Greenhouse gas mitigation benefits and profitability of the GreenSeeker Handheld NDVI sensor: evidence from Mexico

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Abstract

Better targeting of fertilizer application can result in yields that meet or exceed those achieved without improved targeting while reducing total fertilizer use. However, in many growing regions, it may be difficult for farmers to access the necessary data to inform improved fertilizer use. The GreenSeeker Handheld is a low-cost technology that can be used to improve the efficiency of fertilizer applications by providing farmers with recommendations for the amount of nitrogen (N) to apply mid-season to meet the needs of their crops. The technology has been utilized on nearly 2,000 farmer fields representing more than 60,000 hectares in three regions of Mexico. In this study, the net effects of this technology on economic and environmental outcomes for these farmers were assessed. Specifically, farmer field-level data and locally derived greenhouse gas emission factors were analyzed and use of the GreenSeeker Handheld was estimated to have led to a total of $2.6 M USD in additional profits and more than 14,300 tons CO_2e of avoided emissions. However, not all farmers utilizing this technology followed the resulting recommendations. Participating farmers that did not follow the recommendations experienced lower profits, indicating that benefits would have been larger had participants applied fertilizer at the levels recommended for their fields. In addition, the total benefits of higher farm profits and reduced emissions could be scaled up significantly if this technology were applied more broadly. However, development and implementation of the technology had been supported by subsidies and further efforts would be needed to make it sustainable.

Keywords Fertilizer · Mexico · NDVI · Nitrogen · GreenSeeker · Greenhouse gas · Precision agriculture technology

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Introduction

Improved spatial and temporal targeting of fertilizer application based on location-specific crop requirements can potentially result in yields that meet or exceed those achieved based on more general guidance and practices while reducing total fertilizer use (Bruulsema et al., 2016; Buresh & Witt, 2007; Shanahan et al., 2008; Mamo et al., 2003). Fertilizer use can be a major input cost for producing cereals, and nitrogen use efficiency in cereals ranges from 35 to 65% globally depending on the crop (Herrera et al., 2016). Therefore, technologies enabling more efficient use of fertilizer can reduce costs and increase yields, contributing to increased farmer profitability (Langholtz et al., 2021). Lower fertilizer application also provides environmental benefits including improved water quality due to reduced nutrient runoff (Wainger et al., 2013) and reductions in greenhouse gas (GHG) emissions (Beach et al., 2015; EPA, 2019). However, there is considerable heterogeneity in the potential economic and environmental benefits across agricultural systems and there remains a lack of quantification of these impacts for many specific location-crop-technology combinations. Thus, farmers, governments, and other stakeholders often do not have a clear picture of the potential benefits (Balafoutis et al., 2017). The paucity of evidence on the potential impacts of alternative agricultural technologies in a given setting may hamper the development of efficient agricultural policy as well as farmer adoption of beneficial technologies (Finger et al., 2019).

The GreenSeeker Handheld[1] is an example of a low−cost technology that makes using fertilizer more efficient by providing farmers with more accurate recommendations for the amount of nitrogen (N) to apply mid−season to meet the needs of their crops (Crain et al., 2012). The technology uses an optical sensor combined with a reference N−rich strip and a crop−specific algorithm to make mid−season fertilizer N recommendations. As a handheld tool available at low cost, it can be an appealing option for both extension providers as well as low− and middle−income farmers for whom more expensive technologies are inaccessible or unaffordable. This device has been shown to have strong potential to increase farmer profits by reducing fertilizer N costs without significantly affecting yields and has the added social benefit of reducing N pollution, including nitrous oxide (N2O) emissions, one of the largest direct contributors of GHG emissions from the agricultural sector (Ortiz−Monasterio and Raun 2007; Matson 2012).The GreenSeeker Handheld was developed in the early 1990s and since then has been applied in multiple countries, including Mexico, Pakistan, India, and China. In Mexico, it has been applied most extensively in the Yaqui and Mayo Valleys in Southern Sonora, the country's largest wheat-producing region. Since 2012, it has also been piloted in the states of Baja California and Guanajuato. These three regions of Mexico represent different geographic, socioeconomic, and agricultural contexts. Sonora and Baja California are primarily wheat-producing regions where farming has become mechanized over the last several decades, whereas Guanajuato is the breadbasket of the country where there is greater diversity of small-, medium-, and large-scale farmers (Matson, 2012, Servicio de Información Agroalimentaria y Pesquera, 2014).

