CONSERVATION AGRICULTURE:
Documenting Adoption Across the Gangetic Plains of India

FINAL REPORT 2017
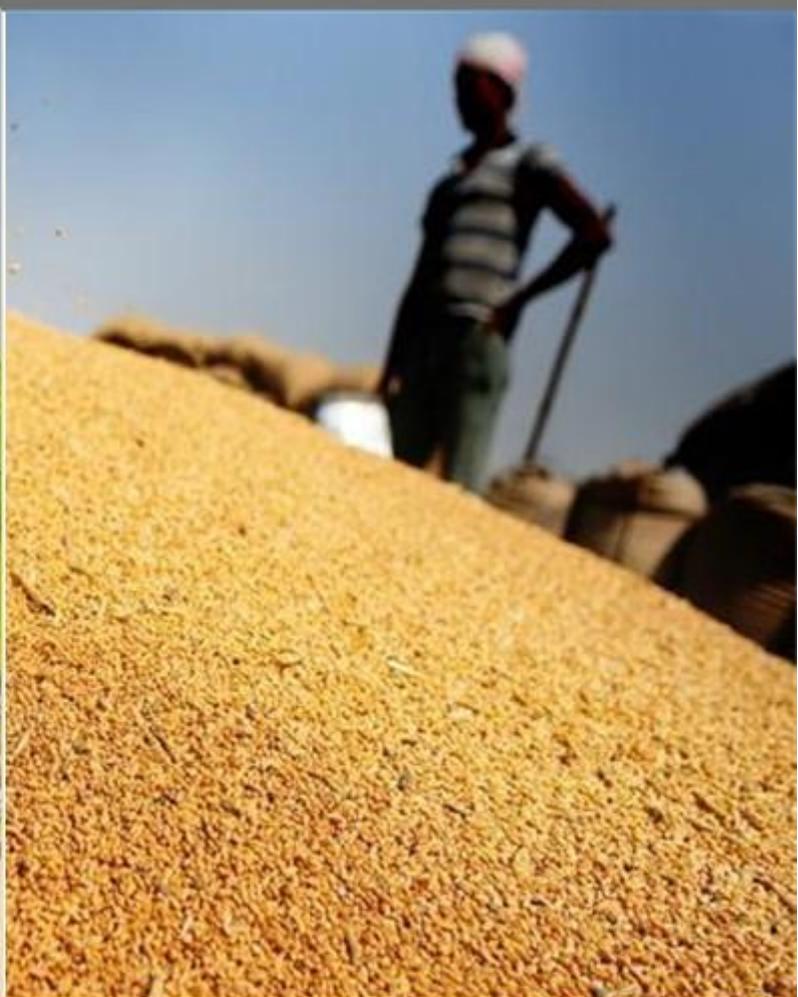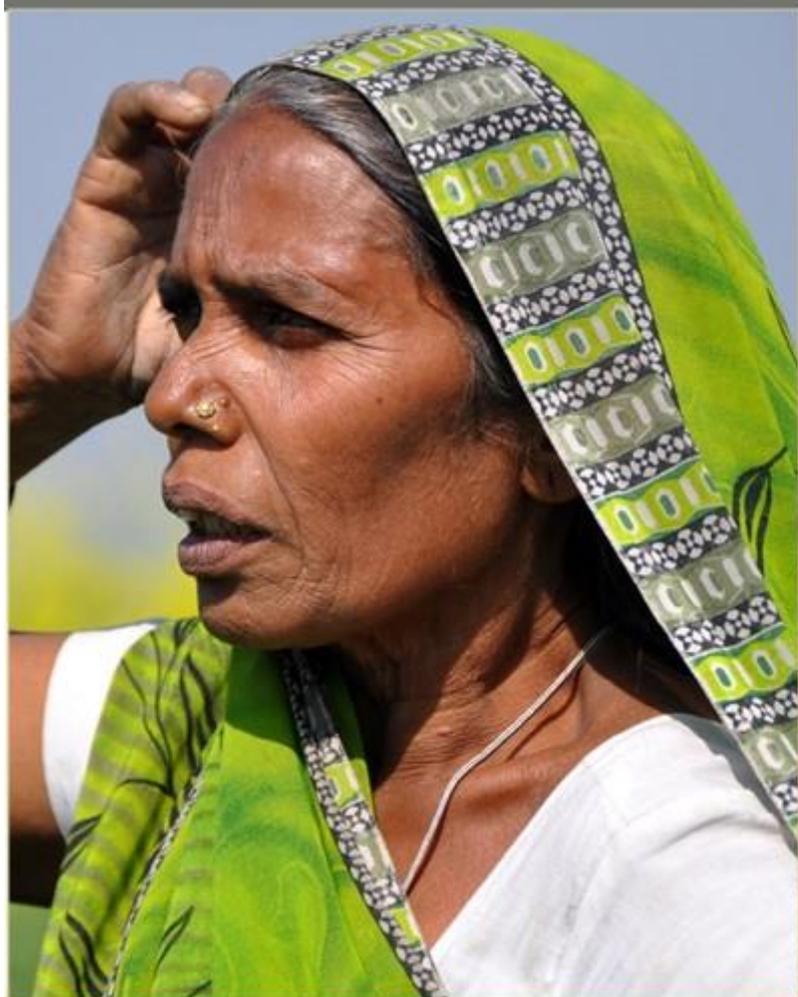
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Contents

Executive Summary

The concept of conservation agriculture (CA) was born in the 1930's when Edward Faulkner first questioned the utility of ploughing in a manuscript called 'Ploughman's Folly', and gained popularity during the 1960's in the mid-western United States as a means of preventing soil degradation. Research efforts of the CGIAR have since been instrumental in adapting CA practices to cropping systems found across the developing world. According to the Food and Agriculture Organisation (FAO), CA is defined as an agricultural management practice including continuous minimal soil disturbance (no-tillage) and permanent organic soil cover (mulching) combined with diversification of crops grown in sequence/association preferably including at least one legume.

The objective of the study is to rigorously evaluate the adoption of CA within the intensive rice-wheat cropping systems of the Indo-Gangetic Plains. In view of this, we conducted a large-scale household survey covering 3600 respondents across four States of the Indo-Gangetic Plains. This primary data collection process was complemented by remote sensing technology to identify land area under zero-tillage and permanent soil cover. The combination of these methods enable us to provide a regional indicator on both - adoption by farmer, as well as surface area estimates. Each approach is used to validate the other, providing the first thorough research response to assessing CA practices across the region.

Abbreviations

AEZ: Agroecogical Zone

CA: Conservation Agriculture

CAPI: Computer Assisted Personal Interview

CGIAR: Consortium Group for International Agricultural Research

CIMMYT: International Maize and Wheat Improvement Centre

CSISA: Cereal Systems Initiative for South Asia

CSPro: Census and Survey Processing System

FAO: Food and Agriculture Organization

FYM: Farm Yard Manure

GPS: Geographic Positioning System

HH: Household

IFMR: Institute for Financial Management and Research

IGP: Indo-Gangetic Plains

IRRI: International Rice Research Institute

LEAD: Leveraging Evidence for Access and Development

LGP: Lower-Gangetic Plains

MGP: Mid-Gangetic Plains

NAES: National Agricultural Extension Systems

NDVI: Normalized Difference Vegetation Index

NRM: Natural Resource Management

RT: Reduced Tillage

RWC: Rice Wheat Consortium

TGP: Trans-Gangetic Plains

UGP: Upper-Gangetic Plains

ZT: Zero Tillage

Introduction

The concept of conservation agriculture was born in the 1930's when Edward Faulkner first questioned the utility of ploughing in a manuscript called 'Ploughman's Folly' (Faulkner 1974), and gained popularity during the 1960's in the mid-western United States as a means of preventing soil degradation. Over the years, the definition of Conservation Agriculture (CA) has been refined to include continuous minimal soil disturbance (zero tillage), permanent organic soil cover (mulching), combined with diversification of crops grown in sequence/association preferably including at least one legume.[1]

It was not until the 1970's that the local research community in India began to explore the concept of zero tillage (ZT) agriculture for local rice-wheat cropping systems. This natural resource management (NRM) practice had the potential to address major economic and agronomic constraints to improving productivity. Eliminating intensive ploughing greatly reduces the turnaround time between the harvest of late maturing rice (e.g. Basmati) and sowing of wheat, resulting on average in 5% higher yields (Krishna & Veettil 2014). Furthermore, farmers employing ZT reported a reduction of approximately 14% in production costs due to savings in water, labour, and other inputs (Krishna & Veettil 2014).

The launch of the CGIAR Rice Wheat Consortium (RWC) in 1994, due to the emerging concern over the sustainability of growth in productivity for rice-wheat systems in the Indo-Gangetic region, helped to reignite efforts to develop and promote ZT agriculture across the Indo-Gangetic Plains (IGP). The consortium was a partnership between national agricultural research systems from Bangladesh, India, Nepal and Pakistan, and international centres including The International Maize and Wheat Improvement Centre (CIMMYT) and the International Rice Research Institute (IRRI). Research efforts of the RWC resulted in the development and introduction of affordable sowing technologies helping to make ZT agriculture accessible to the Indian farmer for the first time (Laxmi et al. 2007). Early adoption of ZT agriculture was concentrated in Haryana due to the availability of technology and the widespread cultivation of late maturing rice (Erenstein & Laxmi 2008).[2]

Further efforts to promoting CA practices are also linked to the Cereal Systems Initiative for South Asia (CSISA), with the aim of sustainably improving cereal productivity, food security and increasing farmers' income in South Asia's Indo-Gangetic Plains.[3] Within this initiative, CA practices are promoted as resource-conserving technology which increases yield with less water, labour and input costs. As a result, CA has been actively promoted in India within the project innovation hubs in Bihar, Uttar Pradesh, Haryana, and Punjab; while, a further five innovation hubs are actively disseminating CA in neighbouring Bangladesh. CSISA is also contributing to promotion of CA outside its own innovation hubs through intensive training programs for researchers from the national agricultural extension systems (NARES), thus increasing awareness, knowledge, and skills of key stakeholders within the target countries.

