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Zero-tillage wheat provides stable yield and economic benefits under diverse growing season climates in the Eastern Indo-Gangetic Plains

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ABSTRACT

Sustainably enhancing wheat productivity in the Indo-Gangetic Plains (IGP) is vital for ensuring future food security. While in controlled field trials zero-tillage (ZT) wheat has demonstrated considerable yield benefits, empirical assessments of the performance stability of the practice in farmers' fields under varying climatic conditions are lacking. Given progressive climate change, this constitutes an important knowledge gap which we address with a unique panel dataset from 961 farm households in Bihar, India, spanning two favourable and two less favourable growing seasons. We employ an endogenous switching regression (ESR) framework to derive unbiased estimates of the expected impacts of ZT on wheat yields and production costs among the farming population (average treatment effect, ATE). The prevailing ZT practices led to significant yield gains in three out of the four years, notably in the less favourable seasons. Overall, the estimated yield ATE was 660 kg ha^{-1}. More importantly from the farmers' perspective, ZT led to significant cost savings in all four seasons, commensurate to a 5% increase in average total household incomes. We conclude that ZT for wheat in Bihar provides tangible and consistent benefits to farmers. Policymakers in Bihar and adjacent states should continue to strongly support its adoption at scale.

1. Introduction

The Indo-Gangetic Plains (IGP) are home to more than 20% of the global population, and sustainably enhancing the productivity of the prevailing rice-wheat cropping systems is vital for ensuring future food security in South Asia (Chauhan et al., 2012). The potential to increase yields is particularly large in the Eastern IGP, such as the state of Bihar (Jain et al., 2017; Singh et al., 2020). On the one hand, Bihar has the lowest wheat yields in the IGP, averaging 2.17 MT ha^{-1} over the period 2010/11–2015/16, less than half of the 4.70 MT ha^{-1} achieved in the Northwestern state of Punjab (MoA, 2017a). On the other hand, the Eastern IGP has a wealth of under-developed water

resources (Aggarwal et al., 2004; DoA, 2019), whereas intensive irrigation has led to dramatic declines in groundwater tables in the Northwest (Humphreys et al., 2010). To meet both state and national-level cereal demand over the coming decades, technologies are urgently needed that sustainably enhance agricultural productivity in the Eastern IGP and are adoptable at scale by smallholders who have landholding sizes well below one hectare.

Across the IGP, the use of zero tillage (ZT) in wheat cultivation has demonstrated agronomic and economic benefits, while improving the environmental footprint of agriculture (Aryal et al., 2015; Chauhan et al., 2012; Erenstein & Laxmi, 2008; Gathala et al.,

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2013; Gupta et al., 2019; Mehla et al., 2000; Sapkal et al., 2019; Singh et al., 2020). Despite this evidence, a global meta-analysis of paired comparisons of crop yields in ZT and conventionally tilled production systems questioned the significance of the technology as an integral part of a sustainable intensification strategy (Pittelkow et al., 2014). The study concluded that ZT tended to entail sizeable yield benefits only if combined with residue retention and crop rotation. However, in the Eastern IGP, retaining soil cover is currently not a viable option for most farmers: first, the commonly used ZT seed drills are unsuitable for sowing crops into large quantities of loose crop residues and, second, rice straw is an important feed source for livestock in the prevailing mixed agricultural systems. Wheat is cultivated in the winter (*rabi*) season, extending from November to early April. The prevailing ZT practice uses a ZT seed drill attached to a relatively small four-wheel tractor[1] to sow wheat directly into unplowed fields with a single pass (Erenstein & Laxmi, 2008; Singh et al., 2020). The typical ZT drill opens 6–13 narrow slits using inverted-T openers to place both seed and fertilizers at a depth of 7.5–10 cm (Mehla et al., 2000). In contrast, CT practices in wheat typically involve multiple passes of the tractor to accomplish plowing, harrowing, planking, and to incorporate hand-broadcasted seeds (Erenstein & Laxmi, 2008; Singh et al., 2020). Since tractor ownership in Bihar is typically confined to larger landowners,[2] the vast majority of other farmers depend on tillage or ZT service providers for wheat establishment.

Based on a random sample of 1,000 farm households in Bihar and production data from the *rabi* seasons 2011/12 and 2012/13, Keil et al. (2015) found that the use of ZT in wheat – with only partial retention of anchored crop residues – led to a yield increase of 498 kg ha^{-1} (19%) over conventional-tillage wheat. In addition, the practice reduced crop establishment costs by 46%. The yield gains and cost savings amounted to an estimated combined average economic benefit of 7,334 INR[3] per hectare, equivalent to a 6% increase in annual household income among sample households. However, due to varying climatic conditions, average wheat productivity in Bihar has fluctuated significantly over the recent past. Whereas the *rabi* season 2012/13 offered favourable growing conditions with average wheat productivity in Bihar of 2.43 MT ha^{-1} (MoA, 2015), average yields declined to 1.85 MT ha^{-1} in the 2014/15 *rabi* season (MoA, 2017a). Wheat yield data

spanning the period since the beginning of the Green Revolution illustrate that, while the yield gap has increased over time between the Western IGP (Haryana) and the Eastern IGP (Bihar), the annual deviations from longer-term trends show a similar pattern with maxima in 2012 and marked depressions in 2015 and 2016. Most of the simultaneous dips in wheat productivity have likely been caused by differences in the onset of the timing of terminal heat stress, a factor that has been identified as the main cause of wheat yield depressions across the IGP (Jain et al., 2017; Lobell et al., 2008). This applies to the year 2016, when average and maximum temperatures in February and March exceeded those in the other three years under consideration by approximately 3°C. In particular, extreme temperatures above 34°C that likely reduced crop growth and growing season duration (see Barlow et al., 2015) were reached on 36 days in the February–March period in 2016 as compared to 18 and 19 days in 2012 and 2013, respectively.[4] In contrast, the wheat yield depressions in 2015 were associated with unseasonal heavy rains and hailstorms: India saw the wettest March in 48 years, with nation-wide average rainfall in the period March 1–18 exceeding that of 'normal' years by 197%. In Bihar alone, 1.458 million ha of wheat were damaged (Bhushan et al., 2015) (Figure 1).

Regarding the suitability of ZT as a sustainable intensification technology for smallholders with a low risk-bearing capacity, it is crucial to assess the performance stability of the practice across both favourable and less favourable growing conditions which are anticipated to occur more frequently under progressive climate change (IPCC, 2018).

To further validate best-bet recommendations for sustainably enhancing wheat productivity in the Eastern IGP, the objective of this study is to assess the stability of agronomic and economic benefits of ZT wheat relative to conventional-tillage (CT) wheat under contrasting growing season climatic conditions with empirical evidence from farmers' fields in Bihar. We address this knowledge gap with a unique panel dataset and contribute to the existing body of literature in several ways: (1) by revisiting the original sample of 1,000 farm households used by Keil et al. (2015), we expanded the existing dataset to encompass two less favourable wheat growing seasons (untimely, excessive rainfall in 2014/15 and heat stress in 2015/16), enabling a comparison across varying climatic conditions; (2) in addition to modelling the impact of ZT technology on wheat yields, we expand
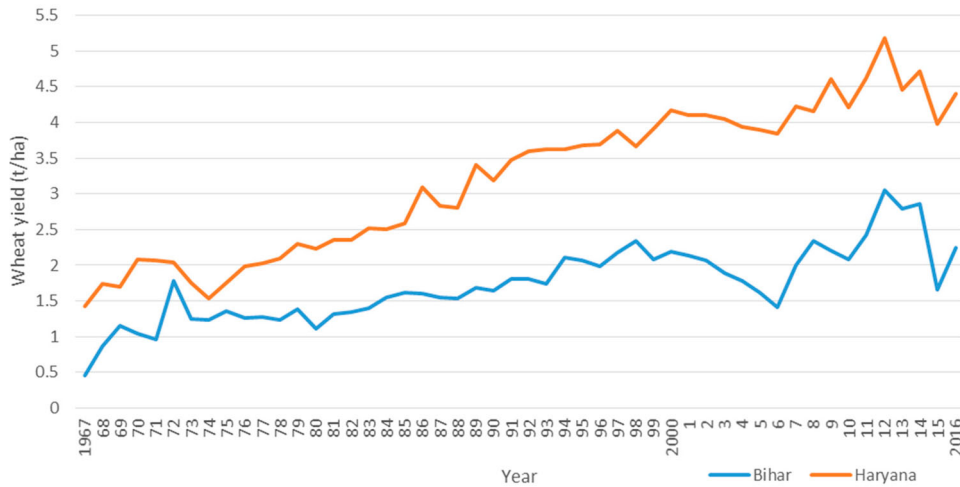
Figure 1. Average wheat yields from 1967–2016 for the states of Bihar and Haryana in the Eastern and Western Indo-Gangetic Plains, respectively. Source: Compiled by the authors from various government resources (DoA, 2017, 2018; DWD, 2017; ICAR, 2018; MoA, 2017a, 2017b, 2018).

the analysis to estimate per-unit production costs; (3) in comparison to the previous assessment by Keil et al. (2015) who used a Stochastic Frontier production function, we apply a methodologically superior approach that takes potential systematic differences between ZT users and non-users into account and allows all regression coefficients to vary between ZT and CT production systems, rather than assuming a shift of the production function.

The remainder of the paper is organized as follows: Section 2 provides a brief description of the research area, the sampling approach, and the kind of data used for the analysis; Section 3 derives our econometric model estimation strategy and details the final model specifications; Section 4 presents the results from our descriptive and econometric analyses, which are then discussed in Section 5. Section 6 concludes and derives policy recommendations.

2. Research area, sampling procedure, and data collection

In Bihar, about 77% of the population are engaged in agriculture (DoA, 2019). Although the state is endowed with good soil, sufficient rainfall and abundant groundwater, its agricultural productivity is one of the lowest among Indian states (MoA, 2017a). Major crops grown are paddy, wheat, pulses, maize, potato, sugarcane, oil seeds, tobacco and jute (DoA, 2019). The research area is composed of six districts

where the Cereal Systems Initiative for South Asia (CSISA; www.csisa.org) has focused research and scaling activities for sustainable intensification technologies since 2009 (Figure 2). Using a cluster sampling approach, a first round of survey was conducted in 2013 among a random sample of 1,000 wheat growing farm households in 40 villages. Owing to the nascent stage of ZT diffusion in the area, the village-level sampling frame was confined to 87 villages with at least 10 ZT users in the target districts, as documented by CSISA. The number of research villages selected per district was proportionate to the distribution of eligible villages, resulting in three research villages each in Begusarai, Lakhisarai and Vaishali districts, six villages each in Buxar and Samastipur, and 19 villages in Bhojpur District.

Based on soil characteristics, rainfall, temperature and terrain characteristics, the agricultural ministry of Bihar has identified four major agro-ecological zones in Bihar (DoA, 2019): the North Alluvial Plain (Zone I), the North-East Alluvial Plain (Zone II), the South-East Alluvial Plain (Zone III-A) and the South-West Alluvial Plain (Zone III-B). We use this classification to group the research districts by agro-ecological zone: (1) Vaishali, Samastipur and Begusarai (falling within Zone I), (2) Bhojpur and Buxar (Zone III-B), and (3) Lakhisarai (Zone III-A).

To ensure an adequate size of the adopter subsample, households were stratified by ZT adoption status before randomly selecting 10 ZT users and 15
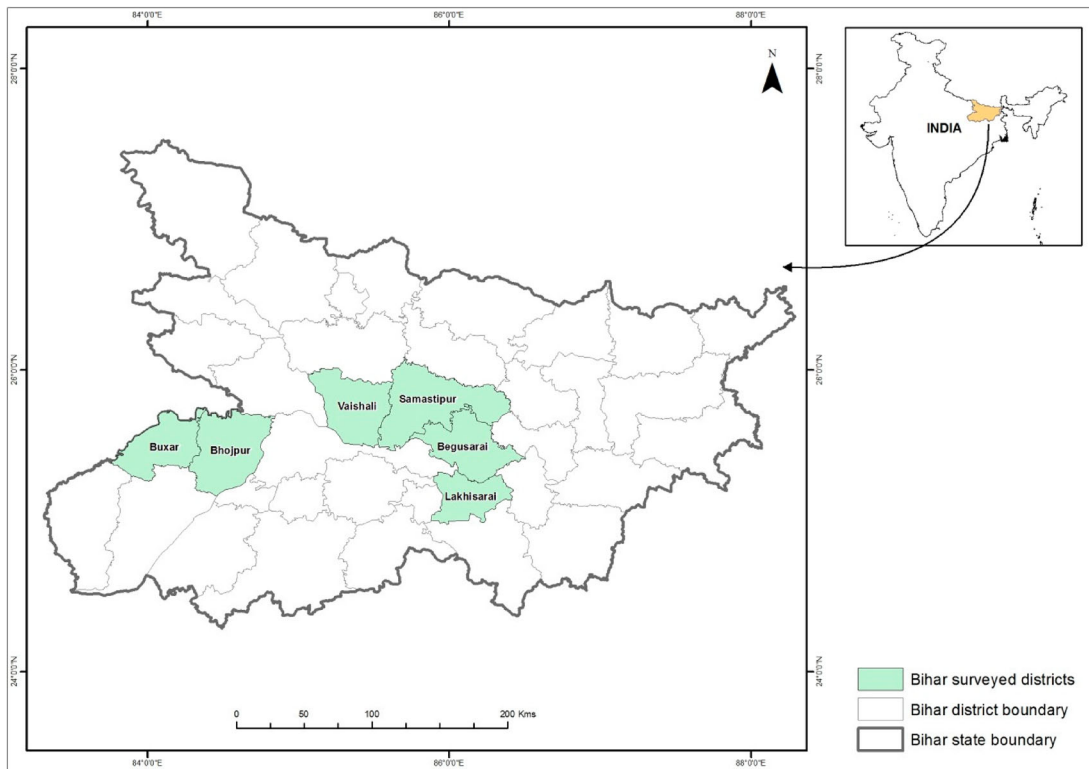
Figure 2. Map of the state of Bihar in northern India, highlighting the survey districts.

non-users in each of the 40 selected villages. Household-level sampling frames were compiled through brief census surveys in these villages, in which wheat growing farmers were identified and their ZT adoption status elicited.