The International Maize and Wheat Improvement Center (CIMMYT), one of the 15 centers of the Consultative Group on International Agricultural Research (CGIAR) system, has facilitated the transfer of the GreenSeeker Handheld to farmers in Mexico. In partnership

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[1] 1 Refers to the Model 505 GreenSeeker Handheld™ Optical Sensor Unit. Referred to in this manuscript simply as GreenSeeker Handheld.

with the Asociación de Organismos de Agricultores del Sur de Sonora (AOASS), CIMMYT has collected extensive data on fertilizer application rates and yields where this technology has been applied. In this study, these data were used to quantify the improved profits for farmers, the physical factors influencing those profits, and the avoided GHG emissions based on Mexico-specific N_2O emission factors.

The objective of this paper is to provide empirical evidence of the economic and GHG impacts that have resulted from adoption of the GreenSeeker Handheld technology across three different regions of Mexico. The primary hypothesis is that farmers who adopt GreenSeeker Handheld are profiting and avoiding more GHG emissions than they would have if they had not adopted the technology. A secondary hypothesis is that the more that farmers deviate from the GreenSeeker Handheld fertilizer recommendation, the lower their profits. A common methodology for assessing the value of an intervention is by comparing the value derived from that intervention with a counterfactual, or what would have happened in the absence of the intervention. It is often difficult to determine the degree to which fertilizer reduction technologies impact profits and GHG emissions on farmers' fields because direct counterfactuals are unavailable or limited to test plots on research stations. Due to the way that the effects of the GreenSeeker Handheld were assessed, where a reference strip was compared with the rest of the field that received the fertilizer application recommendation, it was possible to develop a method to empirically compare outcomes from the farmer's fields with the counterfactual (reference strip).

This study makes several important contributions to scientific knowledge. The GreenSeeker Handheld and other similar N use efficiency technologies have been tested extensively in experimental research settings, but there is relatively little information in the peer-reviewed literature about the extent to which these technologies have affected both economic and environmental outcomes when applied in practice in different regions (Diacono et al., 2013; Ortiz-Monasterio & Raun, 2007). Given the high level of heterogeneity within the agricultural sector, the impacts of a given technology are likely to vary spatially, making it very important to assess impacts across different locations and to consider factors that may influence the net benefits realized. This is the first peer-reviewed study that utilizes historical farm-level data to analyze net economic benefits and avoided GHG emissions from fertilizer use efficiency technology adoption data across multiple regions of Mexico. The analysis can help inform policy-makers, project designers, farmers interested in implementing fertilizer use efficiency technologies, and researchers conducting microeconomic analyses on the cost-effectiveness of GHG mitigation technologies in medium and smallholder farming contexts.

Background and context

GreenSeeker Handheld Technology

The CIMMYT collaborated with Oklahoma State University to design an in-field, handheld, low-cost N diagnostic tool that provides site-specific fertilizer recommendations to farmers. The tool provides an innovative way to estimate nutrient needs mid-season based on actual plant needs at that point rather than estimated needs before planting. The precise readings offered by this diagnostic tool allow farmers to reduce overapplication, thereby reducing

fertilizer costs and air and water pollution. This tool is known as the GreenSeeker Handheld and is now being manufactured by Trimble[22].The GreenSeeker Handheld uses an active light source optical sensor that measures plant biomass and displays it as Normalized Difference Vegetation Index (NDVI) (Trimble, 2012). It is used to assess the health, or vigor, of a crop. The sensor emits red and infrared light and then measures the amount of each type of light that is reflected back at the sensor. The strength of the light detected is an indication of the health of the plant. The sensor displays an NDVI value that is then used to calculate the recommended fertilizer application rate at that location (Trimble, 2012).