Despite significant efforts to promote the technology, especially among smallholder farmers, adoption of CA has been slow and modest. Recent reviews of evidence on yield gains from CA suggest that these may be quite uncertain, require further skills from adaptive farm management, and may only accrue after several years (Bennett & Franzel, 2013). Researchers evaluating these practices and the factors determining adoption suggest that the benefits are highly contextual and further scientific efforts are required to understand the suitability of these methods to certain environments such that promotional efforts can be better targeted to local conditions (Knowler & Bradshaw, 2007; Pannell et al., 2014; Stevenson, et al. 2014).

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[1] Further information on conservation agriculture can be found on the FAO site: http://www.fao.org/ag/ca/
[2] See Ladha et al. (2003) for a review on the extensive work of the RWC.
[3] Initiated in 2009 by bringing together the work of five CGIAR centres (CIMMYT, IFPRI, ILRI, IRRI, and Worldfish)

Existing Estimates of Adoption for the Indo-Gangetic Plains

Annual estimates of adoption of various resource conserving technologies were primarily compiled by the RWC.[4] These were calculated based on expert estimates using a range of proxies such as the sales of zero-tillage drills and average area coverage per drill. Based on this method, the RWC reported a total estimated wheat area under ZT in the Indian Indo-Gangetic Plains to be 820,000 ha in 2003-04, with adoption concentrated in Haryana (46%) and Punjab (26%). A random survey of households in Haryana by Erenstein et al. (2007) over the same agricultural season (i.3. rabi 2003-04), confirmed a considerable adoption rate for ZT drills of 34.5% of surveyed households and 26% of surveyed land area, while a companion survey in Punjab reported much lower rates of adoption (12%).

Post 2005, the RWC has stopped issuing area estimates due to rising concerns of their consistency (see Erenstein & Laxmi, 2008 for a review of the literature on adoption rates). Since then, reports on adoption have been limited to some primary data collection (such as in Erenstein et al., 2007) or via estimates of ZT ownership (such as in Thakur, 2005). Both of these methods have some major drawbacks in providing rigorous large-scale estimates of adoption for agricultural innovations. As identified by Erenstein (2010), primary data collections are highly resource demanding to implement and results depend crucially on the sampling framework. However, use of proxies for adoption especially in the case of CA which encompasses a range of methods, cannot capture salient details such as binary adoption of some techniques over others (Rogers, 2000).

This study therefore aims to compile the first robust and regionally representative estimates of adoption of CA across the Indo-Gangetic Plains of India. These estimates are the result of leveraging remote sensing technology to provide area-wide estimates, and validating these using a large-scale household survey across the Indo-Gangetic Plains.

Study Design

Household Survey

Sample Size Calculations

For the purposes of this study we are interested in accurately evaluating a dichotomous response for adoption of CA within a selected district. While each district has a relatively large population (>100,000), we know very little about the variability in the proportion of farmers that have adopted the practice. In light of this, we take a conservative estimate for the degree of variability in the attribute measured (i.e. adoption) such that a=0.5 (i.e. maximum variability)[5]. Furthermore, assuming we expect a 95% confidence level in our estimates of adoption for CA, we calculate the required sample per district over a range (±3-±10%) of precision levels, based on the following formula (Yamane 1967).

$$n = \frac{N}{1 + N(e)^2}$$

Where n is the sample size, N is the population size, and e is the level of precision. The results show that a sample size of 300 farmers per district will allow us to estimate adoption rates with ±5% precision for populations larger than 100,000 farmers (which is the case for all our districts). This gives us a total sample size of 3600 households across the 12 selected districts.

Sample Selection

The Indo-Gangetic Plains of India spreads from Punjab to West Bengal, covering Haryana, Uttar Pradesh and Bihar along its path. The region is comprised of varying agro-ecological conditions

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[4] www.rwc.cgiar.com for reports on annual adoption rates
[5] That is, we are assuming maximum variability in adoption with 50% of the sample adopting CA and 50% not adopting CA.

including variation in soil type, rainfall, temperature, and water availability, all of which influence the type of crops grown and agricultural practices adopted. The Indo-Gangetic Plains can be divided into four main zones (see Figure 1), the characteristics of which are summarized in Table 1. The four zones span a large precipitation gradient with more arid zones in the west, accompanied by extensive irrigation. Rice - Wheat is the predominant cropping sequence in the Indo-Gangetic Plains (IGP). Rice is planted at the onset of the monsoon (Kharif season) and wheat in the winter (Rabi season).
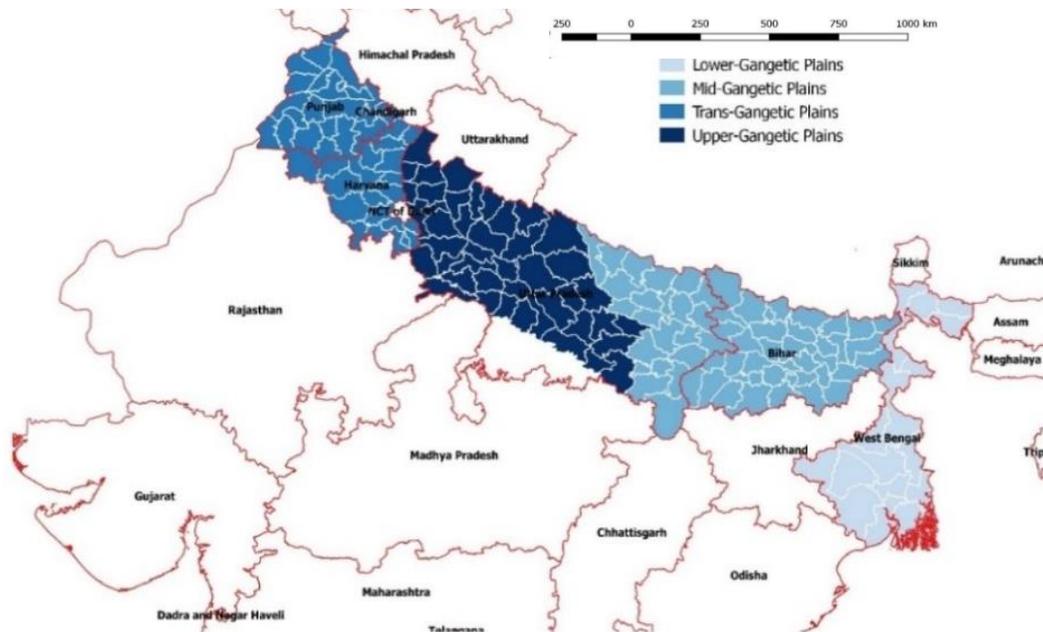

Figure 1: The agro ecological sub-regions of Indo-Gangetic plains in India

Land preparation for rice usually includes puddling, which creates a hardpan and reduces drainage of water thereby also serving as a weed control practice. Coarse rice, which is high yielding, is harvested in October, whereas Basmati rice has a longer growth period and a lower harvest index. Basmati harvest is in late October/early November and is preferred over coarse rice straw as a cattle feed. Hence, straw from Basmati rice fields tends to get collected and is not burned. The region around Karnal (Haryana) is the prime Basmati rice production area in India. The late harvest of Basmati does not leave much time for land preparation for the subsequent wheat crop. Yield of wheat is strongly influenced by date of sowing, and it is not recommended to plant wheat after mid-November in this region, due to a high risk of the crop running into terminal heat stress. Given this setting, CA practices are especially conducive to improving wheat yields.

Table 1: Characteristics of the agro-ecological zones of the Indo-Gangetic Plains of India

Agro-ecological zone	Administrative locations	Annual rainfall range (mm)	Total cultivated area (ha)	Wheat cultivation (%)	Irrigated area (%)
Trans- Gangetic Plains	Punjab & Haryana	360-890	7,754,000	57%	85%
Upper-Gangetic Plains	Western & Central Uttar Pradesh	721-979	12,596,000	32%	58%
Mid-Gangetic Plains	Eastern Uttar Pradesh & Bihar	1211-1470	9,851,000	24%	61%
Lower Gangetic Plains	West Bengal	1302-1607	5,463,000	8%	35%

Source: Food and Agriculture Organization (http://www.fao.org/ag/agp/agpc/doc/field/wheat/asia/india.htm)

Dominance of wheat as the principal crop varies significantly across the IGP; constituting as much as 57% of cultivated area in the Trans-Gangetic Plains (TGP), while falling to approximately 8% in Lower-Gangetic Plains (LGP). Given the particular interest in adoption of CA for intensive wheat

cropping systems, we confine the study to the most prominent wheat producing zones of the TGP UGP, and MGP – thereby covering the states of Punjab, Haryana, Uttar Pradesh, and Bihar. The sample for this study was selected to be representative at the regional level (bulk of Indo-Gangetic Plain) as well as at the administrative level (state and district). We used a stratified three-stage cluster sampling design, wherein:

1. First stage: Within each AEZ four districts were randomly selected from the district list of the 2011 Indian census leading to a total of 12 selected districts across the study area.[6]

2. Second stage: In each selected district, a random sample of 20 villages were chosen from the 2011 Indian census list.[7] Within each selected village, complete listing surveys eliciting information on identification features were conducted for all households.[8]

3. Third stage: From this sampling framework, we randomly selected households for the main survey using a proportional sampling methodology.[9] Only those households that had cultivated at least one crop on one or more plots in the monsoon (Kharif) season were eligible to participate in the survey.[10] The main survey covered, on average, 15 households per village, across 20 villages in each of the selected 12 districts, giving a final total population of 3607 households across 240 villages.[11]