In 2016, a second round of survey was conducted among the same sample households. Thirty-nine households (3.9%) could not be re-interviewed due to prolonged absence or permanent migration, resulting in a sample of 961 households for which panel data are available [dataset] (Keil et al., 2018a). In each survey round, detailed plot-level wheat production data were collected on the two preceding wheat growing seasons, resulting in a dataset encompassing *rabi* seasons 2011/12, 2012/13, 2014/15 and 2015/16. Each wave of survey also elicited data on the households' current asset endowment and other factors potentially influencing ZT adoption. Furthermore, survey respondents were asked to provide basic information on three farmers with whom they interacted most frequently about agricultural issues in order to be able to capture potential individual social network effects on ZT adoption. Data were collected from household heads by professional enumerators through structured interviews using CAPI software.[5]

3. Methodological approach

3.1. Model estimation strategy

3.1.1. Estimating the on farm impacts of zero-tillage adoption

A direct comparison of agronomic and economic performance indicators of wheat production between ZT adopting and non-adopting households can be misleading as these groups may have different characteristics. Keil et al. (2017) illustrated a significant scale bias with respect to ZT wheat adoption in Bihar, with adopters having significantly larger landholdings and higher levels of education, among other factors. Since observable and unobservable factors that influence ZT adoption may also affect the wheat performance indicators of interest, a direct comparison of the latter may be distorted by selection bias. We employ an endogenous switching regression (ESR) framework to produce unbiased estimates of the farm-level impacts of ZT adoption. The ESR

framework involves two stages, first a binary-choice selection equation identifying determinants of ZT adoption and, second, two regime equations explaining the outcome indicator of interest under ZT adoption and non-adoption, i.e. ZT wheat and CT wheat, respectively. To assess the impact of ZT adoption over time, we estimate separate models for each wheat season under consideration, t. The selection equation uses a probit model of the following general form:

$$a_{it} = \beta_t Z_{it} + \vartheta_{it} \qquad (1)$$

where $a_{it} = 1$ if household i used ZT in time period t, and $a_{it} = 0$ otherwise. As emphasized by Feder et al. (1985), a binary (yes/no) measure of technology adoption has severe shortcomings if there is great variation in the adoption *intensity* in terms of share of land allocated to the innovation. However, in our case we find that, once the decision is made to use ZT, the practice is applied to the entire wheat area by 82% of adopters, justifying the use of a binary dependent variable. Further, Z_{it} is a vector of exogenous regressors, β_t is a vector of parameters to be estimated, and ϑ_{it} is a random error term.

The outcome equations under ZT and CT production regimes are linear functions of the following form:

$$\text{CT wheat:} y_{0it} = \alpha_{0t} X_{it} + \varepsilon_{0it} \text{ if } a_{it} = 0 \qquad (2a)$$

$$\text{ZT wheat:} y_{1it} = \alpha_{1t} X_{it} + \varepsilon_{1it} \text{ if } a_{it} = 1 \qquad (2b)$$

where X_{at} are vectors of exogenous regressors affecting the outcome variables y_{at}, α_{at} are parameter vectors to be estimated, and ε_{at} are error terms for $a_{it} = 0$ (CT wheat) and $a_{it} = 1$ (ZT wheat) in period t, respectively.

After conditioning on observable covariates in Equation (1), the estimation procedure used allows unobservable components to affect both ZT adoption and the outcomes of interest:

$$E(\varepsilon_{ait}|a) \neq 0 \qquad (3)$$

The method controls for this potential endogeneity by including the residuals from the selection equation as regressors in the outcome equations. The technical details of this 'control function' approach are described by Wooldridge (2010). For a robust identification of the model, the selection equation should contain at least one variable that is omitted from the outcome equations, i.e. a selection instrument. A valid selection instrument will be correlated with

adoption, but uncorrelated with the outcome among non-adopters, which can easily be tested (Di Falco et al., 2011). We use variables related to the respondents' social networks and some additional characteristics as selection instruments (see Sections 3.1.2 and 3.2.2). The estimation procedure yields estimates of the following parameters of interest for each period t under consideration:

ATE – the average 'treatment' effect in the population ('treatment' = ZT use):

$$\text{ATE}_t = E(y_{1t} - y_{0t})$$

POM – the potential outcome mean for treatment level a:

$$\text{POM}_{at} = E(y_{at})$$

ATET – the average treatment effect among the treated, i.e. among ZT users:

$$\text{ATET}_t = E(y_{1t} - y_{0t}|a = 1)$$

The main focus of this study is the ATE as it estimates the expected impact of ZT technology among the entire underlying population of farm households, rather than the sub-population of ZT adopters only.

3.1.2. Accounting for social network effects in the adoption process

Since the seminal paper by Feder et al. (1985) on the adoption of agricultural innovations, which considered farm and farmer-specific characteristics as potential adoption determinants, micro-level adoption studies have been extended to include more dynamic elements related to social learning (Foster & Rosenzweig, 1995; Granovetter, 2005; Feder & Savastano, 2006). As pointed out by Manski (2000), farmers may not only be influenced by the adoption behaviour of their individual social networks (endogenous network effect), but also by their network members' characteristics (exogenous network effect). Drawing on the approach of Matuschke and Qaim (2009), we extend our selection equation (1) to account for endogenous and exogenous individual network effects as follows:

$$a_{it} = \beta_t Z_{it} + \gamma_t a_{n(it)} + \delta_t Z_{n(it)} + \vartheta_{it} \qquad (4)$$

where $a_{n(it)}$ denotes the adoption behaviour of household i's individual social network, $Z_{n(it)}$ is a vector of exogenous network member characteristics, and γ_t and δ_t are vectors of parameters to be estimated for period t.

3.2. Model specification

3.2.1. Selection equation: determinants of ZT adoption

Based on the review of adoption determinants of agricultural technologies by Feder et al. (1985) and drawing on the concept of livelihood resources as laid out in the sustainable livelihoods framework (Chambers & Conway, 1992; Scoones, 1998), we hypothesize that a household's asset base and risk preferences influence the decision to adopt ZT. The asset base includes (1) natural capital, (2) human capital, (3) financial capital, and (4) social capital and information access.[6] Table 1 provides the definitions and summary statistics of the dependent and explanatory variables used in the selection equation of the ESR. To adequately reflect the concept of information *access*, the variable *Extension access* indicates the extent to which information from the extension service was generally available, assessed on a Likert scale; frequently used alternative specifications, such as extension visits received or field days attended, constitute combined measures of extension access and the farmer's decision whether or not to make use of it (Doss, 2006). For similar reasons, we chose to measure *Credit access* in terms of potential credit availability on a Likert scale, rather than eliciting the amount actually borrowed, which potentially comingles access to credit with demand for credit. While most models of technology adoption treat risk preferences as an unobservable factor, we include a proxy of the household head's risk preferences as an explanatory variable, which is based on a self-assessment question and has been previously applied by Gloede et al. (2011).

As elaborated above, a salient feature of our model is the inclusion of the respondents' individual agricultural information network characteristics as explanatory variables. These variables are based on information provided by the survey respondents regarding those three farmers with whom they interacted most frequently about agricultural issues, referred to as network members (NMs). To capture endogenous network effects, we collected data on the NMs' HS adoption status of ZT wheat, including information on the timing of adoption. The latter is crucial to address what Manski (1993) coined the reflection problem: while the behaviour of NMs potentially influences the survey respondent, the reverse is also true. As suggested by Manski (2000), we therefore assume that the respondents' adoption decision is influenced by the level of success that their NMs had with the

technology. This 'seeing is believing' type of behaviour has been documented in various empirical studies (e.g. Foster & Rosenzweig, 1995; Dong & Saha, 1998). Hence, only those NMs who applied ZT earlier than the respondent enter our model as ZT-adopting NMs. To capture potential exogenous network effects, i.e. those caused by who the NMs are, rather than how they behave, we elicited information about their age, education, and caste (not all of which are included in the final model). Individual social networks tend to be characterized by a high degree of homophily, i.e. they are usually formed among farmers of a similar social status (Keil et al., 2017; Rogers, 2003). Econometrically this means that peer group membership itself is likely to be endogenous (Matuschke & Qaim, 2009; Songsermsawas et al., 2016), which the inclusion of NM characteristics as control variables may mitigate to some extent. Potential endogeneity could be better controlled through instrumental variables: Songsermsawas et al. (2016) employed the characteristics of friends of the respondents' network peers (who were unknown to the respondents themselves) as instruments for the peers' characteristics, but such costly-to-collect data were not available in our case.

3.2.2. Impact of zero-tillage on wheat yields and production costs

We analyse the impact of ZT in wheat on two outcome variables of interest: Model 1 estimates the ATE of ZT wheat relative to CT wheat regarding land productivity, i.e. grain yield measured in kg ha^{-1}; Model 2 estimates the ATE with respect to the profitability of wheat production, measured as per-unit production cost (PUC). To be able to assess the consistency of impacts over time, we estimate Models 1 and 2 for each individual wheat growing season and across the entire period. While recall-based plot-level wheat production data are available for *rabi* seasons 2011/12, 2012/13, 2014/15 and 2015/16, information on household-level determinants of ZT adoption for selection equation (4) was collected at the time of the two survey rounds in 2013 and 2016 only. Assuming that these household-level values are fairly accurate proxies of the situation in the previous year, 2013 and 2016 values were also used for the 2011/12 and 2014/15 outcome models, respectively. For simplicity, we henceforth use the year of crop establishment to refer to the wheat growing seasons under consideration, i.e. years 2011, 2012, 2014 and 2015.

In Model 2, PUC is defined as variable cost per metric ton (MT) of wheat grain produced. We do not

Table 1. Definitions and summary statistics of dependent and explanatory variables in the selection equation of Endogenous Switching regression models on impacts of zero-tillage wheat in Bihar, differentiated by survey year (panel data; standard deviations in parentheses).

Variable			2012 (N = 905)	2015 (N = 896)	Overall (N = 1,801)
Dependent variable					
ZT adoption	=	Dummy, = 1 if HH used ZT in wheat in the respective *rabi* season, 0 otherwise	0.295 (0.438)	0.421 (0.486)	0.357 (0.479)
Natural capital					
Cultivable area	=	Total area available for cultivation (ha)	1.258 (1.223)	1.351 (1.240)	1.304 (1.232)
Maximum plot size	=	Size of largest irrigable plot (ha)	0.599 (0.632)	0.638 (0.626)	0.619 (0.629)
Land owned	=	Dummy, = 1 if HH head owns land, 0 otherwise	0.898 (0.302)	0.891 (0.312)	0.895 (0.307)
Human capital					
Labour/land ratio	=	Labour-to-land ratio (no. HH members aged 15 to 65 ha^{-1})	8.348 (12.533)	7.539 (10.426)	7.945 (11.537)
Age	=	Age of HH head (years)	49.507 (13.200)	52.672 (13.321)	51.082 (13.351)
High education	=	Dummy, = 1 if educational achievement of HH head is > 12th grade, 0 otherwise	0.113 (0.316)	0.125 (0.331)	0.119 (0.324)
SC/ST category	=	Dummy = 1 if HH belongs to Scheduled Castes (SC) or Scheduled Tribes (ST), 0 otherwise[b]	0.123 (0.328)	0.122 (0.327)	0.122 (0.328)
General caste category	=	Dummy = 1 if HH belongs to one of the 'general' (non-marginalized) castes, 0 otherwise	0.406 (0.491)	0.411 (0.492)	0.408 (0.492)
Risk preference	=	HH head's general risk preference, self-assessed on a scale from 0 (= fully avoiding risk) to 10 (= fully prepared to take risk)	5.164 (2.191)	6.015 (1.664)	5.587 (1.992)
Financial capital					
Credit access	=	Logged max. amount HH could currently borrow ('000 INR)[a]	115.034 (246.242)	204.280 (235.631)	159.434 (245.054)
Access to information and ZT services					
Farmer association	=	Dummy, = 1 if HH head is member of the local farmer association	0.020 (0.140)	0.037 (0.188)	0.028 (0.166)
Extension access	=	Access to agricultural extension on a scale from 0 (= no access) to 5 (= very good access)	2.622 (1.388)	2.620 (1.384)	2.621 (1.386)
Mobile phone	=	Dummy, = 1 if HH owns at least one mobile phone, 0 otherwise	0.940 (0.237)	0.973 (0.162)	0.957 (0.204)
Radio	=	Dummy, = 1 if HH owns at least one radio, 0 otherwise	0.245 (0.431)	0.102 (0.302)	0.174 (0.379)
TV	=	Dummy, = 1 if HH owns at least one TV set, 0 otherwise	0.240 (0.427)	0.435 (0.496)	0.337 (0.473)
Social network characteristics					
NM ZT use*smallest	=	NM ZT use, interacted with smallest farm size tercile dummy variable	7.578 (23.881)	15.615 (34.766)	11.576 (30.059)
NM ZT use*middle	=	NM ZT use, interacted with middle farm size tercile dummy variable	13.138 (31.632)	14.950 (33.125)	14.039 (32.387)
NM ZT use*largest	=	NM ZT use, interacted with largest farm size tercile dummy variable	15.212 (33.518)	17.392 (35.196)	16.297 (34.371)
NM age	=	Average age of NMs (years)	48.424 (8.288)	49.662 (8.134)	49.040 (8.233)
District dummies (Bhojpur is base district)					
Begusarai	=	Dummy, = 1 if HH is located in Begusarai district, 0 otherwise	0.077 (0.267)	0.077 (0.267)	0.077 (0.267)
Bhojpur	=	Dummy, = 1 if HH is located in Bhojpur district, 0 otherwise	0.484 (0.500)	0.474 (0.500)	0.479 (0.500)
Buxar	=	Dummy, = 1 if HH is located in Buxar district, 0 otherwise	0.133 (0.339)	0.134 (0.341)	0.133 (0.340)
Lakhisarai	=	Dummy, = 1 if HH is located in Lakhisarai district, 0 otherwise	0.077 (0.267)	0.076 (0.265)	0.077 (0.266)
Samastipur	=	Dummy, = 1 if HH is located in Samastipur district, 0 otherwise	0.159 (0.366)	0.158 (0.365)	0.159 (0.366)