To collect the data, farmers set up a reference strip, typically with a minimum of 10 m width and running the full length of the field. They over apply fertilizer in this strip so that the crops planted are not nutrient-limited. All other crop management practices are kept the same for the reference strip as in the rest of the field (i.e., sowing date and density, variety, other nutrients). Thus, the reference strip represents conditions for a given crop grown under a set of biophysical conditions and management practices when N constraints are removed, serving as a reference point for the diagnostic assessment of N fertilizer to be added (Ortiz-Monasterio & Raun, 2007). The producer or technician then measures plant vigor in the reference strip and the rest of the field and gets an NDVI measurement for each. Using an algorithm that is calibrated for the conditions of each region and crop where the farmland is located, the technician then calculates the amount of fertilizer the crop needs to have applied mid-season (the algorithm for Baja California is published in Santillano-Cazares et al., 2013; the algorithms for Sonora and Guanajuato were developed using the same methodology).

Fertilizer Practices

Nitrogen fertilizer practices vary by region in method of application, number of applications per growing season, and application rates, but farmers normally apply the GreenSeeker recommendation to either the second or third N application during the growing season. In the Yaqui and Mayo Valleys, farmers generally conduct three applications of N fertilizer per crop, some via canal irrigation. They apply more than half of the total N fertilizer that they anticipate using for the season before planting (as urea or soil injected anhydrous ammonia) and apply the rest through a second application that occurs between 40 and 50 days after planting as well as a third application that occurs 20–25 days after the second application. These last two applications are usually applied as anhydrous ammonia in the irrigation canals. The GreenSeeker technology is normally applied between the first and second applications, and the recommendation is usually applied at the second application. In Baja California, farmers conduct up to five applications of N fertilizer for wheat, also via canal irrigation – one before planting and up to four after the initial planting. The GreenSeeker recommendation is typically applied to the third application. In Guanajuato, farmers apply N fertilizer differently to barley, wheat, and maize. For barley, farmers apply N fertilizer in two applications; the first either before planting or at planting, and second 30–40 days after planting. At planting they inject ammonia in the soil and the second application is broadcast with a spreader using urea or ammonium sulfate. The GreenSeeker recommendation is usually applied to the second application. For wheat and maize, farmers apply either two or three N applications, and the GreenSeeker recommendation is normally applied at the

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[2]2https://agriculture.trimble.com/product/greenseeker-handheld-crop-sensor/, accessed 2/15/2022.

second application. In the case of wheat and barley, the technology is applied around the phenological stage of the beginning of stem elongation and in the case of maize during the rapid growth stage of development.

The analysis was focused on three regions in Mexico: the Yaqui and Mayo Valleys in Sonora; the area surrounding Mexicali in Baja California; and throughout the state of Guanajuato and surrounding areas, including bordering fields in Jalisco and Queretaro, which also constitute part of El Bajío. Each region has different farming systems and fertilizer application practices. The Yaqui and Mayo Valleys and Baja California are primarily wheat-producing regions, and the farm sizes are larger on average and producers tend to be more mechanized than in Guanajuato (Fischer et al., 2014; Peña-Cabriales et al., 2001). Farmers in these irrigated regions, as in many regions around the world, tend to overapply fertilizer as a risk aversion strategy (Good & Beatty, 2011; Paulson & Babcock, 2010). As in other post-green revolution agricultural regions in the world, the Yaqui Valley has struggled to address impacts of heavy fertilizer use (Ahrens et al., 2008; Good & Beatty, 2011; Matson, 2012).

Guanajuato and the El Bajío region are much more agriculturally diversified, and field sizes are smaller (due to the similarity in farming practices in locations where the GreenSeeker Handheld was adopted in Guanajuato, Queretaro, and Jalisco, the location is simply referred to as Guanajuato for the remainder of the paper). Fertilization practices are also more diversified. In the northern part of this state, producers tend to underapply fertilizer, because it is a rainfed area with relatively low precipitation, which limits yield potential significantly as well as demand for N. However, in the southern Bajío area, producers have larger farm sizes; more financial resources and irrigation water; and like the Yaqui, Mayo, and Mexicali Valleys, producers tend to overapply fertilizer (Ortiz-Monasterio & Raun, 2007; Santillano-Cazares et al., 2013).