1 Rupnagar   7 Pilibhit
2 Fatehgarh Sahib 8 Balrampur
3 Rohtak   9 Sultanpur
4 Rewari   10 Chandauli
5 Agra   11 Nawadah
6 Etawah   12 Kishangani
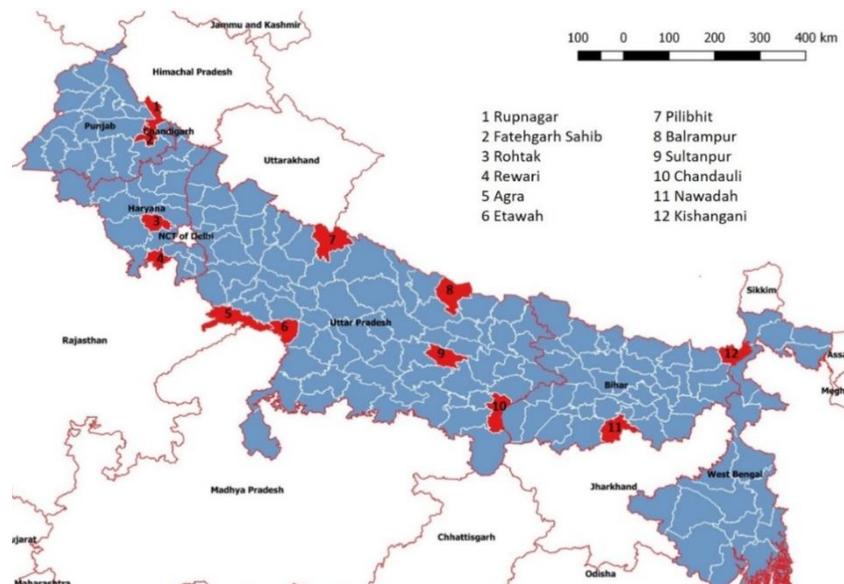
Figure 2: Location of sampled districts

This sampling method enables us to capture a wide-ranging contextual framework. For instance, summary statistics on mechanisation and livestock – two key factors to adoption (Hobbs et al. 2008; Valbuena et al. 2012) – presented in Table 2 using secondary data from the Agricultural and Input Census (2010), suggest that our selected districts capture a significant variation across each AEZ. Specifically, mechanisation ranges from 0.31 tractors per land holding in Rohtak (TGP) to 0.97

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[6] In case of TGP which covers the two states of Punjab and Haryana, 2 districts were randomly selected in each state.

[7] Villages which reported less than 10 households (representing 2% of the total sample) or more than 1000 (representing 5% of the total sample) were excluded from the randomization selection.

[8] Information included name of the household head, colour of the house, and a landmark feature.

[9] The proportion of households to survey in each village was calculated based on the average population of villages in each state. The proportions were as follows: 10.37% in Punjab, 5% in Haryana, 7.75% in Uttar Pradesh and 7.78% in Bihar.

[10] In each village an additional 10% of households were kept as a buffer in case the household initially drawn to participate in the main survey was found to be a non-farming household.

[11] Due to rounding off for the proportional sampling the households, a total of 3607 households were surveyed instead of 3600.

tractors in Kishanganj (MGP). Similarly, livestock ownership ranges from as high as 3.91 units of livestock per land holding in F.G. Sahib (TGP) to as low of 0.39 units in Nawadah (MGP).

Table 2: Agricultural characteristics of sampled districts[12]

State	District	Tractors[1]	Livestock[2]	Average farm size (Ha)	Arable land under wheat cultivation (%)
Trans- Gangetic Plains (TGP)					
Punjab	Rupnagar	0.46	2.63	2.02	83.22
	F.G. Sahib	0.89	2.01	3.91	89.44
Haryana	Rohtak	0.31	2.52	1.49	82.29
	Rewari	0.28	1.84	1.78	44.39
Upper-Gangetic Plains (UGP)					
Uttar Pradesh	Agra	0.71	3.91	1.13	38.17
	Etawah	0.75	2.63	0.77	59.36
	Pilibhit	0.75	1.82	1.04	64.10
	Sultanpur	0.68	3.41	0.51	50.69
Mid-Gangetic Plains (MGP)					
Uttar Pradesh	Balrampur	0.75	1.90	0.77	36.79
	Chandauli	0.63	3.46	0.73	89.67
Bihar	Kishanganj	0.97	5.53	0.44	20.21
	Nawadah	0.92	3.07	0.39	12.05

Source: Agricultural and Input Census of India 2011

Notes: [1]Number of Tractors per land holding, [2]Number of cattle and buffalo per Net cropped area

Data Collection and Instrument

A total of 3607 selected households across 4 States, 12 districts and 240 villages participated in the household survey conducted between the months of November 2016 to January 2017. The questionnaire was initially developed in English and later translated to be delivered in local languages (Hindi and Punjabi). The survey was piloted to the diverse sample population in each of the selected States, thereby ensuring an appropriate design informed by local insights.

The questionnaire included a range of sections covering household demographics, agricultural production decisions (crop choice, labour allocation, input use and expenses), income and consumption expenditure, asset accumulation, and behavioural factors (risk and time preferences). In addition, less-standard questions on adoption of zero-tillage, crop residue management, use of machinery such as seed drills, were also included. All data collection was georeferenced. The full questionnaire in English can be found in Annex I.

The survey was administered to the head of the household maker who was defined as "*the one who took the major economic decisions in the household and was not just the oldest person in the household*". If the household decision maker could not be found, another household member knowledgeable about the agricultural production decisions of the household was interviewed. Data quality was monitored by conducting a random selection of back-check surveys and spot checks for approximately 35% of all surveys.

The survey was conducted using Computer Assisted Personal Interview (CAPI) through the Census and Survey Processing System (CSPro); a public domain software package used by hundreds of organizations and tens of thousands of individuals for entering, editing, tabulating, and disseminating census and survey data. Responses were input using the CSPro android app CSEntry. The data were analysed using STATA statistical software package.

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[12] Definitions: Land Holding - All land which is used wholly or partly for agricultural production and is operated as one technical unit by one person alone or with others without regard to the title, legal form, size or location.

Measures of Adoption of CA

Conservation agriculture (CA) as defined by the Food and Agriculture Organisation (FAO) includes continuous minimal soil disturbance (no-tillage) and permanent organic soil cover (mulching), combined with diversification of crops grown in sequence/association preferably including at least one legume. However in reality, this suite of agricultural management procedures is a prescription of best practices, from which farmers often pick-and-choose the specific aspects of the package which are most beneficial to them. For instance, many "adopters" of CA in the rice-wheat cropping systems of the Indo-Gangetic Plains have been reported not to adhere to continuous no-tillage as inferred from the strict definition, but rather practice no-tilling in rabi wheat season and tilling before sowing the rice crop (Derpsch et al. 2010). Furthermore, tillage practices used by each farmer are clearly influenced by the amount of crop residue cover in fields. Due to this flexibility and interdependence of practices, it would be unreasonable to simply define adoption by the strict FAO definition. Rather adoption needs to be defined along a gradient from complete adoption of all aspects of CA to minimal adoption such as zero-tillage in only one season. As a result, we will measure adoption according to three definitions varying in their degree of completeness (Table 3).

Table 3: Definition of adoption by different aspects of conservation agriculture.

Name	Definition
Partial ZT	ZT in only one season, and less than 15% permanent soil cover.
Complete ZT	Continuous ZT across all growing seasons and between 15-30% permanent soil cover.
Complete CA	Continuous ZT during all growing seasons along with at least 30% permanent soil cover.

Note: Criteria for soil cover under each definition is based upon recommendation from the National Survey of Conservation Tillage Practices (CTIC 2004).

Remote sensing

Sample Selection

Remote sensing has great potential for shedding light on technology adoption, particularly CA as soil quality, mulching, cropping patterns, and tillage may be observable from satellite imagery and machine learning. Ground truthing of remote sensing data is an essential initial step to obtaining robust estimates and was hence conducted in regions of Punjab, Haryana and Bihar. Regions were sampled wherein CIMMYT was known to be actively conducting demonstration and other experiments in relation to CA, as well as regions known to have little adoption. This selection ensured that a sampling of enough ZT and non-ZT sites in order to train the classifier. In Punjab and Haryana 1306 data points were collected whereas in Bihar 339 data points were collected. The locations that were visited in the 3 states are shown in Figures 3 and 4.

