice–wheat system. In: , in: Ladha, J.K., Hill, J.E., Duxbury, J.M., Gupta, R.K., Buresh, R.J. (Eds.), Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts. ASA-CSSA-SSSA, Madison, Wisconsin, USA, pp. 149-172.

Hobbs, P.R., Gupta, R.K., 2004. Problems and challenges of no-till farming for the rice–wheat systems of the Indo-Gangetic plains in South Asia, in: Lal, R., Hobbs, P.R., Uphoff, N., Hansen, D.O. (Eds.), Sustainable Agriculture and the International Rice–Wheat System. Marcel Dekker, New York, pp. 101-120.

Holden, D., 2004. Testing the Normality Assumption in the Tobit Model. Journal of Applied Statistics 31, 521-532.

Huang, C.J., Bagi, F.S., 1984. Technical Efficiency on Individual Farms in Northwest India. Southern Economic Journal 51, 108-115.

Jehangir, W.A., Masih, I., Ahmed, S., Gill, M.A., Ahmad, M., Mann, R.A., Chaudhary, M.R., Turral, H., 2007. Sustaining crop water productivity in rice–wheat systems of South Asia: a case study from Punjab Pakistan, Working Paper 115. International Water Management Institute, Colombo, Sri Lanka.

Johnson, A., Kuosmanen, T., 2011. One-stage estimation of the effects of operational conditions and practices on productive performance: asymptotically normal and efficient, root-<i>n</i> consistent StoNEZD method. Journal of Productivity Analysis 36, 219-230.

Johnson, A.L., Kuosmanen, T., 2012. One-stage and two-stage DEA estimation of the effects of contextual variables. European Journal of Operational Research 220, 559-570.

Kamruzzaman, M., Islam, M.H., 2008. Technical efficiency of wheat growers in some selected sites of Dinajpur District of Bangladesh. Bangladesh Journal of Agricultural Research 33, 363-373.

Kneip, A., Simar, L., 1996. A general framework for frontier estimation with panel data. Journal of Productivity Analysis 7, 187-212.

Kortelainen, M., 2008. Estimation of Semiparametric Stochastic Frontiers Under Shape Constraints with Application to Pollution Generating Technologies Keskustelualoitteita #55 Department of Economics and Business Administration, University of Joensuu, Joensuu, Finland.

Krishna, V., Bhatia, M.M., Teufel, N., Bashnoi, D., 2013. Characterizing the cereal systems and identifying the potential of Conservation Agriculture in South Asia, CIMMYT Socio-Economics Working Paper 4. CIMMYT, Mexico, D.F.

Kumbhakar, S.C., Park, B.U., Simar, L.o., Tsionas, E.G., 2007. Nonparametric stochastic frontiers: A local maximum likelihood approach. Journal of Econometrics 137, 1-27.

Kuosmanen, T., 2012. Stochastic semi-nonparametric frontier estimation of electricity distribution networks: Application of the StoNED method in the Finnish regulatory model. Energy Economics. http://dx.doi.org/10.1016/j.eneco.2012.03.005.

Kuosmanen, T., Kortelainen, M., 2012. Stochastic non-smooth envelopment of data: semi-parametric frontier estimation subject to shape constraints. Journal of Productivity Analysis 38, 11-28.

Laxmi, V., Erenstein, O., Gupta, R.K., 2007. Impact of Zero Tillage in India's Rice-Wheat Systems, Research Report. CIMMYT & RWC, New Delhi, India.

Malana, N.M., Malano, H.M., 2006. Benchmarking productive efficiency of selected wheat areas in Pakistan and India using data envelopment analysis. Irrigation and Drainage 55, 383-394.

Malik, R.K., Gupta, R.K., Singh, C.M., Brar, S.S., Singh, S.S., Sinha, R.K., Singh, A.K., Singh, R., Naresh, R.K., Singh, K.P., Thakur, T.C., 2004. Accelerating the Adoption of Resource Conservation Technologies for Farm Level Impact on Sustainability of Rice–Wheat System of the Indo-Gangetic Plains, NATP Progress Report. CCS HAU, Haryana, India.

Malik, R.K., Yadav, A., Gupta, R.K., Singh, S., Hobbs, P.R., Bellinder, R.R., 2005. Introduction and success of zero tillage in wheat under rice-wheat cropping system in Haryana, India-related stories. In Accelerating the adoption of resource conservation technologies in rice wheat system of the Indo-Gangetic Plains. , in: Malik, R.K., Gupta, R.K., Singh, C.M., Yadav, A., Brar, S.S., Thakur, T.C., Singh, S.S., Singh, A.K., Singh, R., Sinha, R.K. (Eds.), Proceedings of the project workshop June 1-2. Directorate of Extension Education, CCS HAU., Hisar, Haryana, India.

Mehla, R.S., Verma, J.K., Gupta, R.K., Hobbs, P.R., 2000. Stagnation in the Productivity of Wheat in the Indo-Gangetic Plains: Zero-till-seed-cum-fertilizer Drill as an Integrated Solution, Rice-Wheat Consortium Paper Series 8. RWC, New Delhi, India.

Mohanty, M., Painuli, D.K., Misra, A.K., Ghosh, P.K., 2007. Soil quality effects of tillage and residue under rice-wheat cropping on a Vertisol in India. Soil and Tillage Research 92, 243-250.

