Using Satellites to Target and Measure the Impact of Sustainable Agricultural Technologies in Smallholder Systems

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**Abstract**:

**Introduction**

 Food security will be challenged over the coming decades by increased food demand due to growing populations and changing diets, and by reduced food supply caused by factors such as climate change and natural resource degradation {Godfray:2010ey}. One way to enhance food security is to increase the productivity of regions that are currently low yielding and have large yield gaps {Lobell:2009cf}. A majority of the regions where the world’s main staple crops are grown have yield gaps that could likely be narrowed or closed with improved nutrient and water management {Mueller:2012ir}. Yet increasing inputs, such as irrigation and fertilizer, in many of these systems is challenging due to the limited availability and/or high cost of inputs. This is particularly true for smallholder systems, where irrigation systems and fertilizer markets may not be well developed and where farmers may not have access to the capital needed to purchase increased inputs. In response, new low cost technologies are being developed to help smallholder farmers better and more efficiently use scarce inputs {Pretty:2003iy}. These technologies not only offer a way to increase yields, but may also result in ‘win-win’ scenarios that make agricultural systems more sustainable due to increased input use efficiency.

While such technologies have been widely touted as a possible way to sustainably intensify agriculture, there is little understanding of how effective these technologies may be at large spatio-temporal scales and across different social, ecological, and political contexts {Pretty:2003iy}. One reason for this is it is challenging to collect the yield data needed to conduct robust impact evaluation of new agricultural technologies across thousands of fields, sites, and years. Currently, most impact evaluation is done by conducting crop cuts, where crops are harvested and weighed in field to estimate yield, yet this procedure is very time and cost intensive. As an alternative approach, researchers have suggested that satellite data may be used to map yields across large spatial and temporal scales at low cost. Yet, is has historically been difficult to map field-level yield in smallholder systems because the size of a typical farm is smaller than the pixel resolution of most readily-available satellite products (e.g., Landsat, MODIS; {Jain:2013gy}). Recent advances in satellite technology, most notably micro-satellites (e.g., Planet, 2-5 m resolution, daily imagery), have paved a potential way forward to map field and sub-field level yield of smallholder farms {e.g., Jain:2016uy, Burke:2017kd}. These new technologies may provide a viable way to conduct impact evaluation of agricultural interventions across large scales, which is critical for identifying sustainable intensification strategies that are effective across a broad range of socio-ecological contexts.

Satellite data may also offer a new way to target technologies to those regions and fields where they will be most effective, which may result in increased adoption and diffusion of the technology across space and time. While a new technology may result in realized benefits on the ground, previous work has shown that not all farmers will adopt a given technology due to various knowledge, perceptional, and socio-economic constraints. Therefore, a significant amount of research has been done to understand how new technologies can most effectively be introduced to maximize uptake across the population of interest. In particular, previous work has shown that adoption and diffusion is greater when those who first receive the technology see larger benefits upon first use, suggesting that uptake may be increased if those farmers who are expected to see the largest yield gains are targeted first. Yet, identifying such farmers is typically time and cost intensive. Satellite data may offer a low-cost and scalable way to identify which farmers will benefit most from a given technology, resulting in both increased efficacy and adoption and diffusion of the technology across space and time.

This study introduces a new fertilizer spreader technology that more evenly applies fertilizers within fields to wheat-growing farmers in central Bihar, a region that faces some of the largest yield gaps in India. In this region, farmers typically spread fertilizers by hand, which likely leads to inefficiencies due to uneven application of fertilizers within fields. Specifically, we conducted a split plot trial during the wheat growing season with over 150 farmers across two years, where in half of each field farmers applied fertilizers using the typical hand spreading approach, and in the other half of the field farmers applied the same amount of fertilizers using the new spreader technology. We then measured wheat yields at the end of the growing season using crop cuts as well as satellite data. In this study, we ask the following questions: (1) does the spreader technology result in yield gains compared to typical hand spreading approaches when using the same amount of fertilizer, suggesting an effective sustainable intensification strategy?; (2) can these yield gains be detected using micro-satellite data, providing a low-cost way to conduct impact evaluation?; and (3) can micro-satellite data be used to target those fields that have the largest yield gains when using this new technology, suggesting a scalable way to target interventions? Our results offer broad insights into the utility of new micro-satellite data for conducting and measuring the impact of sustainable intensification interventions in smallholder systems.