Data Collection and Instrument

Ground-truthing data was collected using GPS-equipped smartphones and tablets during the first week of December 2016 in Haryana and Punjab, and mid-January in Bihar. This information was then recorded and stored on a GIS cloud software system. From each data point, one close up photo showing the surface of the soil and an overview photo were taken.
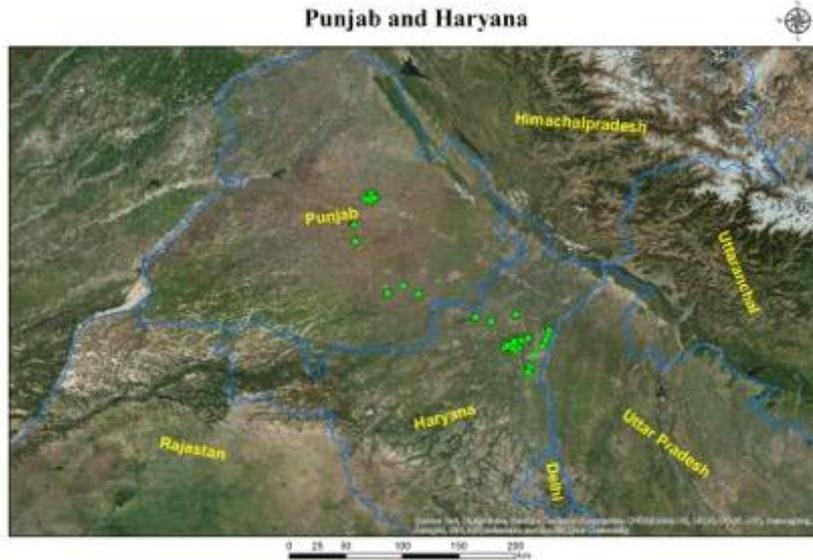
Figure 3: Overview of the sites visited in Haryana and Punjab during the ground truth data collection campaign
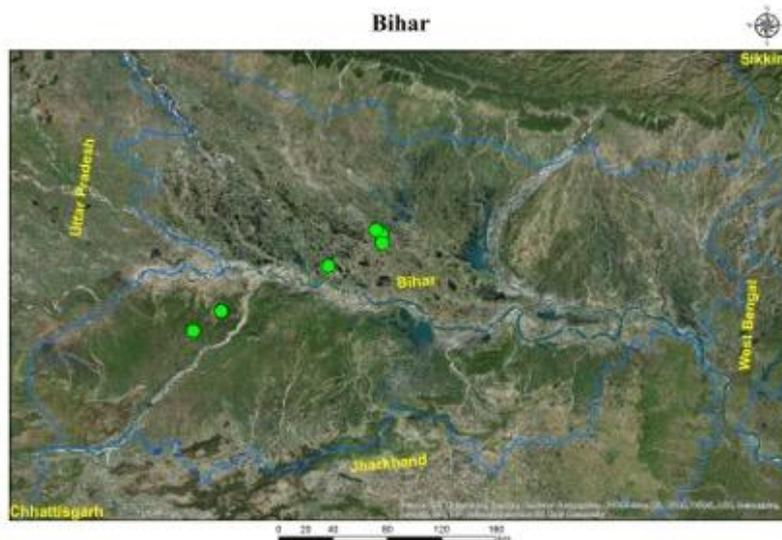
Figure 4: Overview of the sites visited in Bihar during the ground truth data collection campaign

Field boundaries were subsequently mapped using Google Earth background imagery. In a subsequent step, Sentinel 2 images, which are available for free, were chosen to generate the field boundaries used in the analysis. In the fall of 2016, one Sentinel-2 satellite was operational. It collects data at an interval of 10 days. Sometimes acquisitions were being skipped due to limited download capacity. Sentinel 2 generates pixels with a ground resolution of 10 by 10 meters. Additionally Sentinel 1 (radar) data was also used. In this case, despite pixels not being square, for ease of processing these were also resampled to a 10 m resolution.

While the European Space Agency, ESA, assures frequent coverage of the study area with Sentinel 1 data (see Figure 5), the best images that could be used for the Punjab and Haryana analyses could only be acquired on November 21 and 24. Weather in the IGP is usually sunny and dry starting from mid October. However, residue burning is still widely practiced in the IGP. This creates haze and thus limits the usability of the optical Sentinel 2 images. As a result, only a few cloud free

images in the late October – November period were available, which unfortunately already follows the peak of wheat sowing.

Pre-processing of the Data

The data were prepared for the subsequent classification with radar by following:

1. Image Segmentation

The Sentinel-1 data have a low signal to noise ratio. Moreover, the backscattering from the ground is affected by many disturbing factors, such as powerlines, tall objects (trees, houses), terrain, etc. Thus, they are not so suitable for a pixel based classification approach. No archive of publicly available, digitized field boundaries is available for India. We therefore used an image segmentation approach to create relatively homogenous zones (See Appendix, Section A for specific information on this method). These segments encompassed multiple crop fields. While doing the survey, we noticed that the ZT fields often were clumped, i.e., a ZT field was adjacent to another ZT field (accordingly, the same goes for the CT fields). The segments were subsequently classified into cropland and non-cropland. The cropland segments were then used for tillage detection.
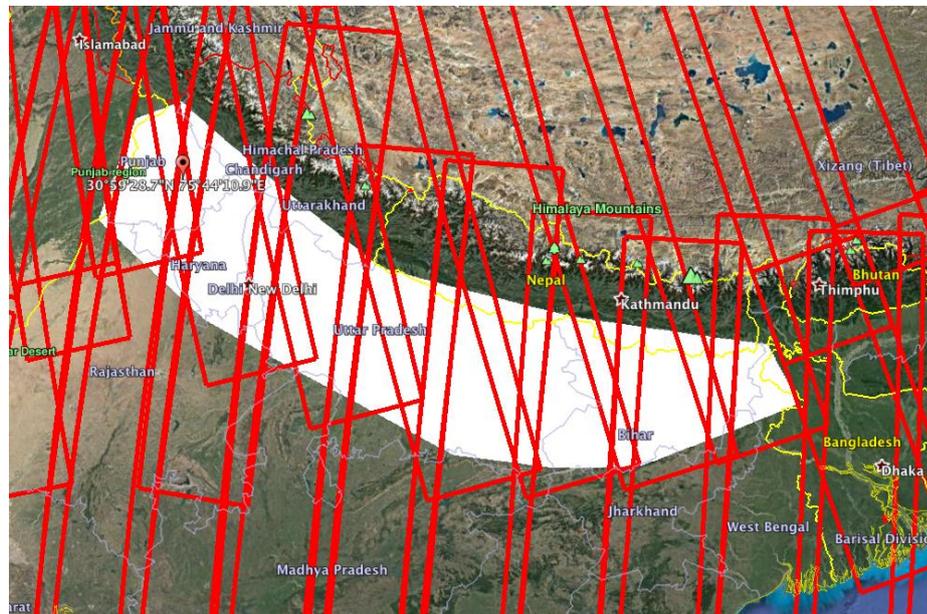
Figure 5: View of the study area in the Indo-Gangetic plane (in white) and the acquisition strips for Sentinel 1-A satellite between October 11 and November 14, 2016.

2. Cropland Detection

The segments were used for the cropland detection. Based on a visual interpretation of the Sentinel-2 image, 500 cropland and another 500 non-cropland segments were identified, using ArcGIS. The shapefile was then exported to a CSV file for subsequent classification in WEKA (Hall et al., 2009) with the random forest classifier. All spectral parameters that had been saved with each segment were used for the classification, together with NDVI. The classified CSV file was then subsequently joined with the original shape for further tillage detection analysis based on radar data.

3. Tillage Detection

Farming practices can be detected using both visible (Daughtry et al., 2004 and Daughtry et al., 2006) and radar (with Synthetic Aperture Radar (SAR)) (Zheng et al., 2014, Lopez-Sanchez et al. 2009, McNairn et al., 2002, McNairn et al., 1998 and Remondiere et al., 1996). Sentinel-1 SAR in C-band dual-pol backscatter measurements are influenced among other by the soil surface roughness and

humidity. The backscattering coefficients modifications are therefore indicators of soil surface intervention such as ploughing, mulching, etc. (Lemoine et al., 1997), soil humidity variations, as well as crop canopy volume development and destruction (McNairn et al., 1998b). Previous studies by Chomé et al., (2016) had indicated that the ratio between the backscattering intensity of the VV and VH bands can be used as a reliable proxy for detecting tillage in Belgium.

The pre-processing of Sentinel-1 SLC images has been realized using SNAP with the Sentinel-1 Toolbox. The pre-processing chain consisted of: applying the precise orbit files, calibrating, removing thermal noise, debursting, multilooking (5x1), and terrain correcting with SRTM 1sec. Since the analysis is performed on an object base, the images have not been filtered for speckle with other methods.

For each object - the previously created segments, the radiometrically and geometrically corrected backscattering coefficient were averaged and then used for a classification with a random forest classifier (RF). The training is performed over three strata in Punjab and Haryana. Each stratum has a different combination of satellite imagery. In those strata, three different RF trees are optimized with 80% of the available manually delineated fields. The creation of the calibration sample is realized in two steps:

- Creating a pool of cleaned fields. The cleaning consists in trimming the outlier fields from the sample. This is a non-parametric trimming using two time the inter-quartile distance of the fields distribution.
- Sampling randomly the required number of fields in this clean pool.

The classification quality is assessed using the confusion matrix metrics such as the overall accuracy, omission rate and commission rate, per stratum. Confusion matrices are estimated on 50% of the ground truth fields polygons randomly sampled in the full pool of ground truth fields, including outliers. They are classified with the corresponding optimized RF tree.

The training and validation are performed 100 times to estimate the variability related to the random sampling for training and validation. The effect of the segments on the classification accuracy is tested since the training is performed on manually delineated fields and the classification on segments. The segments are attributed to the ground truth fields by a majority voting. The RF tree optimized for the stratum with the trimmed ground truth fields is used to classify the segments. Quality is assessed as for the standard protocol described before.

Results

Household survey

Demographic and Socio-Economic Characteristics of Sample Population

The average household (HH) in our sample was on average comprised of 6 members and headed by a male member in 94% of cases. The literacy rate of the HH head varied significantly between states; ranging from as much as 82% in Haryana to 42% in the less affluent Bihar. The monthly per capita expenditure of households in the state of Punjab is quadruple those observed in the states of Haryana and Uttar Pradesh and more than five times those in Bihar. The average land holding size is also lowest in Bihar with on average 0.50 hectares, and highest in Punjab with an average of 1.95 hectares. In terms of the type of crops, we find that while the rice-wheat cropping system is followed on 86% of land area in Punjab, but falls to less than 50% of land area in the other states, with the lowest percentage found in Haryana (31%). On average, 91% of the agricultural land area is irrigated for the entire sample, with only slight variation across states. With regard to expenditure on agricultural inputs per hectare of land, we find that the farmers in the state of Bihar (with the lowest land holding size) tend to incur the highest expenses on fertilizer, seed, labour and machinery. Overall, farmers incur most of the expenditure on machinery and labour with the average expenditure being more than INR 10,000 and INR 7,000 per hectare respectively. While the farmers in Punjab incur almost four times the expenditure on pesticides than the farmers in the

remaining states, they spend the least on fertilizers and seeds. Table 4 below provides summary statistics for the demographic and socio-economic characteristics of the entire sample as well as by State.