Incentives for applying N fertilizer also vary by crop. For example, in Guanajuato, private-sector companies will pay a bonus for less protein content in barley (Impulsora Agrícola 2003), which is achieved by applying less N fertilizer and applying it closer to planting. Thus, barley producers have greater incentives to reduce the amount of fertilizer they apply.

Table 1 shows descriptive statistics of selected crops for which the GreenSeeker Handheld has been calibrated and applied. The table shows descriptive statistics by state, even though the analysis is limited to the small proportion of farm fields where the technology

Table 1 Descriptive statistics of crops, by state (2014, 2015)

State	Crops	Total Area Grown (ha)[a]	% of All Area Grown[a]	Average Yield (Tonnes/ha)[a]	Average Field Size (ha)[b]
Sonora	Wheat	303,272	58%	6.0	29.0
Baja California	Wheat	81,686	56%	6.4	22.0
Guanajuato	Wheat	55,133	6%	5.2	5.0
	Maize	371,502	39%	3.8	4.0
	Barley	69,279	7%	4.9	N/A

[a] Servicio de Información Agroalimentaria y Pesquera (SIAP). 2014. Anuario Estadístico de la Producción Agrícola.

[b] Data from the 2015 agricultural year provided by Servicio de Información Agroalimentaria y Pesquera (SIAP) in February 2022.

was tested and implemented. Wheat makes up over half of the total agricultural area in Sonora and Baja California, while maize is the dominant crop in Guanajuato. The average field size for wheat in Baja California and Sonora is more than four times the size of wheat fields in Guanajuato.

Data

Technicians from farmer organizations (Asociación de Organismos de Agricultores del Sur de Sonora [AOASS] and Unión de Sociedades de Producción Rural del Sur de Sonora [USPRSS]) in Sonora, private farm advisers in Mexicali (Asesoria y Promocion Agropecuaria, Sociedad Colectiva [APASC]), and technicians working for Impulsora Agricola and for the state government in Guanajuato collected data on fertilizer application rates, yields, post-planting NDVI readings, and nitrogen recommendations made to the farmer, both from both the nitrogen-rich reference strip and the adjacent farmer field. CIMMYT generated the formats and maintained the dataset. The data were then reviewed for quality and incomplete data were removed. The data were then entered into the statistical software program Stata 14.0 in a consistent way across crops and regions. Table 2 provides an overview of the crops, crop area, and years where the technology was applied and the number of producers that applied it. The greater number of observations compared with producers reflects the fact that many producers adopted the technology in multiple years.

Methodology

Additional profits from using the technology were determined by calculating net revenues from a farmer's field and then subtracting net revenues that a farmer *would have received* had they used conventional fertilizer practices (the counterfactual) (see Eq. 1 through 3). Net revenues are defined as the revenue received from the crop (yield x crop price) net of fertilizer costs (fertilizer rate x fertilizer cost). There are many other costs of production in addition to fertilizer, but all production costs other than fertilizer were assumed to be the

Table 2 Data characteristics

^a In Sonora/Yaqui and Mayo Valleys there was more area under GreenSeeker management than were formally evaluated. Depending on the year, anywhere from 37–73% of the area under GreenSeeker was evaluated. The 49,321 ha. figure represents an estimate of the full area under GreenSeeker, scaled up based on CIMMYT estimates.