Park, B.U., Sickles, R.C., Simar, L., 1998. Stochastic panel frontiers: A semiparametric approach. Journal of Econometrics 84, 273-301.

Park, B.U., Sickles, R.C., Simar, L.o., 2003. Semiparametric-efficient estimation of AR(1) panel data models. Journal of Econometrics 117, 279-309.

Park, B.U., Sickles, R.C., Simar, L.o., 2007. Semiparametric efficient estimation of dynamic panel data models. Journal of Econometrics 136, 281-301.

Rejesus, R.M., Heisey, P.W., Smale, M., 1999. Sources of Productivity Growth in Wheat: A Review of Recent Performance and Medium to Long-Term Prospects, CIMMYT Economics Working Paper 99-05. CIMMYT, Mexico, D.F.

Reynolds, M.P., Hobbs, P., Ortiz, R., Pietragalla, J., Braun, H.J., 2008. International Wheat Improvement: Highlights from an Expert Symposium, in: M.P., R., Pietragalla, J., Braun, H.J. (Eds.), International Symposium on Wheat Yield Potential: Challenges to International Wheat Breeding. CIMMYT, Mexico, D.F.

S. Singh, A.Y., R.K. Malik, H. Singh, 2002. Long-term effect of zero-tillage sowing technique on weed flora and productivity of wheat in rice–wheat cropping zones of Indo-Gangetic Plains, in: Malik, R.K., Balyan, R.S., Yadav, A., Pahwa, S.K. (Eds.), Herbicide Resistance Management and Zero Tillage in Rice-Wheat Cropping System. CCSHAU, Hisar, India, pp. 155-157.

Saharawat, Y.S., Malik, R.K., Ladha, J.K., Gathala, M., Jat, M.L., V., K., 2010. Evaluation of alternative tillage and crop establishment methods in a rice–wheat rotation in North Western IGP. Field Crops Research 116, 260-267.

Sharma, R.K., Chhokar, R.S., Chauhan, D.S., Gathala, M.K., Rani, V., Kumar, A., 2002. Paradigm tillage shift in rice–wheat system for greater profitability, in: Malik, R.K., Balyan, R.S., Yadav, A., Pahwa, S.K. (Eds.), Herbicide Resistance Management and Zero Tillage in Rice-Wheat Cropping System. CCSHAU, Hisar, India, pp. 131-135.

Shiklomanov, A., Rodda, J.C., 2003. Summary of the Monograph 'World Water Resources at the beginning of the 21 st Century', Prepared in the framework of IHP, UNESCO. Available online: http://webworld.unesco.org/water/ihp/db/shiklomanov/summary/html/summary.html.

Thakur, T., Deshmukh, S.G., Kaushik, S.C., Kulshrestha, M., 2005. Impact assessment of the Electricity Act 2003 on the Indian power sector. Energy Policy 33, 1187-1198.

Timsina, J., Connor, D.J., 2001. Productivity and management of rice–wheat cropping systems: issues and challenges. Field Crops Research 69, 93-132.

SUPPLEMENTARY INFORMATION

This information is derived from another baseline survey, conducted as part of the Cereal Systems Initiative for South Asia (CSISA) project in Haryana. Data were collected by CIMMYT (New Delhi) through the project hub at Karnal, from 323 wheat-growing households of Haryana state, following a multi-stage stratified random sampling procedure. Information was gathered from sample respondents from 18 villages (9 project intervention and 9 control) between June and November 2010. The villages were not selected based on the level of technology adopted, unlike in the present study, and the adoption pattern could be considered representative of Haryana. The key results are presented in Tables S1 and S2.

Table S1: Adoption pattern of ZT technology in Haryana

Farmer class	Number of observations	Familiarity with the ZT technology; per cent farmers				Median year of		per cent disadoption	Duration in years between adoption and dis-adoption
		no information	only heard	heard &seen	adopted on-farm	first adoption	last adoption		
Small (≤ median)	164	6.7	3.7	70.1	19.5	2005/06	2007/08	78.1	2.3 (1.4)
Large (> median)	159	1.9**	1.3	44.0***	52.8***	2005/06	2007/08	69.0	2.3 (1.2)
From intervention village	162	3.7	1.9	55.6	38.9	2005/06	2007/08	71.4	2.2 (1.33)
From non-intervention village	161	5.0	3.1	59.0	32.9	2006/07	2008/09	71.7	2.4 (1.15)

Notes: Figures in parenthesis show std. deviation. *** , **, * : difference between farmer classes is statistically significant at 0.01, 0.05 and 0.10 levels, respectively.

Table S2: Reasons for non-adoption and dis-adoption of the ZT technology

	Farmer class	Number of observations	per cent farmers who based their decision of non/dis-adoption on							
			farmer attributes	land/soil attributes	scarcity of machine	low seedling vigour	high weed infestation	lower yield	other reasons	no stated reason
Non-adoption	Small	121	9.1	12.4	13.2	14.0	10.7	50.4	1.7	4.1
	Large	72	1.4**	1.4***	22.2*	31.9***	20.8*	41.7	1.4	4.2
Disadoption	Small	25	0.0	0.0	4.0	20.0	8.0	48.0	8.0	28.0
	Large	58	0.0	0.0	1.7	17.2	17.2	60.3	6.9	22.4

Notes: *** , **, * : difference between farmer classes is statistically significant at 0.01, 0.05 and 0.10 levels, respectively.