(Continued)

Table 1. Continued.

Variable			2012 (N = 905)	2015 (N = 896)	Overall (N = 1,801)
Vaishali	=	Dummy, = 1 if HH is located in Vaishali district, 0 otherwise	0.070 (0.255)	0.080 (0.272)	0.075 (0.263)

HH = Household.

[a]For ease of interpretation, summary statistics are provided for the unlogged variable.

[b]Scheduled Castes and Scheduled Tribes are government recognized categories of marginalized groups that have historically been discriminated against and are both socially and economically disadvantaged. The Indian Constitution has provisions to protect their rights and provide them with equal opportunities. The base category which HHs belonging to the *SC/ST category* and the *General caste category* are evaluated against are those belonging to the 'Other Backward Castes' (OBC), constituting an intermediate social stratum.

account for fixed costs in our analysis as these are highly idiosyncratic and largely independent of the two technologies under consideration. Land resources can be owned and/or rented in, as is the case with agricultural machinery. Furthermore, machine depreciation depends on use intensity, which in turn depends on the landholding size and the cropping system practiced. Moreover, the multitude of implements used vary widely in their respective investment cost and useful life, compromising any attempt to capture the associated fixed costs in a meaningful way. Hence, PUC includes fees paid for mechanization services[7] and renting of machinery, the cost of all physical inputs (seeds, fertilizers, herbicides, fungicides, pesticides) and irrigation, as well as the cost of hiring labour, covering the entire crop cycle from establishment through harvesting. PUC also includes the imputed cost of family labour input, valued at the median wage rate paid to hired labourers in the research area.

Both models use the same set of explanatory variables, encompassing agricultural input variables as well as agronomic-, management related-, timing related- and geographic control variables (Table 2). Same as yield, agricultural inputs are measured on a per-hectare basis, which is why land is omitted as an input factor. The variable *Capital input* encompasses all non-labour related variable costs; total labour input (both family and hired labour) is measured by *Labour input*. The dependent variables and agricultural input factors enter the model in their logged form as this achieves more compact distributions and a superior fit compared to the unlogged specification. Agronomic control variables are mostly related to wheat varieties and soil characteristics. Since ZT allows to establish wheat in one single pass of the tractor, it facilitates earlier sowing, hence helping to avoid yield depression due to terminal heat stress (Chauhan et al., 2012; Erenstein & Laxmi, 2008;

Gathala et al., 2013; Mehla et al., 2000). To be able to disentangle the yield effects of early sowing and ZT, dummy variables account for whether or not wheat was sown before December 01; as the effect of early sowing may vary geographically, we include interaction terms with agro-ecological zone dummies. However, the variables related to Zone 1 had to be dropped from the analysis due to multicollinearity. Management related control variables encompass the same set of variables as in the first stage (selection equation) of the ESR, apart from the following exceptions: *Credit access* is omitted since capital input is directly accounted for. Similar to Di Falco et al. (2011) who used variables measuring farmer-to-farmer extension as selection instruments, we identify variables related to social network characteristics (*Farmer association*, *NM ZT use* and *NM age*) as potential selection instruments and, hence, exclude them from the outcome equations (see Section 3.1.1). As suggested by Di Falco et al. (2011), we perform a simple test to verify the validity of these instruments: while all network related variables affect the decision to adopt ZT in at least one of the years under consideration (see Table 5), they should not affect wheat yields and PUC among the non-adopting households. The network related variables pass the test jointly and individually in both Model 1 and Model 2. Based on the same validation procedure we identify the age, risk preference and caste membership of the household head, as well as the land tenure related control variable to be additional valid instruments. In both the yield and PUC models, all instruments are jointly and individually insignificant in the outcome equation for CT wheat, overall and for the individual years under consideration.[8] In Model 1 (Model 2), F-tests on the joint significance of the instruments produce P-values of 0.98 (0.91) for the year 2011, 0.91 (0.97) for 2012, 0.54 (0.58) for 2014 and 0.30 (0.26) for 2015. P-values for the joint significance test in the 'Overall'

Table 2. Definitions and summary statistics of dependent and explanatory variables in regression models explaining wheat yield and per-unit production costs in conventional-tillage (CT) and zero-tillage (ZT) wheat growing regimes in Bihar (panel data; standard deviations in parentheses).

Variable		Years 2011 & 2012[a]		Years 2014 & 2015[a]		
		CT wheat (N = 1,370)	ZT wheat (N = 581)	CT wheat (N = 1,023)	ZT wheat (N = 748)	Overall (N = 3,722)
Dependent variables[b]						
Grain yield	= Logged wheat grain yield (kg ha^{-1})	2783.331 (1332.959)	3266.417 (1695.896)	2313.748 (1334.957)	2257.908 (1341.200)	2624.081 (1442.142)
Per-unit cost	= Logged total variable per-unit production cost (INR MT^{-1})[c]	7,869.657 (10,805.280)	5,760.225 (4,530.890)	13,147.880 (12,333.190)	14,200.550 (77,095.110)	10,263.410 (35,941.840)
Agricultural input variables[b]						
Capital input	= Logged total non-labour[d] capital input ('000 INR ha^{-1})	14.361 (6.605)	12.497 (5.585)	17.956 (6.714)	15.203 (6.251)	15.237 (6.679)
Labour input	= Logged hired and family labour input (person-hours ha^{-1})	150.872 (123.291)	126.265 (130.714)	141.169 (84.729)	93.089 (50.193)	132.752 (105.813)
Agronomic control variables						
Manual harvest	= Dummy, = 1 if wheat was manually harvested, 0 otherwise	0.802 (0.398)	0.580 (0.494)	0.848 (0.360)	0.511 (0.500)	0.721 (0.448)
HUW-234	= Dummy, = 1 if HUW-234 variety was used, 0 otherwise	0.107 (0.310)	0.165 (0.312)	0.152 (0.359)	0.171 (0.377)	0.141 (0.348)
Sonalika-1553	= Dummy, = 1 if Sonalika-1553 variety was used, 0 otherwise	0.035 (0.184)	0.086 (0.281)	0.094 (0.292)	0.076 (0.266)	0.067 (0.251)
PBW-154	= Dummy, = 1 if PBW-154 variety was used, 0 otherwise	0.113 (0.317)	0.074 (0.262)	0.055 (0.228)	0.126 (0.332)	0.093 (0.291)
PBW-343	= Dummy, = 1 if PBW-343 variety was used, 0 otherwise	0.335 (0.472)	0.212 (0.409)	0.453 (0.498)	0.116 (0.321)	0.304 (0.460)
UP-262	= Dummy, = 1 if UP-262 variety was used, 0 otherwise	0.131 (0.337)	0.060 (0.238)	0.016 (0.124)	0.024 (0.153)	0.067 (0.249)
LOK-1	= Dummy, = 1 if LOK-1 variety was used, 0 otherwise	0.131 (0.338)	0.155 (0.362)	0.055 (0.228)	0.036 (0.187)	0.095 (0.293)
Sandy soil	= Dummy, = 1 if soil is sandy, 0 otherwise	0.116 (0.324)	0.117 (0.322)	0.085 (0.279)	0.122 (0.327)	0.109 (0.311)
Sandy-loam soil	= Dummy, = 1 if soil is sandy loam, 0 otherwise	0.250 (0.433)	0.256 (0.437)	0.256 (0.437)	0.203 (0.403)	0.243 (0.429)
Loam soil	= Dummy, = 1 if soil is loam, 0 otherwise	0.404 (0.491)	0.410 (0.492)	0.389 (0.488)	0.370 (0.483)	0.394 (0.489)
Wheat damaged	= Dummy, =1 if yield was extraordinarily reduced by pests/diseases/terminal heat, 0 otherwise	0.231 (0.422)	0.251 (0.434)	0.296 (0.457)	0.349 (0.477)	0.276 (0.447)
Management related control variables						
Labour/land ratio	= Labour-to-land ratio (no. HH members aged 15 to 65 ha^{-1})	9.577 (13.575)	5.014 (6.950)	8.808 (11.969)	5.782 (7.455)	7.891 (11.371)
High education	= Dummy, = 1 if educational achievement of HH head is > 12th grade, 0 otherwise	0.085 (0.280)	0.181 (0.385)	0.103 (0.304)	0.159 (0.366)	0.120 (0.325)
Extension access	= Perceived access to agr. extension on a scale from 0 (= no access) to 5 (= very good access)	2.494 (1.381)	2.790 (1.373)	2.524 (1.407)	2.751 (1.343)	2.600 (1.384)
Mobile phone	= Dummy, = 1 if HH owns at least one mobile phone, 0 otherwise	0.936 (0.244)	0.959 (0.199)	0.967 (0.179)	0.984 (0.126)	0.958 (0.201)
Radio	= Dummy, = 1 if HH owns at least one radio, 0 otherwise	0.216 (0.412)	0.305 (0.461)	0.114 (0.318)	0.084 (0.278)	0.175 (0.380)
TV	= Dummy, = 1 if HH owns at least one TV set, 0 otherwise	0.188 (0.391)	0.358 (0.480)	0.391 (0.488)	0.499 (0.500)	0.333 (0.471)
No. implements owned	= No. of implements owned that are used for wheat establishment	0.055 (0.229)	0.120 (0.326)	0.052 (0.222)	0.090 (0.286)	0.071 (0.258)
No. services hired	= No. of custom-hiring services used for wheat establishment	0.938 (0.241)	0.869 (0.337)	0.902 (0.297)	0.876 (0.330)	0.905 (0.293)
Timing related control variables						
Rabi 2012/13	= Dummy, = 1 for *rabi* season 2012/13, 0 otherwise	0.492 (0.500)	0.563 (0.496)	–	–	0.269 (0.443)
Rabi 2014/15	Dummy, = 1 for *rabi* season 2014/15, 0 otherwise	–	–	0.486 (0.500)	0.509 (0.500)	0.236 (0.425)
Rabi 2015/16	=	–	–			

(Continued)

Table 2. Continued.