State/Region	Crops	Years	Total Area (ha)	Number of Producers	Number of Observations
Sonora/Yaqui and Mayo Valleys	Wheat	2005–2016	49,321[a]	183	1,006
Baja California/Mexicali	Wheat	2012–2016	11,606	275	615
Guanajuato	Wheat	2013–2016	216	26	47
	Maize	2014–2015	155	38	67
	Barley	2013–2016	1,217	110	194

same, regardless of whether the GreenSeeker technology had been used. Thus, the assessment of the effects on profitability is based on the change in revenue relative to the change in fertilizer costs, which is the value captured by Eq. (3). Fields where farmers applied the technology are referred to as "sensor areas" (see Eq. 1 for net revenues from sensor areas).

$$Net revenue per ha. (net of fertilizer) on sensor area = NR_{sci} = (P_{ci} * Y_{sci}) - (C_{fi} * Q_{sfi}) \quad (1)$$

$$Net revenue per ha. (net of fertilizer) of counterfactual = NR_{tci} = (P_{ci} * Y_{tci}) - (C_{fi} * Q_{tfi}) \quad (2)$$

$$Total additional profits = (NR_{sci}) - (NR_{tci}) \quad (3)$$

where:

$$NR_{sci} : Net revenue in sensor area (crop c in year i)$$

$$NR_{tci} : Net revenue in counterfactual (crop c in year i)$$

$$P_{ci} : Sale price (crop c in year i)$$

$$Y_{sci} : Yield in sensor area (crop c in year i)$$

$$Y_{tci} : Yield in counterfactual area (crop c in year i)$$

$$Q_{sfi} : Fertilizer applied in sensor area$$

$$Q_{tfi} : Fertilizer applied in counterfactual$$

$$C_{fi} : Fertilizer cost (in year i)$$

For the counterfactual, two different methods were used depending on data availability. When data on a farmer's conventional practices were not available, the counterfactual was calculated based on yields measured from the on-farm reference strips required for GreenSeeker application, but fertilizer application rates were restricted to the regional average (see Eq. 2). This was the case in Sonora and Baja California. In Baja California, yield data was not available for the reference strip, so yields were assumed to be 1.4% higher on the reference strip based on data from the Yaqui and Mayo Valleys. When data on a farmer's conventional practices were available, net revenues were calculated using yields and fertilizer application rates that were directly measured on the farmer's fields. This was the case in Guanajuato.

Because of GreenSeeker's requirements, producers purposefully overapply fertilizer on the reference strip to ensure this area is not nitrogen-limited. Using this application rate for the counterfactual would overstate the profits and fertilizer cost savings from using GreenSeeker. To conservatively estimate how much fertilizer producers would normally apply, that is, without GreenSeeker recommendations, local experts and farmers were consulted to estimate the average fertilizer rates applied during a cycle for each crop in each region. For Yaqui and Mayo Valleys, 250 kg/N per hectare was assumed for the years 2006–2011 and

300 nitrogen kg/N per hectare was assumed for the years 2012–2015. For Baja California, 320 kg/N per hectare was assumed for each season. Assuming that farmers would have spent fewer resources on fertilizer on the reference strip increases the net revenues for the counterfactual (Eq. 2) and thus produces a conservative estimate of additional profits from using GreenSeeker (Eq. 3).

A critical assumption in the methodology was that farmers were able to access GreenSeeker Handheld and recommendations at no cost to themselves. This was done because the GreenSeeker farmers in Mexico did not have to pay for the technology, however subsidies were provided for the technicians to go to the field to take the readings and set up the test strips (technicians were paid approximately 60 pesos [$4USD in 2015] per hectare).

Additional assumptions were made due to data limitations. If yield data for the counterfactual calculation (either reference strips in Baja California/Sonora or conventional practices in Guanajuato) were missing, average yield for the crop in that region was used, assuming that would have been the yield had they not applied the fertilizer amount recommended by GreenSeeker. This was done for 138 observations. If yield data for sensor areas were missing, the observations were excluded because yield data are critical for comparing the benefits of the sensor areas. Likewise, observations were dropped if they did not have data on fertilizer application rates in sensor areas.

CIMMYT provided the historical crop and fertilizer prices. For fertilizer prices, the price per unit of N of the types of fertilizer most commonly used in the different regions were averaged. Table A-1 (appendix) shows a breakdown of the price assumptions that were made for each region and crop.

Calculating Difference in Emissions.