Table 4: Demographic and agricultural characteristics

	Punjab	Haryana	Uttar Pradesh	Bihar	Aggregate
Household demographics					
Household size	*4.88*	*5.79*	*6.30*	*5.84*	*5.90*
	(1.84)	*(2.31)*	*(2.92)*	*(2.64)*	*(2.67)*
HH head male	*92.78*	*92.81*	*95.44*	*90.30*	*93.70*
	(25.89)	*(25.85)*	*(20.86)*	*(29.62)*	*(24.29)*
HH head literate[1]	*64.74*	*81.85*	*57.34*	*42.16*	*59.85*
	(47.83)	*(38.58)*	*(49.48)*	*(49.43)*	*(49.03)*
Per capita monthly expenditure (INR)[2]	5,430.42	1,402.93	1,405.75	1,079.12	1,943.53
	(7,149.62)	*(1,747.14)*	*(2,458.30)*	*(3,159.76)*	*(3,859.07)*
Agricultural Characteristics					
Cultivated land area (ha)[3]	*1.95*	*1.55*	*1.04*	*0.50*	*1.18*
	(2.11)	*(2.43)*	*(2.18)*	*(0.66)*	*(2.09)*
Irrigated area (%)	*97.55*	*92.48*	*92.10*	*82.96*	*91.51*
	(15.15)	*(19.83)*	*(22.51)*	*(31.72)*	*(23.33)*
Wheat area (%)	*94.41*	*80.35*	*69.71*	*49.25*	*72.05*
	(22.77)	*(32.76)*	*(39.35)*	*(43.63)*	*(39.27)*
Rice area (%)	*89.68*	*32.81*	*54.89*	*85.74*	*61.87*
	(30.24)	*(43.04)*	*(45.91)*	*(25.27)*	*(44.88)*
Rice-wheat area (%)	*85.67*	*31.29*	*46.78*	*47.60*	*50.51*
	(34.89)	*(42.65)*	*(45.51)*	*(43.07)*	*(46.08)*
Agricultural Input Expenditure (Monsoon season: June-September)					
Fertilizer (INR/ha)	1,778.95	4,978.5	5,351.96	9,892.85	5,479.14
	(2,727.66)	*(3,953.25)*	*(7,594.02)*	*(10,688.27)*	*(7,577.23)*
Seeds (INR/ha)	1,367.88	3,198.32	1,800.03	3,537.51	2,258.64
	(2,474.89)	*(3,350.99)*	*(3,029.46)*	*(4,324.40)*	*(3,356.58)*
Pesticide (INR/ha)	4,273.86	986.47	1,206.33	1,095.14	1,642.37
	(5,380.48)	*(1,618.29)*	*(3,218.35)*	*(1,804.96)*	*(3,486.36)*
Hired labour (INR/ha)	6,081.47	5,440.76	6,185.99	12,198.39	7,047.24
	(5,041.07)	*(7,754.6)*	*(13,498.34)*	*(24,319.13)*	*(14,489.68)*
Machinery rental (INR/ha)	11,983.87	8,771.97	8,251.27	15,682.43	10,184.11
	(12,563.84)	*(7,345.98)*	*(9,456.78)*	*(15,561.83)*	*(11,299.59)*
Sample Size	595	610	1803	599	3607

Source: Household survey (2017)
Notes: Standard deviations are in parenthesis, [1]Literacy is measured as ability to read and write a sentence in any language, [2]Includes only expenditure for household items, [3]Cultivated land area is the total land area farmed by the household

Awareness

Awareness is a considerable barrier to adoption of a technological change. Exposure to a novel practice has been shown to significantly increase awareness and adoption of agricultural technology (Diagne & Demont, 2007; Conley & Udry 2010). Hence, the questionnaire specifically elicited information on awareness of practices related to CA. Since the term "Conservation

Agriculture" is unlikely to be known among farmers,[13] information on their awareness was obtained through their understanding of specific practices related to CA such residue left on the land after harvest (not burned or fed to livestock) as well as land not being tilled before sowing. Across the entire sample, we observe low levels of awareness for these methods (Table 5), with on average only 19% of participants responding positively to knowing of these practices. Awareness however, is starkly heterogeneous across the IGP, with the majority of awareness – over 50% – present in the TGPs, specifically Punjab (reporting over 80% awareness), compared to only 2% in the MGPs. These differences are likely the result of active early dissemination of the technology in Punjab and Haryana during the 1990s, which only reached the states of Bihar and UP more recently.

Table 5: Awareness of conservation agriculture

	Awareness of Conservation Agriculture (%)	N
Aggregate	18.78	3583
	(39.06)	
Agro-ecological Zone		
Trans-Gangetic Plains	50.87	1203
	(50.01)	
Upper-Gangetic Plains	2.40	1288
	(15.33)	
Mid-Gangetic Plains	2.74	1092
	(16.35)	
State		
Punjab	81.28	593
	(39.04)	
Haryana	21.31	610
	(40.98)	
Uttar Pradesh	2.47	1783
	(15.52)	
Bihar	2.84	597
	(16.65)	

Source: Household survey (2017)
Notes: Standard deviations are in parenthesis

Table 6 explores the percentage of farmers adopting different aspects of conservation agriculture (as defined in Table 4) at both the AEZ as well as at the State level. We find extremely low levels of adoption, even by our broadest definition of partial zero-tillage with less than 4% of the complete sample practicing zero-tillage in at least one agricultural season. Adoption of complete zero-tillage or complete conservation agriculture is close to zero, and limited to the state of Punjab. Due to the low percentages, we focus our discussion only on the case of partial zero-tillage. We find adoption concentrated in the TGP with 9.46% of this sub-sample adopting partial zero-tillage compared to 1.15% and 0.27% for the populations of UGP and MGP, respectively. Moreover, within TGP, this adoption is clustered in Punjab with almost 16% practicing partial zero-tillage. This geographic distribution, similar to that reported in the awareness measure, is likely the result of continuous targeting and promotion in this area, as well as the higher financial status of farmers in Punjab relative to the states of Uttar Pradesh or Bihar. Practicing zero-tillage requires the use of specific machines for sowing, which may not be available to poorer farmers.

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[13] During piloting phase of the questionnaire, farmers were generally unaware of the term "Conservation Agriculture" and the specific practices this encompassed.

Table 6: Adoption rates of zero-tillage and conservation agriculture (% of farmers)

	Adoption of Partial Zero-Tillage (%)				Adoption of Complete Zero-Tillage (%)				Adoption of Conservation Agriculture (%)			
	Complete Population	*Nb of farmers*	*Aware Population*	*Nb of aware farmers*	*Complete Population*	*Nb of farmers*	*Aware Population*	*Nb of aware farmers*	*Complete Population*	*Nb of farmers*	*Aware Population*	*Nb of aware farmers*
Aggregate	*3.66* (18.78)	*3607*	*19.05* (39.30)	*693*	*0.11* (3.33)	*3607*	*0.57* (7.58)	*693*	*0.03* (1.67)	*3607*	*0.14* (3.80)	*693*
Agro-Ecological Zone												
Trans-Gangetic Plains	*9.46* (29.28)	*1205*	*18.50* (38.87)	*616*	*0.33* (5.75)	*1205*	*0.65* (8.04)	*616*	*0.08* (2.88)	*1205*	*0.16* (4.03)	*616*
Upper-Gangetic Plains	*1.15* (10.67)	*1303*	*38.46* (49.29)	*39*	*0.00* (0.00)	*1303*	*0.00* (0.00)	*39*	*0.00* (0.00)	*1303*	*0.00* (0.00)	*39*
Mid-Gangetic Plains	*0.27* (5.22)	*1099*	*7.89* (27.33)	*38*	*0.00* (0.00)	*1099*	*0.00* (0.00)	*38*	*0.00* (0.00)	*1099*	*0.00* (0.00)	*38*
State												
Punjab	*15.96* (36.66)	*595*	*19.71* (39.82)	*482*	*0.67* (8.18)	*595*	*0.83* (9.08)	*482*	*0.16* (4.10)	*595*	*0.21* (4.55)	*482*
Haryana	*3.11* (17.39)	*610*	*14.18* (35.01)	*134*	*0.00* (0.00)	*610*	*0.00* (0.00)	*134*	*0.00* (0.00)	*610*	*0.00* (0.00)	*134*
Uttar Pradesh	*0.99* (9.94)	*1803*	*33.33* (47.58)	*54*	*0.00* (0.00)	*1803*	*0.00* (0.00)	*54*	*0.00* (0.00)	*1803*	*0.00* (0.00)	*54*
Bihar	*0.00* (0.00)	*599*	*0.00* (0.00)	*23*	*0.00* (0.00)	*599*	*0.00* (0.00)	*23*	*0.00* (0.00)	*599*	*0.00* (0.00)	*23*

Source: Household survey (2017)

Notes: Standard deviations are in parenthesis

Table 7: Adoption rates of zero-tillage and conservation agriculture (% of land area)