**Is the Spreader Technology a Sustainable Intensification Strategy?**

**Spreader Technology Leads to Yield Gains**

Overall, we find that the spreader technology results in a 5% yield gain, on average, across all sites and years (Figure 1). These yield gains are realized due to the use of the spreader technology alone, as all other management strategies, including type and amount of inputs, remained constant across treatment versus control plots. While all sites and years showed significant yield gains, the magnitude of gain varied across sites and years, with the largest percent yield gain (7.1%) occurring in the western site (Arrah) in 2015. Interestingly, this same site has a much smaller yield gain in 2016 (3.8%), though the exact cause of this difference is unknown. We additionally ran analyses to understand which management and biophysical factors, including sow date, fertilizer amount, and soil type, explained the most variation in the efficacy of the spreader technology.

* do regression & variable importance analysis to understand which factors are most important in explaining yield gain variation.

**Spreader Technology Improves Nitrogen Use Efficiency**

* calculate nitrogen use efficiency

**Can Yield Gains be Detected Using Satellite Data?**

**Satellite Data Maps Wheat Yields Accurately and Detect Yield Gains**

We find that we are able to accurately map smallholder wheat yields using micro-satellite data trained using field-level crop cut data (Figure 2). When using these satellite yield estimates along with locations of the subplots of the fertilizer experiment, we find that we are able to detect yield gains caused by the fertilizer spreader technology (Table 1). These yield gains, however, are much smaller in magnitude and in significance when compared to the yield gains measured using plot-level crop cut data. This is likely due to increased noise in our satellite yield estimates when compared to crop cut yield estimates. In addition, this is likely because the range of yields produced using satellite data is much smaller than the range produced using crop cut yield estimates in our study. Previous studies that have mapped yield using satellite data have similarly found range restriction, typically constraining both very low and very high yield values (< 2000 kg/ha and > 45000 kg/ha in this study).

**Can Satellite Data be Used to Target Appropriate Fields?**

**Targeting Fields Using Satellite Data**

1. show results of identifying which satellite factors are associated with increased yield gains – across years, and for each individual site x year

**Farmers’ Perceptions and Potential for Diffusion of Spreader Technology**

* farmers’ perceptions of the technology overall
* survey (and satellite?) factors associated with higher willingness to pay and more potential diffusion

**Discussion**

**Methods**

**Fertilizer Experiment**

We conducted the fertilizer experiment on 157 fields across two years and study regions (37 fields in Arrah in 2015-2016, 80 fields in Arrah in 2016-2017, and 40 fields in Vaishali in 2016-2017; Figure S1). We split each field into four equal sub-plots in which different fertilizer treatments were implemented. We used a randomized block experimental design, with two fertilizer amount treatments (75 kg/ha or 100 kg/ha) and two fertilizer application treatments (hand spreading or spreader technology) for a total of four treatments in each field. All other management variables, including wheat variety, sow date, number of fertilizer additions, amount and timing of irrigation, and weeding, remained constant across sub-plots within each field, though these management factors varied across fields. To ensure that the experiment was conducted similarly across all fields, a CSISA-CIMMYT employee was present with each farmer during every fertilizer application throughout the growing season.

*Fertilizer Polygons:* We also collected GPS points at each corner of the full field, the center of the field, and in the center of each of the four sub-plots in each field. We then used the rgeos and spatial polygons packages in R Project Software to create field boundary polygons using these GPS coordinates. However, due to slight inaccuracies in our coordinates, all fields were manually examined in QGIS and were redrawn to match field boundaries that were visible within Google Earth high-resolution imagery. We also overlaid these adjusted polygons on high-resolution SkySat or Planet imagery from the same year and shifted the polygons as needed to match field boundaries that were visible in the high-resolution imagery. If we were unable to determine matching field boundaries in the SkySat or Planet imagery, we did not further adjust the polygon. To draw the boundaries of each of the fertilizer treatment sub-plots, we equally subdivided each field into quadrants, and used the GPS coordinates taken in each sub-plot to link each quadrant with the appropriate fertilizer amount and application treatment.

*Management Survey:* We conducted an interview with each of the farmers in each year about management practices implemented within each field. This information included wheat variety, sow date, irrigation type and number of irrigations, weeding methodology, soil type, and harvest date.

*Crop Cuts:* At the end of the growing season, yield was measured by conducting crop cuts in each sub-plot of each field. In 2015-2016, three 2 x 1 m2 crop cuts were collected in each sub-plot and, in 2016-2017, two 2 x 1 m2 crop cuts were collected in each sub-plot. We also have crop cut data for X fields for 2014-2015 from a previous study {Jain:2016uy}, though the fertilizer experiment was not conducted in this year. Plant height, the number of effective tillers, number of grains per ear, total biomass, grain weight, and grain yield were measured for each crop cut.