For the GHG mitigation analysis on GreenSeeker use, $N_2O - N$ emissions were calculated based on emission factor equations derived from many years of research in the Yaqui Valley (Eqs. 4 and 5), specified in terms of $gN_2O - N$ (Millar et al., 2018). Emissions were then subtracted from the sensor area from the reference strip and converted those values to carbon equivalents using a 100-year global warming potential for N_2O of 310 (Eq. 7).

$$N_2O - N emissions sensor area = N_2O - N sensor = 258 * e\,(0.00676 * Q_{sfi}) \quad (4)$$

$$N_2O - N emissions counterfactual = N_2O - N counter = 258 * e\,(0.00676 * Q_{tfi}) \quad (5)$$

$$\Delta emissions = emissions_{sensor} - emissions_{counter} \quad (6)$$

$$CO_2 eq = \frac{(N_2O - N * 1.57)}{1,000,000} x310 \quad (7)$$

Where:
Q_{sfi} : $Fertilizer applied in sensor area$ (kg N)
Q_{tfi} : $Fertilizer applied in counterfactual$ (kg N)

Results

In the Yaqui and Mayo Valleys, where the technology has been adopted for the longest time, GreenSeeker use has led to an average of $38/ha in additional farmer profits, totaling $1.9 M of additional profits over a 10-year period (Table 3). It has also reduced GHG emissions by an estimated 9,548 tons CO_2e, or the equivalent of taking more than 2,000 cars off the road for a year (GHG equivalency for passenger vehicles per year was assumed to be 4.7 metric tons CO_2e/vehicle/year [US EPA, 2014]). These favorable totals mask a significant variation in profits by year. For example, because of unseasonably high temperatures, the average yield for wheat crops during the 2014–2015 growing season was much lower than expected at only 5.2 tons/hectare. Many GreenSeeker producers did not follow the recommendation during this season and attempted to offset low yields by applying much more N fertilizer. Paradoxically, farmers may have been able to partially offset the revenue losses from the lower yields by applying the GreenSeeker recommendations. Instead, the combination of lower yields and greater fertilizer application explains these negative profits for an unusual year (warmest in more than 38 years [email communication with Ivan Ortiz-Monasterio, 05/2018]).

Because Baja California had no yield data for reference strips, and higher rates of N fertilizer were applied on the reference strip, yields for the reference strips were assumed to be higher than in the sensor area by the same average amount as in the Yaqui Valley, or 1.4% of mean yields. Even with this conservative assumption, additional profits were $51.5 per hectare for a total of $597,630 in additional profits over the 4 years in which the technology was tested. Total avoided emissions were 4,528 tons CO_2e, which equates to 963 cars taken off the streets for a year (Table 4).

In Guanajuato, GreenSeeker was applied to barley, maize, and wheat, leading to additional profits averaging $59.40/ha (total of $88,692) and avoided GHG emissions of 215 tons CO_2e, equivalent to taking approximately 45 cars off the road for a year. Although GreenSeeker led to higher profits overall, there was significant variation by crop (Table 5).

Tables 6, 7 and 8 provide breakdowns by year for the individual crops studied in Guanajuato. Cumulative additional profits were highest for barley crops, totaling $58,420 of additional profits over a 4-year period. For wheat, additional profits per hectare were $45 for the 2 years for which data were available. Wheat profits were negative for 2013–2014, in part because the average yield for the producer area was greater than the average yield in sensor areas and this did not outweigh fertilizer savings. Additional profits per hectare were the highest for maize, at $48 per hectare, which can be explained by the differences in farmer fertilizer practices. In 2014, 18 of the 39 observations were rainfed rather than irrigated. These producers tend to underapply fertilizer. According to local experts, this is a risk avoidance strategy in case it does not rain, in which case they believe they will lose their investment because the crop will not be able to use the N fertilizer unless there is water present. Some fertilizer may be left for the next cycle, but, in general, farmers see the N application as a loss when it does not rain. The GreenSeeker tool recommends applying more N, which improves yields significantly. For these rainfed fields, the average yield was 2.8 tons, while with GreenSeeker, even though farmers were spending more money on fertilizer, the average yield was 5.3 tons. This higher yield led to much higher average profits, but the greater N application rates also led to higher GHG emissions.