	Variable	Years 2011 & 2012[a]		Years 2014 & 2015[a]		Overall ($N = 3,722$)
		CT wheat ($N = 1,370$)	ZT wheat ($N = 581$)	CT wheat ($N = 1,023$)	ZT wheat ($N = 748$)	
	Dummy, = 1 for *rabi* season 2015/16, 0 otherwise			0.514 (0.500)	0.491 (0.500)	0.240 (0.427)
Early*Z2*Rabi 11/12	= Interaction effect between Agricultural Zone 2, sowing before Dec 01 and *rabi* season 2011/12	0.162 (0.369)	0.184 (0.388)	–	–	0.088 (0.284)
Early*Z3*Rabi 11/12	= Interaction effect between Agricultural Zone 3, sowing before Dec 01 and *rabi* season 2011/12	0.016 (0.126)	0.026 (0.159)	–	–	0.010 (0.099)
Early*Z2*Rabi 12/13	= Interaction effect between Agricultural Zone 2, sowing before Dec 01 and *rabi* season 2012/13	0.150 (0.356)	0.232 (0.423)	–	–	0.091 (0.288)
Early*Z3*Rabi 12/13	= Interaction effect between Agricultural Zone 3, sowing before Dec 01 and *rabi* season 2012/13	0.017 (0.129)	0.024 (0.153)	–	–	0.010 (0.099)
Early*Z2*Rabi 14/15	= Interaction effect between Agricultural Zone 2, sowing before Dec 01 and *rabi* season 2014/15	–	–	0.080 (0.272)	0.131 (0.338)	0.048 (0.215)
Early*Z3*Rabi 14/15	= Interaction effect between Agricultural Zone 3, sowing before Dec 01 and *rabi* season 2014/15	–	–	0.020 (0.044)	0.027 (0.052)	0.001 (0.033)
Early*Z2*Rabi 15/16	= Interaction effect between Agricultural Zone 2, sowing before Dec 01 and *rabi* season 2015/16	–	–	0.081 (0.273)	0.130 (0.336)	0.048 (0.215)
Early*Z3*Rabi 15/16	= Interaction effect between Agricultural Zone 3, sowing before Dec 01 and *rabi* season 2015/16	–	–	0.010 (0.031)	0.013 (0.037)	0.001 (0.023)
District dummies (Bhojpur is base district)						
Begusarai	= Dummy, = 1 if HH is located in Begusarai district, 0 otherwise	0.075 (0.264)	0.062 (0.241)	0.095 (0.293)	0.053 (0.225)	0.074 (0.262)
Bhojpur	= Dummy, = 1 if HH is located in Bhojpur district, 0 otherwise	0.446 (0.497)	0.632 (0.483)	0.442 (0.497)	0.523 (0.500)	0.489 (0.500)
Buxar	= Dummy, = 1 if HH is located in Buxar district, 0 otherwise	0.120 (0.325)	0.131 (0.337)	0.057 (0.235)	0.235 (0.424)	0.128 (0.334)
Lakhisarai	= Dummy, = 1 if HH is located in Lakhisarai district, 0 otherwise	0.060 (0.237)	0.091 (0.288)	0.088 (0.093)	0.159 (0.366)	0.071 (0.256)
Samastipur	= Dummy, = 1 if HH is located in Samastipur district, 0 otherwise	0.189 (0.392)	0.055 (0.228)	0.268 (0.443)	0.012 (0.109)	0.154 (0.361)
Vaishali	= Dummy, = 1 if HH is located in Vaishali district, 0 otherwise	0.110 (0.313)	0.029 (0.169)	0.128 (0.334)	0.017 (0.131)	0.084 (0.277)

Note: HH = Household.

[a]In the interest of saving space and since values are quite similar, descriptive statistics are aggregated across the two earlier and the two later years under consideration.

[b]For ease of interpretation, summary statistics are provided for the unlogged variables.

[c]INR = Indian Rupees; 1 USD = 65.3 INR (Nov 01, 2015); MT = metric ton. PUC includes imputed cost of family labour, valued at the median agricultural wage rate of 15.00 and 17.86 INR/hour across years 2011/2012 and 2014/2015, respectively.

[d]Including fees paid for mechanization services encompassing a labour- and a machine rental component.

specifications amount to 0.18 and 0.46 in Models 1 and 2, respectively.

4. Results

4.1. Characterization of zero-tillage adopters versus non-adopters

The rationale behind applying the ESR approach in the present study is to correct for selection bias due to potential systematic differences between ZT adopters and non-adopters (see Section 3.1.1). While the outcome equation of the ESR is based on plot-level data encompassing four wheat growing seasons, the following analysis uses household-level data collected in 2013 and 2016. The 2013 data comprise 269 ZT users and 541 users of conventional tillage (CT) who entered our ESR analysis,[9] whereas the 2016 data contain 367 ZT users and 526 CT users. Table 3 compares basic household

Table 5. Probit estimates of an Endogenous Switching Regression (ESR) explaining the adoption of ZT wheat in Bihar over the period 2011–2015 (= 1st stage of ESR; coefficients are marginal effects).

Variable	2011 Coeff.[a]	2011 z-value[b]	2012 Coeff.[a]	2012 z-value[b]	2014 Coeff.[a]	2014 z-value[b]	2015 Coeff.[a]	2015 z-value[b]	Overall Coeff.[a]	Overall z-value[b]
Cultivable area	0.1032	2.34**	0.1026	2.50**	0.0774	1.93*	0.0718	1.62	0.1127	3.65****
Cultivable area, sqd.	−0.0119	−1.78*	−0.0130	−2.01**	−0.0164	−3.30***	−0.0138	−2.58**	−0.0182	−4.19****
Maximum plot size	0.0062	0.20	0.0141	0.42	0.0650	2.12**	0.0636	1.87*	0.0668	2.35**
Land owned	0.0880	1.63	0.1137	2.30**	−0.0421	−1.16	−0.0595	−1.74*	0.0160	0.63
Labour/land ratio	−0.0053	−1.53	−0.0033	−1.32	−0.0013	−1.00	−0.0008	−0.68	−0.0025	−1.73*
Age	−0.0005	−0.48	0.0000	0.00	−0.0013	−1.24	−0.0004	−0.44	−0.0002	−0.24
High education	0.0739	1.52	0.0712	1.23	0.0551	1.56	0.0552	1.78*	0.0513	1.36
SC/ST category	0.0035	0.06	−0.0168	−0.28	−0.0642	−1.80*	−0.0441	−1.15	−0.0273	−0.61
General caste category	0.0898	2.15**	0.0736	1.76*	0.0387	1.19	0.0593	1.72*	0.0664	2.34**
Risk preference	0.0093	1.71*	0.0253	3.84****	0.0203	1.90*	0.0232	2.07**	0.0164	2.36**
Credit access	−0.0037	−1.22	−0.0009	−0.28	0.0403	3.12***	0.0167	1.14	0.0019	0.53
Farmer association	0.1507	1.72*	0.1187	1.26	0.0840	1.14	0.0883	1.43	0.1079	2.08**
Extension access	0.0045	0.60	0.0031	0.41	−0.0079	−0.95	−0.0065	−0.76	−0.0005	−0.10
Mobile phone	−0.0479	−0.72	−0.0310	−0.43	0.0192	0.27	0.0177	0.24	−0.0030	−0.05
Radio	0.0416	1.64	0.0160	0.59	0.0682	1.47	0.0710	1.40	0.0077	0.40
TV	0.0359	0.88	0.0412	1.05	0.0103	0.37	0.0297	1.11	0.0546	1.88*
NM ZT use*smallest	0.0018	3.11***	0.0019	3.26***	0.0034	6.85****	0.0033	6.71****	0.0031	9.69****
NM ZT use*middle	0.0010	2.12**	0.0013	2.20**	0.0037	11.60****	0.0036	11.53****	0.0025	6.54****
NM ZT use*largest	0.0009	2.42**	0.0012	2.88***	0.0030	5.67****	0.0028	6.18****	0.0017	4.23****
NM age	−0.0025	−1.94*	−0.0030	−1.71*	0.0018	1.14	0.0003	0.18	−0.0008	−0.67
Begusarai	−0.2396	−4.01***	−0.1689	−3.06***	−0.1711	−3.38***	−0.1423	−2.87***	−0.1806	−5.42****
Buxar	−0.0183	−0.42	0.0258	0.63	0.0791	1.95*	0.1063	2.77***	0.0756	2.54**
Lakhisarai	−0.1136	−3.95****	−0.1707	−5.43****	0.3449	4.34****	0.3990	4.87****	0.0861	3.02***
Samastipur	−0.2608	−2.51**	−0.2325	−3.03***	−0.5317	−5.14****	−0.4430	−4.11****	−0.3462	−5.44****
Vaishali	−0.4537	−5.67****	−0.3134	−5.13****	−0.4437	−6.00****	−0.5105	−8.56****	−0.3814	−7.37****
N =	950		1,001		878		893		3,722	
Pseudo R-squared	0.213		0.164		0.444		0.435		0.254	
Explanatory power										
Cases of ZT adopters correctly predicted (%)=	37.4		40.4		81.1		80.4		63.0	
Cases of ZT non-adopters correctly predicted (%)=	91.4		87.8		84.3		83.7		83.1	
Overall cases correctly predicted (%)=	77.0		72.3		82.9		82.3		75.9	

*(**)[***]{****} Significant at the 10%(5%)[1%]{0.1%} level of alpha error probability.
[a]Coefficients are marginal effects (evaluated at means of all explanatory variables); for dummy variables, marginal effects are for a discrete change from 0 to 1.
[b]Based on robust standard errors adjusted for 40 village-level clusters.

(head) characteristics of ZT adopters and non-adopters at these two points of time and tests for statistically significant differences between the two groups as well as over time.

A comparison of farm sizes (Column 1) shows that both in 2013 and 2016 ZT adopters had significantly larger cropped area than non-adopters. However, while landholdings of ZT adopters exceeded those of non-adopters by on average 68.6% in 2013, the gap had narrowed to 38.5% in 2016. The bottom part of Column 1 indicates that conventional-tillage users in our sample had slightly larger landholdings in 2016 than in 2013, whereas the average farm size of ZT users remained statistically the same. Since, apart from overall farm size, the degree of land fragmentation may influence ZT adoption (see Section 3.2.1), Column 2 displays the average size of the largest irrigable plot, which is typically used for wheat cultivation during *rabi* season in the research area. It shows statistically highly significant differences in both years, with the average size of the largest plot of ZT adopters exceeding that of non-adopters by 68% and 79% in 2013 and 2016, respectively. Column 3 illustrates that the two groups of farmers also differ in terms of household labour endowment, with labour being relatively scarcer among ZT adopters than among non-adopters. Although the displayed means differ somewhat across years, the bottom part of the table indicates no statistically significant change in the labour-to-land ratio over time. The age of the household head did not differ between the two groups in either year (Column 4), but their level of schooling did: on average, ZT adopters had spent an extra 2.4 and 1.4 years at school in our 2013 and 2016 assessments, respectively (Column 5). Since the study uses panel data, we do not expect the level of formal education of household heads to vary over time. The slight but statistically significant increase in overall years of schooling (bottom row) is caused by the fact that the number of households we could use for our analysis differs across years. Columns 6 and 7 show that a larger share of ZT adopters belonged to castes of a higher social status, whereby caste related differences were more pronounced in 2013 than in 2016. Finally, Column 8 illustrates that the rate of ZT adoption was significantly higher among the informal social networks of ZT adopters than among the social networks of non-adopters. Furthermore, as the bottom part of the column indicates, the gap widened significantly over time as adoption rates within the social networks of

adopters increased while rates among non-adopter networks stagnated.

Overall, the numerous highly significant differences in basic household characteristics found between ZT adopters and non-adopters imply that the use of an ESR approach in the present study is well justified.

4.2. Comparative analysis of conventional-tillage and zero-tillage wheat production systems

This section provides a descriptive comparison of key input and performance related indicators of wheat production under ZT and CT production regimes (Table 4). Similarly to the previous section, we compare the two regimes across time, the first aggregating production values across the years 2011 and 2012 (period I) and the second aggregating those of the years 2014 and 2015 (period II). As highlighted in Section 1, the two periods represent years of diverging yield potential with period I substantially more favourable than period II.

Starting with a comparison of yields attained, Column 1 of Table 4 shows that in period I ZT wheat yields exceeded CT wheat yields by approximately 500 kg on the average. In contrast to this relatively high-yielding period with an overall average wheat yield of 2.927 MT ha^{-1} among sample households, the descriptive comparison indicates no significant difference between CT and ZT in period II which, across treatments, was generally lower-yielding at 2.290 MT ha^{-1}. The bottom part of the table confirms that under both production regimes yields were significantly depressed in period II.

Column 2 compares the average price received per kg of grain produced and detects a statistically significant advantage of CT users over ZT users in period II, whereas there was no difference between the two groups in period I. The difference is probably attributable to a geographically inhomogeneous expansion of ZT adoption into areas where relatively lower prices were obtained, on average. Nevertheless, both CT and ZT users received significantly higher prices for their produce in period II as compared to period I.

Column 3 shows that labour input was significantly lower under ZT in both periods, and the bottom part of the table indicates that labour input was further reduced under ZT over time, while it remained at the same level under CT. While total variable costs increased significantly from period I to period II, Columns 4 and 5 illustrate that costs under the ZT

Table 3. Basic respondent household (HH) characteristics, differentiated by zero-tillage (ZT) adoption status (values are means unless indicated otherwise).

	ZT adoption status	(1) Cultivable area (ha)[a]	(2) Size of largest irrigable plot (ha)[a]	(3) Labour-to-land ratio[a]	(4) Age of HH head (years)[a]	(5) Years of education of HH head[a]	(6) % HH heads belonging to Scheduled castes[b]	(7) % HH heads belonging to General caste[b]	(8) % ZT adoption among NMs[a,c]
(I) 2013	Adopters (N = 269)	1.72	0.84	5.52	48.8	9.1	7.8	52.4	47.7
	Non-adopters (N = 541)	1.02	0.50	9.96	49.7	6.7	12.6	36.0	28.5
	Sig. of diff.	***	***	***	n.s.	***	*	***	***
	Overall (N = 810)	1.25	0.61	8.49	49.4	7.5	11.0	41.5	34.9
(II) 2016	Adopters (N = 367)	1.62	0.86	5.80	52.9	8.6	10.1	46.9	71.1
	Non-adopters (N = 526)	1.17	0.48	8.75	52.6	7.2	13.7	36.9	32.1
	Sig. of diff.	***	***	***	n.s.	***	n.s.	**	***
	Overall (N = 893)	1.35	0.64	7.54	52.7	7.8	12.2	41.0	48.2
Sig. of diff. (I) vs. (II) among adopters		n.s.	n.s.	n.s.	***	n.s.	n.s.	n.s.	***
Sig. of diff. (I) vs. (II) am. non-adopters		**	n.s.	n.s.	***	n.s.	n.s.	n.s.	n.s.
Sig. of diff. (I) vs. (II) overall		**	n.s.	n.s.	***	*	n.s.	n.s.	***

*(**)[***] Significant at the 5% (1%)[0.1%] level of alpha error probability.
[a]Differences tested for statistical significance using Mann-Whitney test.
[b]Differences tested for statistical significance using chi-square test.
[c]Based on three primary network members (NMs); only ZT adoption prior to the respondent is considered.

production regime, both excluding and including hired labour, were consistently around 15% lower than under CT.