*Spreader Perception Survey:* In 2016-2017, we also conducted an end-of-season survey to identify farmers’ perceptions of the spreader technology and their willingness to use and pay for the technology in subsequent years. Specifically we collected information on whether farmers thought the spreader technology improved yields, if so by how much, whether they would use the technology again, their willingness to pay 2000 INR, 3000 INR, and 4000 INR to purchase the spreader technology, and the maximum amount they were willing to pay for the technology. These costs represented a realistic range for what these spreaders may be sold for in subsequent years. To gain an understanding of the potential for this spreader technology to diffuse across the community to other farmers, we also asked each farmer if he/she told anyone else about the technology, if so how many people did he/she tell and whom, and whether the people who were told about the technology are interested in using the fertilizer spreader.

**Satellite Imagery**

*Image Processing:* High-resolution satellite data (SkySat, 2 x 2 m2 or PlanetScope, 3 x 3 m2) were processed for both study regions for 2014-2015, 2015-2016, and 2016-2017 using methods from Jain et al. {Jain:2016uy}. All images for 2014-2015 and 2015-2016 were already processed for Jain et al. {Jain:2016uy}. Based on data availability, in 2014-2015 and 2015-2016 we used only SkySat imagery, and in 2016-2017 we used only PlanetScope imagery. SkySat imagery were provided by Terra Bella (now part of the Planet constellation) and PlanetScope data were provided by Planet ([www.planet.com](http://www.planet.com)). Individual tiles for these high-resolution products were mosaicked using ENVI’s seamless mosaicking tool with histogram matching of the overlapping areas across tiles. We also visually inspected each image to ensure that it was geo-referenced to match all images within the same region and year, as well as the high-resolution Google Earth imagery used to geo-reference the fertilizer polygons. We selected one image that was well geo-referenced to Google Earth imagery, and then conducted image-to-image registration using ENVI’s image registration tool for all additional images. Images in the western region of Arrah were well geo-referenced using these methods but images in the eastern region of Vaishali had geo-reference mismatches that could not be removed using these methods. Radiance in SkySat images was converted to surface reflectance using histogram matching to the nearest Landsat image date (see methods from {Jain:2016uy}) and PlanetScope data were corrected to top of the atmosphere reflectance using equations obtained through the imagery metadata.

*Yield Estimates:* We calculated satellite yield estimates for each year and region using methods from Jain et al. {Jain:2016uy}. First, we calculated the GCVI (Green Chlorophyll Vegetation Index; Equation 1) for each image as previous studies have shown that GCVI has a fairly linear relationship with wheat LAI {NguyRobertson:2014bs}. We then extracted mean GCVI for each field polygon for 2014-2015, 2015-2016, and 2016-2017.

**Table 1. Mean Yield by Region, Experimental Plot, and Yield Measure.** We report mean wheat yield (t/ha) under the 100 kg/ha fertilizer treatment, the 75 kg/ha fertilizer treatment, and both treatments combined across the manual and the spreader fertilizer application method. If the mean yield value is significantly different between the manual versus spreader fertilizer application for a given treatment (as measured using a paired t-test), it is marked with a symbol (+ < 0.10; \* < 0.05; \*\* < 0.01).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Region x Year | Yield Measure | Mean Yield Spreader  | Mean Yield Manual  | Mean Yield Spreader (100 kg)  | Mean Yield Manual (100 kg) | Mean Yield Spreader (75 kg) | Mean Yield Manual (75 kg) |
| Arrah 2015-2016 | Crop Cut | 2.53\*\* | 2.36\*\* | 2.79\*\* | 2.61\*\* | 2.32\*\* | 2.16\*\* |
| RS | 2.42+ | 2.40+ | 2.47 | 2.46 | 2.45+ | 2.42+ |
| Arrah 2016-2017 | Crop Cut | 3.48\*\* | 3.33\*\* | 3.80\*\* | 3.63\*\* | 3.16\* | 3.03\* |
| RS | 3.42+ | 3.40+ | 3.44+ | 3.41+ | 3.41+ | 3.39+ |

 + < 0.10; \* < 0.05; \*\* < 0.01

**Figure 1. Mean Yield Increase Across Site and Year.** Overall mean wheat yield between manual versus spreader fertilizer application methods across all sites, years, and treatments (1A). The amount of mean wheat yield gain achieved by the spreader versus manual application method is compared across fertilizer amount (1B) and all site x year combinations (1C).

**Figure 2. Satellite Yield Prediction Accuracy.** Scatterplots showing observed (as measured using crop cuts) versus predicted yields (as measured using satellite data) across all sites and years. R2 and RMSE values are noted for each analysis and the one-to-one line is represented as a dashed line.

**Figure 1.**



**Figure 2.**