	Adoption of Partial Zero-Tillage (%)				Adoption of Complete Zero-Tillage (%)				Adoption of Conservation Agriculture (%)			
	Complete Population	Nb of farmers	Aware Population	Nb of aware farmers	Complete Population	Nb of farmers	Aware Population	Nb of aware farmers	Complete Population	Nb of farmers	Aware Population	Nb of aware farmers
Aggregate	3.37 (17.78)	3585	17.93 (37.69)	675	0.10 (3.17)	3585	0.56 (7.29)	675	0.02 (1.67)	3585	0.15 (3.85)	675
Agro-ecological Zone												
Trans-Gangetic Plains	8.84 (27.98)	1183	17.49 (37.39)	598	0.31 (5.51)	1183	0.63 (7.74)	598	0.08 (2.90)	1183	0.17 (4.09)	598
Upper-Gangetic Plains	1.03 (9.80)	1303	34.48 (45.93)	39	0.00 (0.00)	1303	0.00 (0.00)	39	0.00 (0.00)	1303	0.00 (0.00)	39
Mid-Gangetic Plains	0.27 (5.22)	1099	7.89 (27.33)	38	0.00 (0.00)	1099	0.00 (0.00)	38	0.00 (0.00)	1099	0.00 (0.00)	38
State												
Punjab	15.96 (36.49)	574	19.75 (39.66)	464	0.65 (7.90)	574	0.81 (8.78)	464	0.17 (4.17)	574	0.22 (4.64)	464
Haryana	2.12 (13.19)	609	9.68 (26.88)	134	0.00 (0.00)	609	0.00 (0.00)	134	0.00 (0.00)	609	0.00 (0.00)	134
Uttar Pradesh	0.91 (9.27)	1803	30.46 (44.81)	54	0.00 (0.00)	1803	0.00 (0.00)	54	0.00 (0.00)	1803	0.00 (0.00)	54
Bihar	0.00 (0.00)	599	0.00 (0.00)	23	0.00 (0.00)	599	0.00 (0.00)	23	0.00 (0.00)	599	0.00 (0.00)	23

Source: Household survey (2017)
Notes: Standard deviations are in parenthesis

Table 8: Adoption rates of zero-tillage and conservation agriculture (% of rice-wheat area)

	Adoption of Partial Zero-Tillage (%)				Adoption of Complete Zero-Tillage (%)				Adoption of Conservation Agriculture (%)			
	Complete Population	Nb of farmers	Aware Population	Nb of aware farmers	Complete Population	Nb of farmers	Aware Population	Nb of aware farmers	Complete Population	Nb of farmers	Aware Population	Nb of aware farmers
Aggregate	4.36 (20.43)	2131	17.55 (38.07)	530	0.14 (3.75)	2131	0.57 (7.50)	530	0.05 (2.17)	2131	0.19 (4.34)	530
Agro-ecological Zone												
Trans-Gangetic Plains	12.33 (32.89)	730	18.60 (38.95)	484	0.41 (6.40)	730	0.62 (7.86)	484	0.14 (3.70)	730	0.21 (4.54)	484
Upper-Gangetic Plains	0.00 (0.00)	638	0.00 (0.00)	15	0.00 (0.00)	638	0.00 (0.00)	15	0.00 (0.00)	638	0.00 (0.00)	15
Mid-Gangetic Plains	0.39 (6.26)	763	9.68 (30.05)	31	0.00 (0.00)	763	0.00 (0.00)	31	0.00 (0.00)	763	0.00 (0.00)	31
State												
Punjab	17.04 (37.64)	493	20.74 (40.60)	405	0.61 (7.78)	493	0.74 (8.59)	405	0.20 (4.50)	493	0.25 (4.97)	405
Haryana	2.53 (15.74)	237	7.59 (26.66)	79	0.00 (0.00)	237	0.00 (0.00)	79	0.00 (0.00)	237	0.00 (0.00)	79
Uttar Pradesh	0.29 (5.39)	1027	10.34 (30.99)	29	0.00 (0.00)	1027	0.00 (0.00)	29	0.00 (0.00)	1027	0.00 (0.00)	29
Bihar	0.00 (0.00)	374	0.00 (0.00)	17	0.00 (0.00)	374	0.00 (0.00)	17	0.00 (0.00)	374	0.00 (0.00)	17

Source: Household survey (2017)
Notes: Standard deviations are in parenthesis

Results based on adoption by percent of land area (see Table 7) mirror those seen at the household level, with approximately 3% of the total land area under partial zero-tillage though this ranges from as low of 0.27% in MGP to 8.84% in TGP. Similar to the previous results, Punjab dominates the adoption rate with 16% of the land area cultivated under partial zero-tillage while Haryana and Uttar Pradesh have rates as low as 2%, falling further to 0% in Bihar. Among the aware population we find 18% of this sub-sample adopt conservation agriculture. Adoption among the aware population is highest under UGP (Uttar Pradesh) despite this area having low levels of overall awareness rates (2.47%). As mentioned previously, conservation agriculture is largely adopted under a rice-wheat cultivation system. Table 8 reports the adoption rates as a percent of land area under this cropping system (where rice is grown in the kharif season and wheat in the rabi season). We find similar rates of adoption with partial zero-tillage being adopted on 4.3% of the land area under rice-wheat cultivation. Adoption is highest in TGP, especially Punjab.

Profile of Adopters

As an initial investigation into the factors which may influence adoption rates, we analyse the differences in means individual, household and agricultural indicators between adopters and non-adopters of zero tillage (see Table 9). We use a simple t-test to verify whether the difference in means is statistically significant. For adopters of ZT, the household head is 17% more likely to be literate and approximately 5 years older; both of which denote a statistical significance at the 1% level. Additionally, adopters are on average significantly richer than non-adopters with the difference in total value of assets being more than INR 470,000 and owning more than double the land area. Adopters also cultivate a significantly higher land area under rice-wheat cropping system compared to non-adopters.

Table 9: Differences in means of Adopters and Non-adopters of zero-tillage

	Adopters	(SD)	Non-Adopters	(SD)	P-Value	
Household size	5.81	2.46	6.01	2.71	0.55	
Household head is male	0.95	0.22	0.93	0.26	0.49	
Household lead is literate	0.79	0.41	0.62	0.49	0.01	***
Age of household head	55.63	12.46	50.88	13.95	0.01	***
Degree of risk aversion	2.93	2.30	2.48	2.41	0.15	
Household head is impatient	0.68	0.47	0.62	0.48	0.39	
Per capita monthly HH expenditure	6,084.61	12,500.90	1,566.24	3,048.16	0.00	***
Value of total HH assets	588,541.10	682,962.30	114,180.50	322,500.40	0.00	***
Total farming land area (ha)	2.47	2.92	1.01	1.61	0.00	***
Area under rice-wheat cultivation (ha)	1.85	2.36	0.50	1.11	0.00	***
Total livestock	4.82	4.66	2.51	2.77	0.00	***
Agricultural input expenses (per ha)	21,343.38	1,2853.84	27,254.48	27,022.21	0.09	*
Awareness of CA	1.00	0.00	0.12	0.32	0.00	***
Number of Households	62		1946			

Source: Household survey (2017)
Notes: Level of Significance (P-value) *** <0.01, ** <0.05, * <0.1

Given this initial insight into the profile separating adopters and non-adopters, we further analyse the factors influencing adoption of ZT using a probit model. The regression equation can be written as:

$$Y_i \ = \ \beta_0 \ + \ \beta_1 X_i + \ u_i$$

where, Y_i is a binary variable indicating adoption of ZT (i.e. equal to 1 if individual i is an adopter of zero-tillage) and X_i denoting a range of individual level variables (including age, sex, risk aversion, and patience of the HH head), household level variables (including assets, and household size), agricultural variables (including land area, input expenses, and livestock ownership). Furthermore we control for agro-ecological zone in each regression and make use of standard-clustered errors at the village level, u_i reflects the error term. We use three specifications of this regression framework wherein we add different series of control variables listed above. This analysis enables us to understand the significance and interaction of various individual, household and agricultural level variables in explaining the adoption of zero-tillage.

Table 10: Probit Model for Adoption of Zero-Tillage

	Adopter (1)	Adopter (2)	Adopter (3)
Household size	0.019	0.004	-0.002
	(0.036)	(0.036)	(0.037)
Household head is male	0.225	0.166	0.156
	(0.312)	(0.320)	(0.337)
Household head is literate	0.163	0.159	0.173
	(0.175)	(0.178)	(0.186)
Age of household head	0.008	0.009	0.010*
	(0.005)	(0.006)	(0.006)
Degree of risk aversion	0.099***	0.108***	0.100***
	(0.028)	(0.029)	(0.031)
Household head is impatient	0.160	0.187	0.180
	(0.153)	(0.155)	(0.154)
Value of total HH assets		0.000***	0.000***
		(0.000)	(0.000)
Area under rice-wheat cultivation (ha)			0.079**
			(0.034)
Total livestock			0.025
			(0.016)
Agricultural input expenses (per ha)			-0.000
			(0.000)
Trans-Gangetic Plains	1.447***	1.274***	1.169***
	(0.301)	(0.304)	(0.306)
Upper-Gangetic Plains	0.164	0.139	0.096
	(0.316)	(0.325)	(0.319)
Constant	-4.023***	-3.992***	-3.895***
	(0.544)	(0.551)	(0.551)
Observations	2,008	2,008	2,008

Source: Household survey (2017)

Notes: Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1, Number of observations is reduced due to missing responses from participants on some of the indicators.

Table 10 looks at the factors that relate to adoption of partial zero-tillage. Firstly, we note that the majority of the differences in means observed in the previous section are absorbed by the geographical dummies. As a result, the demographics and financial status of the household do not appear to be significantly associated with the average probability of adoption for partial zero-tillage. Additionally, agriculture related variables such as land area under rice-wheat, ownership of livestock and input expenses have no statistically significant relationship with the average probability of adoption for partial zero-tillage. Furthermore, value of household assets, which can be taken as proxies for household wealth, capture a statistically significant and positive difference between adopters and non-adopters, however the coefficients are zero.

Risk preferences, measured using a lottery of options capturing a range of constant risk aversion, appears to reflect the importance of behavioural traits in technology adoption. We measure risk preferences using hypothetical questions in which the respondent is offered five

options to choose from, with each option having two monetary outcomes. The respondent is informed that in each option the probability of occurrence of each of the outcomes is 0.5 (the outcome is dependent on a coin toss). The first option is always the safest with the same monetary return, irrespective of whichever outcome happens. However, in the remaining options, while the expected return increases with each option, the risk also increases in proportion to the amount of money at stake. The last option always has the highest expected return as well as the highest amount of risk. Based on the responses to these questions we estimate a coefficient of Constant Relative Risk Aversion (CRRA) (Charness et al., 2013). A unit increase in the CRRA increases the probability of adoption by 0.13 percentage points. This suggests that more risk averse farmers are likely to adopt CA methods, compared to risk neutral individuals.