As a result of reduced yields and increased costs, gross margins across both production systems (i.e. returns to land) were depressed by a substantial 36% from approximately 22,000 INR ha^{-1} in period I to 14,000 INR ha^{-1} in period II (Column 6). While gross margins under ZT exceeded those under CT by some 39% in period I, the descriptive comparison indicates no significant difference in period II; however, if imputed costs of family labour are accounted for (Column 7), ZT produces a significantly higher gross margin than CT in both periods. Column 8 shows that returns to labour were roughly halved in period II relative to period I under both production regimes; however, in both periods, returns to labour under ZT were around double those under CT. Returns to capital show a similar pattern with a somewhat narrower gap between the two practices (Column 9); under CT, returns to capital amounted to approximately 70% and 80% of those under ZT in periods I and II, respectively.

Wheat yield, as displayed in Column 1, is one of the performance indicators considered in the ESR model; the other is per-unit production cost (PUC) which is shown in Column 10. Due to the fact that average PUC under ZT are inflated by some large values in period II, this column displays medians as well. In period I, both mean and median PUC were approximately 25% lower under ZT than under CT. In period II, however, mean PUC were 8% higher whereas median PUC were 13% lower under ZT as compared to CT. The Mann–Whitney tests indicate that PUC under ZT were significantly *lower* than under CT in both periods. PUC were significantly higher in period II than in period I under both regimes, as shown in the bottom part of the column.

Table 4. Major input and performance indicators of wheat production among sample households in Bihar, differentiated by establishment method and time period.

Time period	Wheat growing practice	(1) Grain yield (MT ha⁻¹)	(2) Grain price (INR kg⁻¹)[a]	(3) Total labour input (hours ha⁻¹)	(4) Total non-labour variable cost (`000 INR ha⁻¹)	(5) Total variable cost (`000 INR ha⁻¹)	(6) Gross margin (GM; `000 INR ha⁻¹)	(7) GM accounting for.imputed cost of family labour (`000 INR ha⁻¹)[b]	(8) Returns to labour (INR hour⁻¹)	(9) Returns to capital (INR INR⁻¹)	(10) Total variable per-unit production cost (INR MT⁻¹)[c]
(I) 2011 & 2012	**CT** (N = 1,370)	2.783	12.35	150.87	14.38	14.67	19.74	16.62	229	2.77	7,870 (6,559)
	ZT (N = 581)	3.266	12.32	126.27	12.50	12.80	27.51	25.24	501	3.91	5,760 (4,942)
	Overall (N = 1,951)	2.927	12.34	143.54	13.82	14.11	22.06	19.19	310	3.11	7,241 (6,135)
	Sig. of diff. CT vs. ZT	****	n.s.	****	****	****	****	****	****	****	****
(II) 2014 & 2015	**CT** (N = 1,023)	2.314	14.13	141.17	17.96	19.48	13.26	11.31	114	1.81	13,148 (9,406)
	ZT (N = 748)	2.258	13.73	93.09	15.20	16.12	14.82	13.50	215	2.28	14,201 (8,167)
	Overall (N = 1,771)	2.290	13.96	120.86	16.79	18.06	13.92	12.23	157	2.01	13,592 (8,830)
	Sig. of diff. CT vs. ZT	n.s.	****	****	****	****	n.s.	**	****	****	****
Overall	**CT** (N = 2,393)	2.583	13.11	146.72	15.91	16.72	16.97	14.35	180	2.36	10,126 (7,634)
	ZT (N = 1,329)	2.699	13.11	107.59	14.02	14.67	20.37	18.64	340	2.99	10,511 (6,529)
	Overall (N = 3,722)	2.624	13.11	132.75	15.24	15.99	18.18	15.88	237	2.58	10,263 (7,286)
	Sig. of diff. CT vs. ZT	n.s.	n.s.	****	****	****	****	****	****	****	****
Sig. of diff. (I) vs. (II) under CT		****	****	n.s.	****	****	****	****	****	****	****
Sig. of diff. (I) vs. (II) under ZT		****	****	*	****	****	****	****	****	****	****
Sig. of diff. (I) vs. (II) overall		****	****	****	****	****	****	****	****	****	****

*(**)[***]{****} Significant at the 10%(5%)[1%]{0.1%} level of alpha error probability. Comparisons based on Mann-Whitney tests.
[a]INR = Indian Rupees. 1 USD = 65.3 INR (Nov 01, 2015).
[b]Including imputed cost of family labour, valued at the median agricultural wage rate of 15.00 and 17.86 INR/hour in time periods I and II, respectively.
[c]Medians in parentheses; Mann-Whitney tests indicate that values are significantly *lower* in the case of ZT wheat in both time periods.

4.3. Determinants of zero-tillage adoption

Table 5 displays the marginal effects produced by the probit models explaining ZT adoption in the first stage of the ESR model. The models were tested for potential multicollinearity, and no cause for concern was found. Aside from the variables *Cultivable area* and its squared term, which are by definition highly correlated, the highest variance inflation factor (VIF) found was 2.98 (variable *Maximum plot size*) in the 2014 model, and the average across VIFs amounted to 1.49 in the same model. As a rule of thumb, a value of 10 should not be exceeded by individual VIFs (Myers, 1990). The explanatory power of the probit regressions ranges from 72.3% of cases correctly predicted for wheat established in 2012 to 82.9% for 2014 (bottom row of Table 5). While all models produce predicted adoption probabilities that differ highly significantly between observed adopters and observed non-adopters, the 2014 and 2015 models are far superior in correctly predicting both cases of adoption and non-adoption,[10] which may be due to the substantially larger adopter sub-sample.

In the following, we highlight key findings from the selection equation, emphasizing the evolution of estimates over time. The variable *Cultivable area* is included in the models as a wealth indicator and a factor that may influence the adoption of ZT directly, since the provision of ZT services on small farms may be less attractive for service providers due to higher per-hectare transaction costs (Keil et al., 2016). For all four years we estimate a positive quadratic relationship with ZT adoption, but the magnitude of the coefficient on *Cultivable area* declines over time and is only statistically significant at $P < 0.11$ in the 2015 model. The magnitude of the significant coefficients indicates that the marginal effect would turn negative beyond a farm size of 8.67 ha[11] in 2011, 7.92 ha in 2012, and 4.72 ha in 2014. Given an average farm size of 1.3 ha and a 99% percentile of 5.7 ha, this means that the marginal effect remained positive across the range of landholdings usually encountered in the research area, but it also indicates that, over time, landholding size became less relevant for ZT adoption.[12] In contrast, *Maximum plot size* became a significant adoption determinant in 2014 and 2015. This indicates that, while the share of ZT users that are smaller-scale farmers increased over time, farmers with less fragmented land were more likely to use the technology. Very small plots may pose a technical limit to operating four-wheel tractor-based equipment; moreover, per-hectare transaction costs for ZT services increase with decreasing plot size, potentially influencing the willingness of service providers to work on very small plots. While there is strong previous evidence of immediate benefits from the use of ZT in wheat in Bihar in terms of yield increase and cost savings (Keil et al., 2015), *Land owned* was included as a control variable for land tenure status. While land owners were more likely to use ZT in 2012, the weakly significant negative coefficient in 2015 indicates that, three years later, farmers were also willing to use it on rented land, which is likely related to their growing confidence in the technology's short-term benefits.

Regarding human capital, there is some indication of a positive influence of *High education* on ZT adoption. Although statistically significant in 2015 only, coefficients are of similar magnitude and significantly different from zero at $P < 0.15$ in 2011 and 2014 as well. Significant coefficients on *General caste category* (2011, 2012, 2015) and *SC/ST category* (2014) indicate some influence of caste membership in favour of those of a higher social standing. Based on a self-assessment measure of *Risk preference*, we find evidence across years that less risk-averse farmers were significantly more likely to use ZT. Although objectively a risk-reducing technology, ZT was likely *perceived* to be risky, similar to other agricultural innovations at a relatively early stage of diffusion (Feder et al., 1985; Rogers, 2003, p. 20 f.).

While we find a significant positive influence of membership in a farmer group in the 2011 model only, the variables related to farmers' *informal* social networks yield consistently highly significant coefficients across years and landholding terciles. Over time, we observe that the magnitude of the effect increased for all landholding terciles; furthermore, while in the earlier years the network effect was particularly pronounced among farmers in the smallest landholding tercile, the coefficients are of a more similar magnitude across terciles in the later years. For instance, while in 2011 a one-percentage point increase in the ZT adoption rate among the smallest (middle) farmers' NMs entailed a 0.18 (0.10) percentage point increase in their own propensity to use the technology, in 2015 the marginal effect amounted to 0.33 and 0.36 percentage points, respectively. Apart from these highly significant endogenous network effects, the NMs' age had a weakly significant negative impact in the earlier years, representing an exogenous network effect.

Finally, dummy variables control for systematic differences between districts. ZT-related CSISA activities started in Bhojpur district, which serves as the base district in the models. In 2011 and 2012, all statistically significant coefficients are negative, which is likely related to the shorter time of exposure to ZT technology and the lag in the development of the respective service economy. It is interesting to note that in the later years the coefficient on the district *Lakhisarai* turned positive and very substantial in magnitude while the coefficients on *Samastipur* and *Vaishali* have grown more negative, illustrating that the rate of uptake of ZT technology varies significantly across geographies.

4.4. Quantifying the impact of zero-tillage on wheat yields and production costs

A test for potential multicollinearity among the explanatory variables in the second stage of the ESR showed that the only VIFs exceeding a value of 10 are related to the variables *No. services hired* (VIF = 11.45) and *No. implements owned* (11.06) in the 2012 model. However, the fact that both variables produce highly significant coefficients in the same model indicates that there is no problem of collinearity.[13] The maximum VIF among the remaining variables is 2.87 (variable *PBW-343*), and the overall average amounts to 1.66, indicating no cause for concern (Myers, 1990). In the other models the VIFs of the two critical variables are below 10, and all other VIFs are at similar levels as in the 2012 model.

Table 6 displays the regression results for Model 1, identifying determinants of wheat yields under ZT and CT production regimes across the years under consideration, which varied widely in terms of general yield levels (see Table 4). Table 6 shows that the level of capital input positively affected wheat yields under both production regimes across years. Overall, the estimated elasticities indicate a 0.24% and 0.21% increase in wheat yield for a one-percent increase in capital input under the CT and ZT regimes, respectively. While the estimated effects of labour input are generally low for the earlier years, the coefficients are much larger and highly significant in the less favourable years 2014 and 2015, especially for the more labour-intensive CT production regime.

Regarding the agronomic control variables, we find evidence of greater (post-) harvest losses in cases where the harvest was accomplished manually (*Manual harvest*). As expected, a dummy variable indicating whether the yield was depressed by any extraordinary biotic or abiotic stresses (*Wheat damaged*) produces highly significant negative coefficients in most cases. Furthermore, we find consistent evidence across all years that the variety UP-262 produces particularly low yields under ZT. Under CT, we find statistically weak evidence of season-specific yield-enhancing effects of other varieties (Sonalika-1553 in 2012 and HUW-234 in 2015). With respect to soil conditions, CT wheat appears to perform less well in sandy loam soils as compared to the base category of clayey soils (the coefficient is negative and significant in three out of four years); most likely, this is due to the effect of the lower water holding capacity of relatively sandy soils and indicates conditions of deficit irrigation.

Regarding variables related to information acquisition, we find relatively consistent evidence of a positive effect of access to agricultural extension on CT wheat yields; a similar effect is not found for ZT wheat, indicating that ZT has not been a particular focus of the extension service thus far. Furthermore, we find positive effects of TV ownership on CT and ZT wheat yields in different years, reflecting that farmers do utilize this medium for agriculture related information. Radio ownership produces mixed results with, overall, a positive effect on CT and a weakly significant negative effect on ZT wheat yields; as shown above, it cannot be ruled out that radio messages regarding wheat management were geared towards the prevailing CT practice, but were much less applicable under a ZT production regime. The models produce a consistently negative and highly significant coefficient for mobile phone ownership under the ZT regime, which is absent in the CT regime. Since this variable is highly skewed especially for ZT users (see Table 2), this result should not be over-interpreted.

Moving to the timing-related control variables, the seasonal dummies for the 2014/15 and 2015/16 *rabi* seasons in the 'Overall' model produce highly significant negative coefficients reflecting the observed general reduction in yield levels (cf. Table 4). Relative to the base season 2011/12, the magnitude of the coefficients indicates a yield reduction by 19[14] and 38 percent in 2014/15 and by 37 and 52 percent in 2015/16 under the CT and ZT regimes, respectively. However, apart from overall seasonal effects, also the time of crop establishment affected yields in each season, with effects varying by agro-ecological zone and production regime. While sowing time

Table 6. **Model 1:** OLS estimates of an Endogenous Switching Regression (ESR) explaining wheat yield under conventional-tillage (CT) and zero-tillage (ZT) production regimes (= 2nd stage of ESR; z-values in parentheses, based on robust standard errors adjusted for 40 village-level clusters).

Variable	2011 CT (N = 696)	2011 ZT (N = 254)	2012 CT (N = 674)	2012 ZT (N = 327)	2014 CT (N = 497)	2014 ZT (N = 381)	2015 CT (N = 526)	2015 ZT (N = 367)	Overall CT (N = 2,393)	Overall ZT (N = 1,329)
Capital input	0.2815	0.2048	0.2075	0.2389	0.1760	0.2349	0.1594	0.2369	0.2414	0.2122
	(5.74****)	(2.35**)	(4.30****)	(2.94***)	(1.92*)	(4.04****)	(1.87*)	(4.46****)	(5.28****)	(5.02****)
Labour input	0.0546	0.0034	0.0327	0.0460	0.2427	0.1293	0.3590	0.1194	0.1417	0.0800
	(2.08**)	(0.08)	(1.18)	(1.10)	(4.84****)	(2.56***)	(5.70****)	(2.31**)	(4.81****)	(3.00***)
Manual harvest	−0.1295	−0.1078	−0.1626	−0.0947	0.1721	−0.1410	0.0061	−0.1158	0.0085	−0.0983
	(−2.26**)	(−1.52)	(−2.78***)	(−1.65*)	(1.80*)	(−1.84*)	(0.07)	(−1.54)	(0.13)	(−2.27**)
HUW-234	0.0982	−0.1131	0.1531	0.0471	0.1225	0.1132	0.1824	0.0555	0.1261	0.0333
	(1.23)	(−0.88)	(1.40)	(0.40)	(1.37)	(1.09)	(1.79*)	(0.52)	(2.18**)	(0.43)
Sonalika-1553	0.1625	−0.0373	0.25051	0.0262	0.1746	−0.0037	0.1572	0.0335	0.1361	0.0087
	(1.37)	(−0.24)	(1.91*)	(0.18)	(1.46)	(−0.04)	(1.25)	(0.34)	(1.63)	(0.12)
PBW-154	0.0165	−0.0586	0.0813	0.0501	−0.1650	0.0623	0.0005	0.0973	−0.0040	0.0745
	(0.17)	(−0.40)	(0.82)	(0.33)	(−1.21)	(0.55)	(0.00)	(0.92)	(−0.05)	(0.77)
PBW-343	0.0693	−0.0598	0.0458	−0.0219	−0.0766	0.0766	0.0201	0.0932	0.0450	0.0175
	(1.02)	(−0.45)	(0.46)	(−0.21)	(−1.38)	(0.80)	(0.30)	(0.79)	(0.87)	(0.29)
UP-262	0.1003	−0.2323	0.0603	−0.1997	−0.0441	−0.7036	0.0956	−0.8345	−0.0039	−0.3799
	(1.08)	(−1.87*)	(0.49)	(−1.86*)	(−0.47)	(−2.03**)	(0.55)	(−1.72*)	(−0.05)	(−1.73*)
LOK-1	0.0803	−0.0912	0.0805	−0.0176	0.0728	0.0338	0.2958	0.0181	0.0925	−0.0024
	(0.93)	(−0.73)	(0.72)	(−0.12)	(0.58)	(0.31)	(1.85*)	(0.15)	(1.33)	(−0.03)
Sandy soil	−0.0480	0.2623	0.0326	0.1078	0.0425	0.0259	−0.1330	−0.0288	0.0132	0.0822
	(−0.72)	(1.98**)	(0.44)	(0.91)	(0.47)	(0.30)	(−1.75*)	(−0.34)	(0.25)	(1.36)
Sandy-loam soil	−0.2069	0.0324	−0.1287	−0.0383	0.0355	−0.0207	−0.1290	0.0367	−0.0963	−0.0048
	(−3.74****)	(0.32)	(−2.86***)	(−0.49)	(0.47)	(−0.29)	(−1.72**)	(0.42)	(−2.07**)	(−0.08)
Loam soil	−0.0941	0.1298	0.0164	0.0653	0.0207	0.0216	−0.1072	0.0875	−0.0038	0.0599
	(−1.74*)	(1.44)	(0.38)	(0.90)	(0.30)	(0.27)	(−1.77*)	(1.20)	(−0.09)	(1.39)
Wheat damaged	−0.1688	−0.1064	−0.1788	−0.2224	−0.0885	−0.2892	0.0905	−0.1121	−0.1406	−0.2034
	(−3.51****)	(−1.50)	(−3.28***)	(−3.09***)	(−0.96)	(−3.36***)	(1.08)	(−1.37)	(−3.14***)	(−4.20****)
Labour/land ratio	0.0010	0.0041	0.0029	0.0016	−0.0008	0.0024	−0.0007	0.0002	0.0016	0.0012
	(0.87)	(1.20)	(2.74***)	(0.50)	(−0.40)	(0.54)	(−0.31)	(0.05)	(1.68*)	(0.29)
High education	−0.0585	−0.0642	−0.1508	−0.0058	0.0676	0.2080	0.0292	0.1938	−0.0276	0.0754
	(−0.80)	(−1.10)	(−2.03**)	(−0.07)	(0.84)	(2.31**)	(0.31)	(2.03**)	(−0.57)	(1.25)
Extension access	0.0374	0.0405	0.0378	0.0248	0.0326	0.0033	0.0139	−0.0083	0.0302	0.0083
	(2.55**)	(1.39)	(2.24**)	(0.99)	(1.61)	(0.17)	(0.65)	(−0.44)	(2.40**)	(0.54)
Mobile phone	0.1026	−0.3679	0.0483	−0.3570	0.1256	−0.3506	0.1445	−0.2394	0.1117	−0.3567
	(1.28)	(−2.51**)	(0.61)	(−2.60***)	(1.16)	(−3.71****)	(1.26)	(−3.11***)	(1.70*)	(−3.93****)
Radio	0.0885	−0.0222	0.1183	−0.1171	0.0645	−0.2403	0.0534	−0.1330	0.0810	−0.1236
	(2.05**)	(−0.28)	(2.62***)	(−1.63)	(0.91)	(−2.34**)	(0.62)	(−1.12)	(2.23**)	(−1.80*)
TV	0.0438	0.2219	0.0071	0.1927	0.1847	0.0179	0.1958	0.1332	0.1376	0.1214
	(0.67)	(3.16***)	(0.11)	(2.70***)	(3.83****)	(0.21)	(3.46***)	(1.43)	(2.99***)	(1.99**)
No. implements owned	0.4116	0.1241	0.9516	0.2720	−0.4655	0.0950	−0.4931	−0.0459	−0.2089	0.0867
	(1.54)	(0.59)	(4.93****)	(1.39)	(−2.57**)	(0.61)	(−2.92***)	(−0.23)	(−1.39)	(0.65)
No. services hired	0.3467	0.2073	0.8351	0.2891	−0.2785	0.1045	−0.3475	0.0322	−0.1627	0.0757
	(1.27)	(1.04)	(4.06****)	(1.53)	(−2.24**)	(0.84)	(−2.64***)	(0.18)	(−1.33)	(0.61)

(Continued)

Table 6. Continued.

	2011		2012		2014		2015		Overall	
	CT	ZT	CT	ZT	CT	ZT	CT	ZT	CT	ZT
Variable	(N = 696)	(N = 254)	(N = 674)	(N = 327)	(N = 497)	(N = 381)	(N = 526)	(N = 367)	(N = 2,393)	(N = 1,329)
Rabi 2012/13									−0.0036	−0.0799
									(−0.16)	(−2.33**)
Rabi 2014/15									−0.2113	−0.4813
									(−3.52****)	(−5.50****)
Rabi 2015/16									−0.4665	−0.7427
									(−5.97****)	(−10.3****)
Early*Z2*Rabi 11/12	0.0523	−0.1150							0.1536	−0.0748
	(0.86)	(−1.53)							(1.90*)	(−0.93)
Early*Z3*Rabi 11/12	0.2207	0.1854							0.2327	−0.0976
	(2.35**)	(1.49)							(3.16***)	(−0.87)
Early*Z2*Rabi 12/13			0.1042	−0.0525					0.1324	0.0172
			(1.42)	(−0.58)					(1.72*)	(0.22)
Early*Z3*Rabi 12/13			0.2049	0.2727					0.1347	−0.1256
			(3.92****)	(2.15**)					(1.46)	(−0.73)
Early*Z2*Rabi 14/15					−0.0628	0.1004			−0.1368	−0.0111
					(−0.67)	(1.11)			(−1.39)	(−0.14)
Early*Z3*Rabi 14/15					0.2817	0.0325			0.4095	0.2564
					(4.19****)	(0.56)			(5.96****)	(4.72****)
Early*Z2*Rabi 15/16							0.0506	0.1111	−0.0115	0.1839
							(0.52)	(1.23)	(−0.11)	(2.06**)
Early*Z3*Rabi 15/16							−0.3481	−0.2006	−0.0862	−0.2033
							(−5.12****)	(−2.00**)	(−1.06)	(−2.47**)
Begusarai	0.2157	0.3241	0.2818	0.1677	0.0717	0.0378	0.0921	−0.1241	0.1491	0.0816
	(2.35**)	(2.97***)	(4.03****)	(1.39)	(0.30)	(0.16)	(0.42)	(−0.48)	(1.08)	(0.69)
Buxar	0.1112	−0.0190	0.0464	0.0620	0.1244	0.0242	0.3791	0.2836	0.1583	0.0929
	(1.41)	(−0.22)	(0.65)	(0.81)	(1.03)	(0.27)	(2.25**)	(3.05***)	(2.43**)	(1.90*)
Lakhisarai	−0.1393	−0.3768	−0.1425	−0.4306	0.1818	0.3272	0.4965	−0.0416	−0.0156	−0.0024
	(−1.43)	(−2.83***)	(−1.35)	(−3.77****)	(1.72*)	(3.53****)	(3.47***)	(−0.37)	(−0.24)	(−0.04)
Samastipur	0.1234	−0.1479	0.2672	0.0568	0.5080	0.5303	0.6018	0.1700	0.3118	0.0820
	(1.81*)	(−1.53)	(3.64****)	(0.37)	(3.60****)	(3.38***)	(3.97****)	(0.96)	(2.94***)	(0.58)
Vaishali	−0.1747	0.4570	0.1638	−0.0008	0.4415	0.5187	0.7532	0.8868	0.2529	0.3817
	(2.02**)	(2.69***)	(1.76*)	(−0.00)	(2.48**)	(2.79***)	(4.79****)	(3.66****)	(2.27**)	(2.15**)
Constant	4.5189	6.1786	4.6548	5.6889	4.5617	5.2010	4.0086	4.8645	4.6833	6.1074
	(9.13****)	(6.88****)	(10.4****)	(7.37****)	(6.33****)	(8.73****)	(4.90****)	(9.24****)	(10.1****)	(14.6****)
IMR[a]	0.1636	−0.0496	−0.1326	−0.1658	0.0788	−0.2553	−0.1058	−0.2518	−0.0445	−0.2012
	(0.97)	(−0.23)	(−0.85)	(−0.84)	(0.55)	(−1.66*)	(−0.77)	(−1.30)	(−0.32)	(−1.37)
Endogeneity test[b]	0.98 (n.s.)		1.34 (n.s.)		3.73 (n.s.)		2.04 (n.s.)		2.11 (n.s.)	
Outcome_pot	7.8514		7.7693		7.5874		7.3056		7.6294	
	(142.97****)		(124.03****)		(100.92****)		(93.98****)		(128.10****)	
ATE	0.1853		0.2882		0.2892		0.2931		0.2781	
	(1.15)		(2.01**)		(2.49**)		(2.22**)		(2.48**)	

*(**)[***]{****} Significant at the 10%(5%)[1%]{0.1%} level of alpha error probability.

Note: ATE = Average Treatment Effect ZT vs. CT (explanations in the text).

[a]Inverse Mills Ratio derived from the selection equation; its inclusion in the second stage equations corrects for potential selection bias.

[b]Chi-square test; H_0: Treatment and outcome unobservables are uncorrelated.

effects are altogether statistically insignificant for Zone 2, for Zone 3 we estimate a consistently positive and highly significant yield-enhancing effect of early sowing on CT wheat yields in the years 2011, 2012 and 2014. Interestingly, the 2015 model indicates a highly significant yield *reducing* effect of early sowing in Zone 3 for both CT wheat and, to a lesser extent, ZT wheat. Finally, the district dummies control for location- and season-specific yield effects caused by variations in climatic conditions and biotic stresses, many of which produce statistically significant coefficients.