Remote Sensing

Ground Truthing Data

For this research, we relied on a methodology that had been developed for ZT estimation in Belgium, as described by Chomé (2016). We observed that residue management varies greatly: Only very few farmers follow the conservation agriculture guideline, which proposes to retain at least 1/3 of the residues in the fields (Figure 6). Most farmers burn the residues (Figure 7). Straw burning is forbidden in India, and farmers can be fined for this practice. Hence, farmers tend to burn the straw at night and immediately till the soil at dawn such that any remains of burned stubble can only be seen at the edges of the fields and is therefore impossible to detect whether a rotavated field was burned or not. This explains why conventional till numbers are most often marked as unknown in this region. Nevertheless, we see that most plots under zero till are not burned in Punjab and Haryana, and burning is much less common in Bihar.

VH and VV Trends

The SAR signal, averaged by fields seem to be stable trough time and space for classification (see Figure 1A in Appendix Section B). The signal peaks when the farmers are starting to plough the fields. Indeed, surface roughness and humidity increases temporarily. Over all the fields, the trend remains both for no-tillage and tillage since land is prepared in both case. Nevertheless, the increase in backscattering is lower for no-tillage fields. As can be seen in Figure 2A (see Appendix Section B) there was a general increase in the difference in backscattering intensities between VV and VH starting in late October. This coincides with the main land preparation and sowing period. The box plots in Figure 2A also show that differences were the largest on the following dates in 2017: October 28, November 2, 9, 14 and on December 3. Therefore, these dates were chosen for the classification. Considering the average field behaviour, the separability is clearly visible on the selected dates (3A).

Estimating Adoption and Classification Accuracy

Classification accuracy depends on several factors. The segments are not a representation of individual crop fields. They represent a group of fields with similar spectral characteristics. Thus, when moving from pure fields to segments, a loss in classification accuracy was to be expected. The results showed that accuracy decreased by about 2-3%. One limitation of the use of machine learning algorithms is their limited applicability for other input data sets. The Sentinel 1 images are being acquired in swaths that are approximately 250 km wide. It is not possible to train it with data acquired on e.g., November 1 and then to apply it to another data set that had been acquired on November 5 in a neighbouring swath. As a consequence of this, the classification accuracy changed within the Punjab-Haryana Area of Interest (AOI). Average accuracies varied between 78 and 90 % (Table 11). The highest accuracy was achieved for northern Punjab.

Overall, we estimated an area of 0.59 million ha that are under ZT within an area of 3.24 million ha of cropland, or 18% of the land area. The distribution of the percentage of ZT fields by administrative sub-district (Level 3) is shown in Figure 8.

Figure 6: On the left, a zero-till field with residue retention is shown. The field on the right was rotavated after the residues had been removed and a drill seeder was used for sowing.

Figure 7: Zero-till fields with different levels of straw burning and residue retention.

	All	Haryana	Southern Punjab	Northern Punjab
Total cropland area [ha]	3243829.40	1579084.94	917178.23	747566.23
ZT area [ha]	587758.00	445238.80	132292.30	10226.90
CT area [ha]	2656071.40	1133846.14	784885.93	737339.33
Corrected ZT area [ha]	583857.68	403358.53	170184.59	10314.56
Corrected CT area [ha]	2659971.72	1175726.41	746993.64	737251.67
ZT proportion	0.18	0.28	0.14	0.01
Corrected ZT proportion	0.18	0.26	0.19	0.01
Classification overall accuracy	0.88	0.89	0.78	0.91
Classification overall accuracy 95% lower bound	-	0.82	0.63	0.83
Classification overall accuracy 95% upper bound	-	0.93	0.89	0.96
Ground truth sample size	598	339	88	179

In Bihar, classification accuracies range of 84% and 85% (Table 12). They are globally lower than in Punjab and Haryana but are still in the standard for a good classification. Cropland area considered is 1.6 million ha. It was noticed that the algorithm predicted rather high ZT adoption rates in Eastern Uttar Pradesh. That area was trained with data collected from the other side of the satellite swath and we therefore have little confidence in those results. Hence, only the administrative sub-districts centred around the sampling areas are shown in Figure 9.

Table 12: Summary of the accuracy assessment in Bihar by strata.

	All	Western Bihar	Eastern Bihar
Total cropland area [ha]	1582582.1	1270853.8	311728.3
ZT area [ha]	528383.9	466229.7	62154.2
CT area [ha]	1054198.2	804624.1	249574.1
Corrected ZT area [ha]	446734.9	395472.5	51262.4
Corrected CT area [ha]	1135847.2	875381.3	260465.9
ZT proportion	0.33	0.37	0.20
Corrected ZT proportion	0.28	0.31	0.16
Classification overall accuracy	0.84	0.84	0.85
Classification overall accuracy 95% lower bound	-	0.72	0.71
Classification overall accuracy 95% upper bound	-	0.92	0.93
Ground truth sample size	176	125	93

The results from this study need to be interpreted with caution as there are several caveats from the following assumptions:

1. The ground truth data are representative for the entire region. We sampled in regions where CIMMYT is actively conducting demonstration and other experiments, in order to make sure that we would get enough ZT samples to train the classifier. Interestingly, the algorithm predicted higher ZT percentages for regions outside of the sampling area, except for northern Punjab. Within the sampling areas, the estimated percentage of ZT was lower than in the regions where no ground truth data had been collected. Thus, it is well possible that our ground truth data do not adequately

represent the situation in the study area. The southwest of the study area, in the Punjab, is for instance drier than the other regions.

2.   The average size of the segments was 3.6 Ha. They were comprised of many fields, which may or may not have been tilled in the same way, although the loss in prediction accuracy was only 3 % when going from a field based classification to a segment based one. The segments were based on the optical Seninel 2 data. The edge detection layer mainly picked up edges, as indicated by its name. These were roads, fields with vegetation surrounded by bare fields, etc.

3.   The accuracy obtained within the sampling area varied as well. The highest accuracies were achieved in southern Karnal (89 %), whereas southern central Punjab had the lowest accuracy with 78 %. This indicates that the environmental conditions were probably more challenging for ZT detection in southern Punjab, where annual rainfall gradually increases from the south to the north.

4.   Bihar results should be considered extremely carefully. Indeed, it is known that adoption rate and CA awareness rate are very low (around 3%). Our result combining an accuracy of 84% and a proportion of 30% is probably due to three main reasons: the small size of the fields, the small size of the training and validation sample and the hypothesis of representativity. This last hypothesis is clearly not respected here. Indeed, the sample is mainly collected along the SH12 south to Patna and SH49 north to Patna.


Figure 8: Percentage of zero till fields per administrative sub-district during the Rabi season of 2016/17 in Punjab and Haryana.

Figure 9: Percentage of zero till fields per administrative sub-district during the Rabi season of 2016/17 in Bihar and Eastern Uttar Pradesh.

Discussion

Overall, the household survey estimated an adoption rate ranging from 15.96% of total cultivated area under partial ZT in Punjab to 0% in Bihar (see Table 7 and Table 13). When scaling these estimates to the cultivated land area under the four states of Punjab, Haryana, Uttar Pradesh and Bihar, we find that on average only 3.37% of the cultivated land area can be categorised under partial ZT practice. This corresponds to approximately 0.86 million Ha of cultivated land. If the categorisation is extended to a complete measure of CA wherein farmers do not till the land in all seasons and maintain 30% permanent soil cover, this measure drops to less then 1% of the land area. We find similar adoption rates under wheat cultivated land ranging from 16.47% of wheat area under partial ZT in Punjab to 0% in Bihar (see Table 4A and Table 5A in Appendix Section C). This corresponds to only 3.89% (approximately 0.7 million Ha) of the total wheat area under partial ZT practice across the Indo-Gangetic Plains.

Table 13: Estimate of Net Cultivated Area under partial zero-tillage

State	Net Cultivated Area	% of Net cultivated area under Partial Zero-Tillage	Area under Partial Zero Tillage
Punjab	3,965,749	15.96	632,933.56
Haryana	3,638,875	2.12	77,144.15
Uttar Pradesh	17,507,954	0.91	159,322.39
Bihar	6,134,254	0.00	0.00
Indo-Gangetic Plains	31,246,832	3.37	869,400.1

Source: Household survey (2017) and agricultural census of India (2010-11)

The remote sensing analysis, aimed at complementing the household survey with an objective measure of adoption of zero-tillage, reports an average adoption measure of approximately 18% (corresponding to 0.59 Ha of cropland) in Punjab and Haryana and 28% (corresponding to 0.44 Ha of cropland) in Bihar and Eastern Uttar Pradesh. However, the reliability of the measure for Bihar and Eastern Uttar Pradesh is highly questionable mainly due to the small size of the fields, the small size of the training and validation sample (ground truthing sample) and diverseness in agricultural practices across and within districts in a given state.

Importantly, both measures of adoption report very high rates of heterogeneity in adoption of conservation agriculture across the area studied. Large differences across States is shown in the household survey, however, interestingly the remote sensing evidence suggests that this variance can take place within a much smaller geographical coverage as represented in Figure 8 and 9. This variation is important for interpreting any figures scaled up at the State or Agro-Ecological Zone, since the granularity of the data is limited in comparison to the area covered.

Overlap in household survey and remote sensing sample

The sampled districts for the household survey were chosen randomly. However, the same could not be done for ground truthing for the remote sensing analysis. In order to train the classifier, regions were sampled wherein CIMMYT was known to be actively conducting demonstration and other experiments in relation to CA, as well as regions known to have little adoption. This selection ensured that a sampling of enough ZT and non-ZT sites are collected. As a result, there isn't much overlap in the areas sampled by ground truth analysis and the household survey. Only one sub-district/tehsil (Fatehgarh Sahib) of the Fatehgarh Sahib District in Punjab is covered by both the household survey as well as remote sensing. The remote sensing analysis predicts 16-20% of the plots in this sub-district adopting zero-tillage (Figure 8). The household survey data shows a corresponding rate of 19.2% farmers adopting zero-tillage in this sub-district (covering approximately 16.8% of the total cultivated land area).