In the bottom part of Table 6, the mostly insignificant coefficients on the IMR and endogeneity tests indicate no significant correlation between unobserved factors in the selection and outcome equations. More than the coefficients on individual explanatory variables, the ATE estimates at the bottom of the table are of primary interest in our analysis. They indicate that, accounting for observable differences between ZT adopters and non-adopters (as captured by the 1st-stage equation) as well as potential selection bias due to unobserved factors (found to be insignificant), and controlling for numerous factors in the outcome equation, ZT technology had a positive yield impact at $P < 0.05$ in all years but the first for which data are available. Importantly, the magnitude of the statistically significant estimates is consistent across years despite varying growing conditions. Calculating the difference between the estimated counterfactual yield ($Outcome_{pot}$) and the sum of the counterfactual yield plus the estimated ATE[15] in the 'Overall' model, the ATE translates into a yield gain of 660 kg ha^{-1} or 32.1%. However, in this quantitative interpretation the fairly wide 95% confidence interval (CI) should be kept in mind, which extends from 123 to 1,329 kg ha^{-1}.

Table 7 presents the regression results and ATE estimates for Model 2, using per-unit cost (PUC) of wheat production as dependent variable. As expected, *Capital input* produces highly significant and large elasticities across all years and in both production regimes; overall, they indicate 0.57% and 0.65% increases in PUC for a one-percent increase in capital input under CT and ZT, respectively. *Labour input* produces much smaller coefficients which are positive in 2011 and 2012 and negative in 2014 and 2015. The reversal of the sign may reflect the use of more labour- and, hence, cost-saving technologies in the later years, enhancing the marginal benefit of labour. The coefficient estimates of the remaining control

variables are generally very similar to those in the yield model, but with reversed signs; i.e. a yield enhancing factor becomes a cost reducing factor and vice versa.

Moving to the bottom part of Table 7, same as in the yield analysis the coefficients on the IMR and endogeneity tests indicate no significant correlation between treatment and outcome unobservables. Most importantly, the models demonstrate that the use of ZT led to a statistically significant reduction of PUC across all years under consideration. The overall model estimates a ZT-induced cost saving of 26.1% or, in absolute terms, 2,114 INR per ton of wheat produced. The estimate is statistically significant at $P < 0.01$, and the 95% CI extends from 645 to 3,293 INR MT^{-1}. The estimated PUC saving is slightly higher across the years 2011 and 2012 (29.6% overall) than across the less favourable years 2014 and 2015 (23.6%). However, due to the substantial increase in variable production costs over time (cf. Table 4), at 2,520 INR MT^{-1} the absolute saving was greater in the later period than in the earlier years (1,895 INR MT^{-1}).

5. Discussion

In Model 1, the overall ATE estimate across years of 32.1% or 660 kg ha^{-1} in absolute terms represents the average ZT-induced yield gain to be expected in the underlying population if *all* farm households used ZT. Since potential selection bias between ZT adopters and non-adopters and numerous other yield determinants are controlled for in the analysis, the estimated yield gain is likely caused by soil related factors, especially the reduction of evaporative losses of soil water under deficit irrigation conditions (Schwartz et al., 2010). On the other hand, other studies in NW India have documented that the improved water infiltration and soil drainage commonly associated with ZT (Mondal et al., 2019) is conducive to enhancing crop performance under conditions of excessive rainfall (Aryal et al., 2016).

While the ATE is somewhat higher than the average yield gain of 498 kg ha^{-1} estimated by Keil et al. (2015), the two values are conceptually not directly comparable. Using a Stochastic Frontier production function approach, the previous estimate was based on the observed sample of ZT wheat plots only, producing an estimate of ATET rather than ATE. Furthermore, the previous estimate applied to ZT wheat over CT *broadcast-sown* wheat in particular. When

Table 7. Model 2: OLS estimates of an Endogenous Switching Regression (ESR) explaining per-unit cost of wheat production under conventional-tillage (CT) and zero-tillage (ZT) regimes (= 2nd stage of ESR; z-values in parentheses, based on robust standard errors adjusted for 40 village-level clusters).

Variable	2011		2012		2014		2015		Overall	
	CT (N = 696)	ZT (N = 254)	CT (N = 674)	ZT (N = 327)	CT (N = 497)	ZT (N = 381)	CT (N = 526)	ZT (N = 367)	CT (N = 2,393)	ZT (N = 1,329)
Capital input	0.5045	0.6494	0.6142	0.6204	0.7092	0.6459	0.7308	0.6507	0.5740	0.6522
	(8.39****)	(7.56****)	(12.4****)	(8.02****)	(7.54****)	(10.9****)	(9.29****)	(13.1****)	(11.4****)	(16.2****)
Labour input	0.0807	0.1155	0.0872	0.0852	−0.1892	−0.1297	−0.3456	−0.0885	−0.0117	0.0201
	(2.52**)	(2.28**)	(2.90***)	(1.88*)	(−2.84***)	(−1.99**)	(−4.25***)	(−1.34)	(−0.41)	(0.59)
Manual harvest	0.1923	0.1513	0.2174	0.1534	−0.0947	0.2251	0.1148	0.1839	0.0599	0.1698
	(2.68***)	(1.66*)	(3.11***)	(1.94*)	(−0.87)	(3.32***)	(1.29)	(2.72***)	(0.85)	(3.47***)
HUW-234	−0.0700	0.1631	−0.1246	−0.0105	−0.1081	−0.1014	−0.1825	−0.0525	−0.1195	−0.0063
	(−0.79)	(1.18)	(−1.06)	(−0.08)	(−1.22)	(−1.03)	(−1.84*)	(−0.51)	(−1.93*)	(−0.08)
Sonalika-1553	−0.2011	0.0544	−0.2782	−0.0207	−0.1645	0.0191	−0.1360	−0.0292	−0.1488	−0.0079
	(−1.68*)	(0.33)	(−2.23**)	(−0.14)	(−1.33)	(0.18)	(−1.12)	(−0.30)	(−1.81*)	(−0.11)
PBW-154	−0.0296	0.0197	−0.0993	−0.0909	0.1651	−0.0536	0.0222	−0.0857	−0.0054	−0.0842
	(−0.33)	(0.15)	(−0.89)	(−0.65)	(1.16)	(−0.46)	(0.15)	(−0.79)	(−0.07)	(−0.87)
PBW-343	−0.0771	0.1145	−0.0459	0.0377	0.0838	−0.0795	−0.0146	−0.0992	−0.0487	0.0017
	(−1.01)	(0.84)	(−0.44)	(0.35)	(1.55)	(−0.86)	(−0.22)	(−0.85)	(−0.91)	(0.03)
UP-262	−0.0897	0.2944	−0.0630	0.2751	0.0619	0.6674	−0.0571	0.8046	0.0087	0.4242
	(−0.96)	(2.16**)	(−0.54)	(2.10**)	(0.59)	(1.86*)	(−0.31)	(1.64)	(0.10)	(1.93*)
LOK-1	−0.0727	0.1588	−0.0806	0.0638	−0.0970	−0.0355	−0.3191	−0.0286	−0.0892	0.0433
	(−0.83)	(1.16)	(−0.70)	(0.38)	(−0.76)	(−0.30)	(−1.94*)	(−0.22)	(−1.26)	(0.42)
Sandy soil	0.0172	−0.2223	−0.0644	−0.0896	−0.0399	−0.0037	0.1477	0.0508	−0.0424	−0.0747
	(0.25)	(−1.56)	(−0.96)	(−0.74)	(−0.47)	(−0.04)	(2.08**)	(0.61)	(−0.83)	(−1.22)
Sandy-loam soil	0.2178	−0.0018	0.1385	0.0399	−0.0295	0.0245	0.1374	−0.0424	0.1012	−0.0060
	(3.56****)	(−0.02)	(2.88***)	(0.46)	(−0.39)	(0.34)	(1.87*)	(−0.49)	(2.12**)	(−0.09)
Loam soil	0.0985	−0.1464	−0.0171	−0.0642	−0.0171	−0.0289	0.1047	−0.0924	0.0088	−0.0646
	(1.53)	(−1.61)	(−0.35)	(−0.84)	(−0.27)	(−0.37)	(1.89*)	(−1.27)	(0.19)	(−1.54)
Wheat damaged	0.1303	0.0681	0.1464	0.1781	0.0811	0.2917	−0.0903	0.1118	0.1245	0.1969
	(2.57**)	(0.92)	(2.67***)	(2.38**)	(0.89)	(3.35***)	(−1.07)	(1.32)	(2.56**)	(4.14****)
Labour/land ratio	−0.0003	−0.0039	−0.0021	−0.0020	0.0019	−0.0005	0.0014	0.0012	−0.0010	−0.0014
	(−0.24)	(−1.25)	(−1.94*)	(−0.53)	(0.95)	(−0.11)	(0.63)	(0.23)	(−0.97)	(−0.34)
High education	0.1383	0.0843	0.1921	0.0168	−0.0621	−0.1985	−0.0185	−0.1922	0.0509	−0.0734
	(1.75*)	(1.25)	(2.40**)	(0.21)	(−0.77)	(−2.19**)	(−0.20)	(−2.01**)	(0.90)	(−1.17)
Extension access	−0.0357	−0.0373	−0.0375	−0.0219	−0.0317	0.0003	−0.0113	0.0130	−0.0294	−0.0027
	(−2.11**)	(−1.27)	(−1.86*)	(−0.90)	(−1.60)	(0.01)	(−0.55)	(0.70)	(−2.16**)	(−0.18)
Mobile phone	−0.1278	0.3410	−0.0640	0.3219	−0.0994	0.3851	−0.1149	0.2538	−0.1199	0.3315
	(−1.66*)	(1.88*)	(−0.81)	(1.96*)	(−0.97)	(4.75****)	(−1.04)	(3.32***)	(−1.82*)	(2.96***)
Radio	−0.1003	0.0120	−0.1186	0.0994	−0.0751	0.2162	−0.0699	0.1111	−0.0820	0.1165
	(−2.15**)	(0.14)	(−2.48**)	(1.39)	(−1.07)	(2.00**)	(−0.85)	(0.90)	(−2.32**)	(1.65*)
TV	−0.0161	−0.1916	0.0069	−0.1635	−0.1636	0.0116	−0.1593	−0.1080	−0.1280	−0.0992
	(−0.22)	(−2.44**)	(0.10)	(−1.97**)	(−3.26***)	(0.14)	(−2.77***)	(−1.19)	(−2.66***)	(−1.55)
No. implements owned	−0.4480	−0.5550	−0.9425	−0.5284	0.3854	−0.1465	0.4060	0.0053	0.1265	−0.1841
	(−1.49)	(−1.80*)	(−3.52****)	(−2.84***)	(2.28**)	(−0.90)	(2.50**)	(0.03)	(0.87)	(−1.23)
No. services hired	−0.3671	−0.6619	−0.8334	−0.5403	0.1520	−0.1701	0.2173	−0.0941	0.0670	−0.1850
	(−1.18)	(−2.23**)	(−2.98***)	(−2.89***)	(1.30)	(−1.21)	(1.80*)	(−0.50)	(0.59)	(−1.29)

Rabi 2012/13									0.0055 (0.24)	0.0829 (2.36**)
Rabi 2014/15									0.1659 (2.75***)	0.4474 (5.21****)
Rabi 2015/16									0.4268 (5.43****)	0.7088 (9.77****)
Early*Z2*Rabi 11/12	−0.0595 (−0.96)	0.1006 (1.36)							−0.1677 (−2.02**)	0.0779 (0.98)
Early*Z3*Rabi 11/12	−0.1868 (−2.72***)	−0.2362 (−2.23**)							−0.2839 (−3.87****)	0.0667 (0.60)
Early*Z2*Rabi 12/13			−0.1015 (−1.42)	0.0198 (0.21)					−0.1438 (−1.87*)	−0.0267 (−0.33)
Early*Z3*Rabi 12/13			−0.2093 (−4.58****)	−0.2945 (−3.02***)					−0.1732 (−1.77*)	0.0956 (0.57)
Early*Z2*Rabi 14/15					0.0555 (0.61)	−0.0574 (−0.64)			0.1340 (1.31)	0.0588 (0.71)
Early*Z3*Rabi 14/15					−0.2400 (−3.41***)	0.1022 (1.60)			−0.2400 (−3.33***)	−0.1613 (−2.85***)
Early*Z2*Rabi 15/16							−0.0622 (−0.66)	−0.0725 (−0.80)	0.0090 (0.09)	−0.1360 (−1.47)
Early*Z3*Rabi 15/16							0.3431 (5.36****)	0.2288 (2.23**)	0.2606 (3.13***)	0.2362 (2.69***)
Begusarai	−0.2501 (−2.59**)	−0.4142 (−2.95***)	−0.3017 (−4.63****)	−0.2169 (−1.69*)	−0.0257 (−0.11)	0.0562 (0.24)	−0.0371 (−0.18)	0.2101 (0.82)	−0.1402 (−1.06)	−0.0663 (−0.54)
Buxar	−0.0904 (−1.34)	−0.0136 (−0.16)	−0.0329 (−0.54)	−0.0366 (−0.55)	−0.0551 (−0.44)	−0.0218 (−0.23)	−0.3019 (−1.80*)	−0.2869 (−3.08***)	−0.1185 (−1.99**)	−0.0864 (−1.75*)
Lakhisarai	0.0621 (0.71)	0.3462 (2.39**)	0.0944 (0.97)	0.3834 (3.01***)	−0.0067 (−0.06)	−0.3025 (−3.02***)	−0.3151 (−2.27**)	0.0502 (0.44)	0.0182 (0.27)	−0.0071 (−0.10)
Samastipur	−0.1434 (−2.02**)	0.0620 (0.55)	−0.2931 (−4.10****)	−0.1062 (−0.70)	−0.4569 (−3.37***)	−0.3186 (−2.01**)	−0.5240 (−3.74****)	−0.0058 (−0.03)	−0.2998 (−2.93***)	−0.0888 (−0.76)
Vaishali	0.2001 (1.90*)	−0.5925 (−3.11***)	−0.1196 (−0.99)	−0.0795 (−0.35)	−0.3885 (−2.14**)	−0.4532 (−2.50**)	−0.6703 (−4.14****)	−0.8457 (−3.48***)	−0.2394 (−1.86*)	−0.4429 (−2.43**)
Constant	4.0303 (7.97****)	2.1012 (2.12**)	3.5954 (7.83****)	2.3737 (2.99***)	3.4261 (4.61****)	2.9618 (5.04****)	4.0990 (5.07****)	3.1259 (5.85****)	3.6845 (7.05****)	1.8889 (4.53****)
IMR[a]	−0.0608 (−0.32)	0.1864 (0.84)	0.1927 (1.22)	0.2379 (1.20)	−0.0642 (−0.46)	0.2313 (1.48)	0.0946 (0.72)	0.2264 (1.16)	0.0552 (0.40)	0.2533 (1.76*)
Endogeneity test[b]	0.77 (n.s.)		2.54 (n.s.)		2.94 (n.s.)		1.66 (n.s.)		3.36 (n.s.)	
Outcome$_{pot}$	8.6971 (146.45****)		8.8211 (134.31****)		9.1334 (122.78****)		9.4212 (124.97****)		8.9983 (153.89****)	
ATE	−0.3105 (−1.86*)		−0.3537 (−2.34**)		−0.2667 (−2.28**)		−0.2752 (−2.09**)		−0.3029 (−2.70***)	