Next Steps

While only a small region overlaps between the household survey and the remote sensing, both methods find similar rates of adoption of zero-tillage for this area. This shows that both these methods are indeed capable of detecting zero-tillage practices in the Indo-Gangetic Plains and help in validating each other. However, the remote sensing methodology assumes that the environmental conditions as well as farming practices are identical in the entire region which is being classified. The results from this study seem to show that this assumption was not met, as unreasonably high ZT adoption rates were observed for regions outside of the ground truth data collection areas. Thus, more efforts for ground truth data are required if this approach is to be applied to larger areas.

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Appendix

Section A: Image Segmentation Methodology

The 10 m bands of Sentinel 2 were used for the segmentation. These are the steps that were followed:

1. Run the Sobel edge-detection algorithm with a 3x3 filter
2. Load these images into eCognition
   a. 4 band Sentinel image, where B stands for the band, followed by the number of the band
      i. B1= blue
      ii. B2 = green
      iii. B3 = red
      iv. B4 = NIR
   b. 4 band image resulting from edge detection
      i. B1edge = blue
      ii. B2edge = green
      iii. B3edge = red
      iv. B4edge = NIR
3. Run segmentation algorithm with the following parameters
   a. Image layer weights
      i. B1 = 2
      ii. B2 = 2
      iii. B3 = 2
      iv. B4 = 3
      v. B1edge = 1
      vi. B2edge = 1
      vii. B3edge = 1
      viii. B4edge = 3
   b. Scale parameter = 60
   c. Composition of homogeneity criterion
      i. Shape = 0.8
      ii. Compactness = 0.1
4. Export of segments. Each segment contains the mean reflectance of each band, plus the mean brightness

For each Sentinel 2 tile, about 160,000 segments resulted. A tile measures 1 million ha, thus the average size of a segment was about 6.3 ha.

Section B: Radar Image Analysis
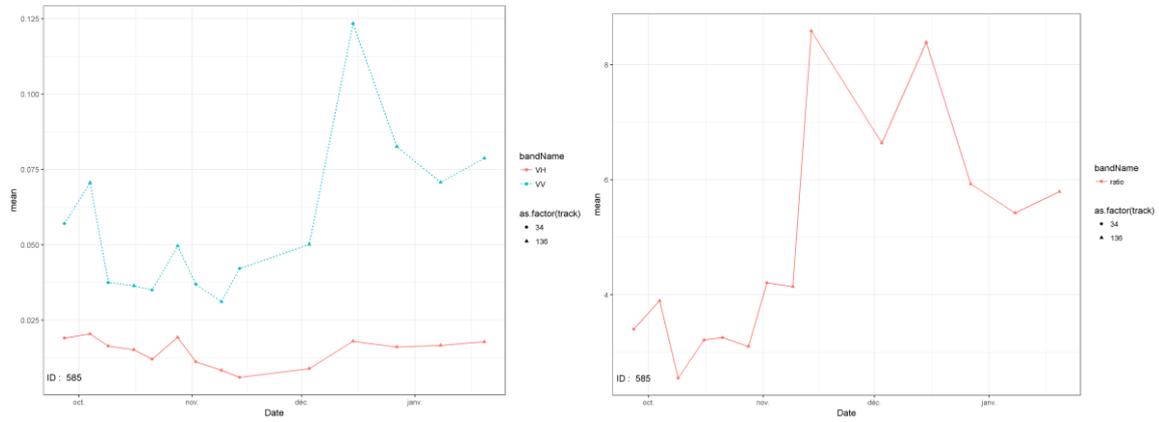
Figure 1A: Average time profile of SAR metrics over one field in Haryana - 2016.
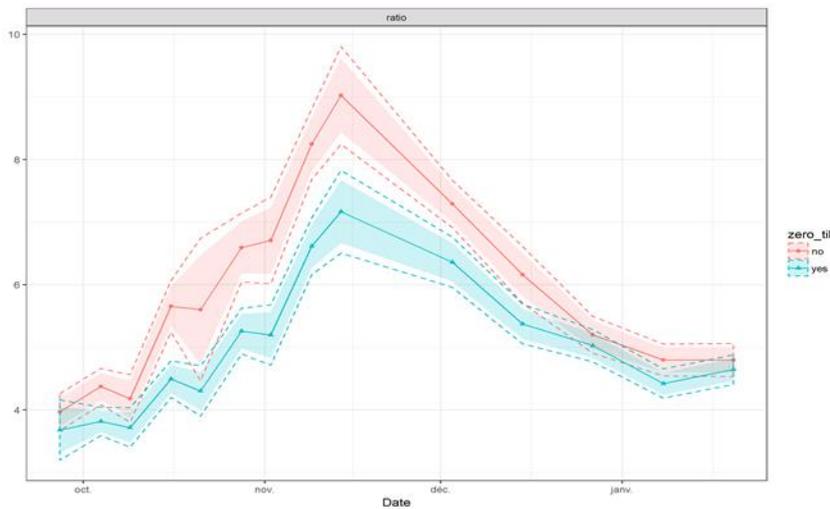

Figure 2A: Trends in the backscattering intensity difference between the VV and VH channels derived from Sentinel-1 radar data.
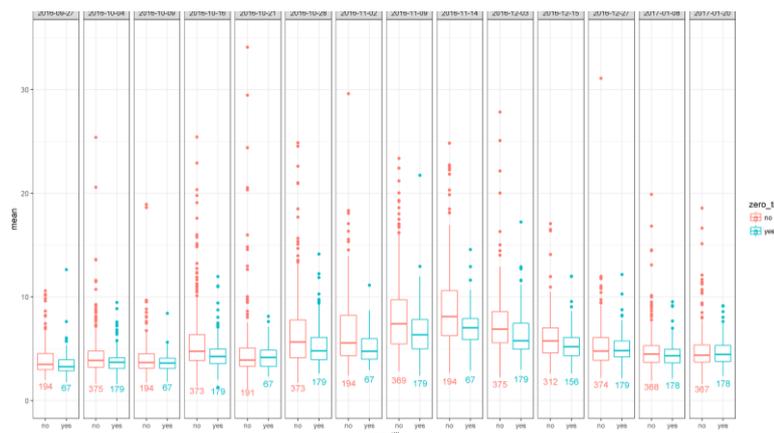

Figure 3A: Average trends in the backscattering ratio between VV and VH channels derived from Sentinel-1 SAR data.

Section C: Household Survey

Table 4A: Adoption rates of zero-tillage and conservation agriculture (% of wheat area)

	Adoption of Partial Zero-Tillage (%)				Adoption of Complete Zero-Tillage (%)				Adoption of Conservation Agriculture (%)			
	Complete Population	*Nb of farmers*	*Aware Population*	*Nb of aware farmers*	*Complete Population*	*Nb of farmers*	*Aware Population*	*Nb of aware farmers*	*Complete Population*	*Nb of farmers*	*Aware Population*	*Nb of aware farmers*
Aggregate	*3.89* (19.15)	*2987*	*18.16* (38.12)	*641*	*0.13* (3.47)	*2987*	*0.59* (7.48)	*641*	*0.03* (1.83)	*2987*	*0.16* (3.95)	*641*
By Agroecological Zone												
Trans-Gangetic Plains	*9.41* (28.90)	*1105*	*18.06* (38.04)	*576*	*0.34* (5.70)	*1105*	*0.66* (7.89)	*576*	*0.09* (3.01)	*1105*	*0.17* (4.17)	*576*
Upper-Gangetic Plains	*0.86* (9.14)	*1083*	*27.45* (44.55)	*34*	*0.00* (0.00)	*1083*	*0.00* (0.00)	*34*	*0.00* (0.00)	*1083*	*0.00* (0.00)	*34*
Mid-Gangetic Plains	*0.37* (6.12)	*799*	*9.68* (30.05)	*31*	*0.00* (0.00)	*799*	*0.00* (0.00)	*31*	*0.00* (0.00)	*799*	*0.00* (0.00)	*31*
By State												
Punjab	*16.47* (36.95)	*544*	*20.15* (39.95)	*445*	*0.69* (8.12)	*544*	*0.85* (8.97)	*445*	*0.18* (4.29)	*544*	*0.22* (4.74)	*445*
Haryana	*2.56* (15.07)	*561*	*10.99* (29.75)	*131*	*0.00* (0.00)	*561*	*0.00* (0.00)	*131*	*0.00* (0.00)	*561*	*0.00* (0.00)	*131*
Uttar Pradesh	*0.81* (8.93)	*1506*	*25.69* (43.62)	*48*	*0.00* (0.00)	*1506*	*0.00* (0.00)	*48*	*0.00* (0.00)	*1506*	*0.00* (0.00)	*48*
Bihar	*0.00* (0.00)	*376*	*0.00* (0.00)	*17*	*0.00* (0.00)	*376*	*0.00* (0.00)	*17*	*0.00* (0.00)	*376*	*0.00* (0.00)	*17*

Source: Household survey (2017)
Notes: Standard deviations are in parenthesis

Table 5A: Estimate of area under partial zero-tillage

District	Total area under wheat (ha)	% of Wheat area under Partial Zero-Tillage	Area under Partial Zero Tillage (ha)
Punjab	3,430,084	16.47	564,934.81
Haryana	2,721,508	2.56	69,670.60
Uttar Pradesh	10,140,558	0.81	82,138.52
Bihar	2,060,316	0.00	0.00
Indo-Gangetic Plains	18,352,466	3.89	716,743.93

Source: Household survey (2017) and agricultural census of India (2010-11)