*(**)[***]{****} Significant at the 10%(5%)[1%]{0.1%} level of alpha error probability.

Note: ATE = Average Treatment Effect ZT vs. CT (explanations in the text).

[a]Inverse Mills Ratio derived from the selection equation; its inclusion in the second stage equations corrects for potential selection bias.

[b]Chi-square test; H_0: Treatment and outcome unobservables are uncorrelated.

we exclude 195 cases of line-sown CT wheat from our analysis,[16] the estimated ATE and ATET amount to 647 kg ha^{-1} ($P < 0.01$) and 511 kg ha^{-1} ($P < 0.10$), respectively, the ATET being very similar to the estimate produced by Keil et al. (2015). Another methodological difference between the two studies is that, due to conditioning of plot-level outcome equations on a household-level selection equation, in the ESR we omitted 134 observations of CT wheat plots of farmers who also used ZT wheat and were, therefore, classified as ZT users. Compared to the previous study, the lack of direct comparisons of ZT and CT wheat on identical farms is probably the reason for relatively wide confidence intervals around our ATE and ATET estimates and lacking statistical significance in the 2011 model.

Moving beyond our yield impact estimate to the explanatory factors in Model 1, an important aspect emphasized in the literature is the time-saving potential of ZT. Since crop establishment is completed in one single pass of the tractor, the use of ZT facilitates earlier sowing, hence reducing the risk of yield depressions due to terminal heat stress (Chauhan et al., 2012; Erenstein & Laxmi, 2008; Gathala et al., 2013; Gupta et al., 2019; Mehla et al., 2000; Singh et al., 2020). In our analysis we control for 'early' (before December 01) versus 'late' sowing and find that, in Zone 3, early sowing enhanced yields significantly in three out of the four years under consideration. Non-detection of positive effects of early sowing in Zone 2 is plausible as this is a low-lying area which tends to be waterlogged during November. Operating tractors under wet field conditions may cause soil compaction with adverse effects on crop yields. However, the positive estimates for Zone 3 indicate that farmers are achieving substantial benefits from earlier sowing in well-drained areas, implying that the use of ZT can entail further economic benefits if its time-saving potential is harnessed.

By allowing regression coefficients to vary between ZT and CT production regimes, our analysis provides evidence of differential performance of certain wheat varieties under each regimes. This is particularly true for the variety UP-262 which performs consistently poorly under ZT across all years under consideration. Such genotype by management interactions (G x M effects) should be considered in ZT related agricultural extension messages.

While the impact of ZT on land productivity is of primary interest to policy makers with respect to ensuring food security for a growing population, the economic performance of the technology is of particular interest to farmers. To put the ATE estimates produced by Model 2 into perspective, we multiply them with average wheat yields to arrive at ATE estimates of economic gains per hectare. Given an average ZT wheat yield of 2.624 MT ha^{-1} across the years under consideration (cf. Table 4, Column 1), the estimated overall ATE of 2,114 INR MT^{-1} is commensurate to an expected total average gain of 5,547 INR ha^{-1} in the underlying population of all farm households. Considering that in 2012 the average annual income of the sample households amounted to 112,900 INR (Keil et al., 2015), this translates into a substantial increase in household income by 4.9%. Importantly, our analysis shows that the ATE estimates are consistent across years, also and especially in the climatically less favourable years. For the higher-yielding years 2011 and 2012 the estimated ZT-induced gains amount to 5,547 INR ha^{-1} (1,895 INR MT^{-1} * 2.927 MT ha^{-1}), whereas across the years 2014 and 2015 the estimate amounts to 5,771 INR ha^{-1} (2,520 INR MT^{-1} * 2.290 MT ha^{-1}).

It is important to note that the estimated average ZT induced saving of 5,547 INR ha^{-1} is some 29% larger than the observed overall difference in gross margins, amounting to 4,290 INR ha^{-1} (Table 4, Column 7). This illustrates that a descriptive analysis that neither controls for potential systematic differences between ZT users and non-users regarding their crop management capabilities nor for potential systematic differences in crop responses to production inputs under ZT and CT regimes can be very misleading. This becomes even more apparent when comparing the estimated and observed savings separately for the higher- and lower-yielding years. When interpreting the results one also needs to keep in mind that the sub-samples of ZT adopters and non-adopters were not identical in the two periods; in particular, the group of ZT users expanded from 269 to 367 households (see Table 3). For the earlier period the observed gap between gross margins according to Table 4 was 8,620 INR ha^{-1}, exceeding the estimated ATE of 5,547 INR ha^{-1} by 55%. For the later period, however, the opposite is the case with the estimated ATE (5,771 INR ha^{-1}) exceeding the observed difference between gross margins (2,190 INR ha^{-1}) by 63.5%.

To compare our result with the earlier assessment by Keil et al. (2015), we estimate ATET instead of ATE and exclude cases of line-sown CT wheat from the analysis (see the discussion of Model 1 results

above); furthermore, we multiply ATET per ton of wheat produced with the average yield attained by *ZT users* across the years 2011 and 2012. The resulting estimated ATET for this period amounts to 6,346 INR ha^{-1} (1,943 INR MT^{-1} * 3.266 MT ha^{-1}), which is 15.6% lower than the previous estimate of 7,334 INR ha^{-1}. As indicated above, we need to keep in mind that the two estimates are not based on the exact same data since the direct comparison of ZT wheat versus CT wheat plots on identical farms is missing in the ESR analysis. Therefore, obtaining estimates of a similar magnitude using different methodological approaches and varying datasets is re-assuring and corroborates previous findings of substantial economic gains from the use of ZT in wheat in Bihar. Nevertheless, we argue that the methodological approach used in the present study is superior as it allows all regression coefficients to vary between ZT and CT production regimes, rather than assuming a shift of the production function. Furthermore, the current approach produces estimates of ATE rather than ATET, which is a more meaningful indicator of the expected impact of ZT if the technology is widely adopted. A recent survey of 79 farm households in Vaishali district of Bihar by Sapkal et al. (2019) provides further empirical evidence of significant yield and cost advantages of ZT wheat over CT wheat.

6. Conclusions and recommendations

In the context of the dominantly irrigated wheat production systems of Bihar where the adoption of 'full' conservation agriculture (i.e. ZT in combination with soil cover from crop residues) is currently not a tenable goal, this study corroborates earlier empirical evidence that farmers reap substantial yield and monetary benefits from ZT practices with only partial residue retention. However, we add to previous assessments by applying a more rigorous methodological approach producing impact estimates that control for potential selection bias between ZT users and non-users and account for potential systematic differences in crop responses under ZT and CT production regimes. We estimate the average ZT induced gain to be expected among the farming population to be around 5,500 INR ha^{-1}, which is commensurate to an increase in average farm household incomes by almost 5%. More than that, by using panel data covering four wheat growing seasons of varying climatic conditions, including one with particularly hot temperatures and one with excessive,

untimely rainfall, our analysis shows that the gains from using ZT are consistent over time and also accrue under less favourable growing conditions. In the context of progressive climate change, response consistency becomes an ever-more crucial evaluation criterion when assessing the suitability of a technology for smallholders with a low risk-bearing capacity.

Our analysis confirms previous evidence that the productivity impacts of early sowing of wheat vary across agro-ecological zones due to temporal differences in soil drainage, which needs to be considered when targeting extension messages. Furthermore, we find evidence of genotype x management interactions affecting wheat productivity under ZT versus CT production regimes. Such effects should be taken into account in plant breeding as well as agricultural extension programmes to ensure the best possible outcomes as the use of the ZT expands.

To help increase the number of ZT beneficiaries in the densely populated Eastern IGP and, hence, contribute to enhancing wheat productivity and food security in an environmentally sustainable manner, an expansion of the network of ZT service providers is required since tractor and drill ownership is not a tenable goal for most capital-constrained small and medium-sized farmers.

On the whole, this study provides strong evidence that ZT for wheat in Bihar provides tangible and consistent benefits to farmers under varying climatic conditions, while reducing environmental externalities commonly associated with extensive tillage. Therefore, the State Departments of Agriculture and State Agricultural Universities in Bihar and adjacent states should continue to strongly support its diffusion.

In the longer term, increasing mechanization of agriculture in the Eastern IGP due to rising costs of manual labour may present an opportunity for greater adoption of 'full' conservation agriculture: similar to the Western IGP, the harvest of rice will most probably increasingly be accomplished by combine harvesters. This will result in larger quantities of crop residues which are hard to collect (Kumar et al., 2015, p. 6). In the Western IGP, the so-called Happy Seeder is demonstrating its capacity to sow wheat directly into a thick layer of mulched rice residues (Sidhu et al., 2015), and there is mounting evidence that its use is profitable for farmers (Shyamsundar et al., 2019). Hence, there is scope for future use of the Happy Seeder in the Eastern IGP as well, especially if a slightly smaller and lighter version is developed that is better adapted to the smaller plot sizes and

lower-horsepower tractors, and if appropriate policies, such as a purchase subsidy, support its adoption by ZT service providers.

Notes

1. Based on a random sample of ZT service providers in Bihar, tractors averaged 38.4 HP in 2013, with a range from 25 to 60 HP [dataset] (Keil et al., 2018b).
2. Only 8,3% of our sample households owned a four-wheel tractor in 2013. Their per-capita land endowment amounted to 1.27 acres as compared to 0.54 acres among the remaining households (Mann-Whitney test significant at $P < 0.001$). The use of two-wheel tractors is very uncommon in Bihar, and non-existent in combination with ZT machinery.
3. Indian Rupees. 1 USD = 66.5 INR (Sept. 2013).
4. Analysis based on daily temperature data for Patna, Bihar, downloaded from NASA POWER. Retrieved November 18, 2019 from: https://power.larc.nasa.gov/downloads/POWER_SinglePoint_Daily_20100101_20190505_025d73N_085d13E_316c91f0.txt
5. Household heads were male in 98% of cases. Due to the non-sensitive nature of the research topic, the male enumerators did not face any problem in interviewing the few female household heads. The enumerators worked for a New Delhi-based consulting firm specialized in research and communications in the social and agricultural sectors.
6. Variables measuring access to input and output markets were tested and found to not influence ZT adoption; for reasons of statistical efficiency they were omitted from the final models.
7. Encompassing both a labor- and a machine rental component.
8. With one exception: only for the year 2015 the variable *General caste category* is statistically significant at $P < 0.05$ and $P < 0.10$ in Models 1 and 2, respectively.
9. Cases of zero-yields as well as non-sensically high yield estimates were excluded from the analysis.

10. Based on the conventionally used cut-off probability of 50%.
11. Condition for maximum fulfilled for *Cultivable area* = 0.1032438/0.0119063 = 8.67 ha (rounded coefficients are shown in Table 5).
12. cf. Keil et al. (2019) for an in-depth analysis and discussion of the development of the social inclusiveness of ZT technology in Bihar.
13. Which would lead to inflated standard errors and, hence, statistically insignificant coefficients.
14. Calculated as 100*[exp(-0.2113) − 1], which is the correct interpretation of the marginal effect of an intercept dummy variable in a model with a logged dependent variable (see Giles, 2011).
15. Calculated as exp(7.629427+0.2781175) − exp(7.629427); rounded values are shown in Table 6.
16. We cannot control for line-sowing through the inclusion of a dummy variable as there would be no variation under the ZT production regime.

Disclosure statement

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