Table 3 Additional profits and avoided greenhouse gas emissions by year in Yaqui and Mayo Valleys (wheat)

Year	Additional Profits (USD/ha)	Avoided Emissions (tCO$_2$e/ha)	Total Area (ha)	Total Profits (USD)	Total Avoided Emissions (tCO$_2$e)
2006–2007	$6.80	0.19	2,445	$16,636	464
2007–2008	–$5.77	0.20	4,232	–$24,410	861
2008–2009	$113.54	0.23	6,598	$749,164	1542
2009–2010	$62.30	0.23	7,724	$481,190	1752
2010–2011	$38.29	0.14	8,877	$339,901	1212
2011–2012	$33.51	0.24	5,671	$190,032	1373
2012–2013	$18.92	0.22	5,665	$107,183	1265
2013–2014	$10.85	0.16	7,149	$77,568	1163
2014–2015	–$49.76	–0.09	960	–$47,768	-83
All Years	**$38.31**[a]	**0.19**[b]	**49,321**[c]	**$1,889,497**[c]	**9,548**[c]

Note: Based on 1,006 observations. Values are in 2015 U.S. dollars, discounted using World Bank Open Data Consumer Price Index for Mexico.

[a] This number is calculated by dividing Total Profits by Total Area from All Years.

[b] This number is an average of the numbers in this column.

[c] This number is a total of the numbers in this column.

Table 4 Additional profits and avoided greenhouse gas emissions by year in Baja California (wheat)

Year	Additional Profits (USD/ha)	Avoided Emissions (tCO$_2$e/ha)	Total Area (ha)	Total Profits (USD)	Total Avoided Emissions (tCO$_2$e)
2012–2013	$76.05	0.44	3,652	$277,745	1607
2013–2014	$39.46	0.35	5,232	$206,470	1821
2014–2015	$52.63	0.47	1,521	$80,046	718
2015–2016	$27.78	0.32	1,201	$33,370	382
All Years	**$ 51.49[a]**	**0.39[b]**	**11,606[c]**	**$597,630[c]**	**4,528[c]**

Note: Based on 615 observations. Values are in U.S. 2015 dollars, discounted using World Bank Open Data Consumer Price Index for Mexico.

[a] This number is calculated by dividing Total Profits by Total Area from All Years.

[b] This number is an average of the numbers in this column.

[c] This number is a total of the numbers in this column.

Table 5 Additional profits and avoided greenhouse gas emissions by crop in Guanajuato in El Bajío region

Crop	Additional Profits (USD/ha)	Avoided Emissions (tCO$_2$e/ha)	Total Area (ha)	Total Profits (USD)	Total Avoided Emissions (tCO$_2$e)
Barley	$46.7	0.11	1217	$58,420	141
Wheat	$44.96	0.37	216	$9,692	67
Maize	$132.43	−0.08	155	$20,580	7
All Crops	**$59.40[a]**	**0.14[a]**	**1,588[b]**	**$ 88,692[b]**	**215[b]**

Note: Based on 308 observations. Values are in U.S. 2015 dollars, discounted using World Bank Open Data Consumer Price Index for Mexico.

[a] This number is a weighted average of the numbers in this column, weighted by number of observations of each crop.

[b] This number is a total of the numbers in this column.

Influence of Fertilizer Application Rates on Profits

Since farmers did not always follow the GreenSeeker recommendation, understanding how the additional profits they received were related to the recommendation itself vs. farmers' decisions to deviate from the recommendation will provide clues as to the effectiveness of the technology. Five main factors affect additional profits for GreenSeeker adopters: fertilizer application rate, crop yield, fertilizer price, fertilizer type, and crop price. Because there is little that a farmer can do to affect prices (which is related to choices around fertilizer type), and the GreenSeeker technology directly affects both fertilizer application rates and yields, it is important to examine both (a) how GreenSeeker use has affected crop yields and

Table 6 Additional profits and avoided greenhouse gas emissions by year in Guanajuato (barley)

Year	Additional profits (USD/ha)	Avoided Emissions (tCO$_2$e/ha)	Total Area (ha)	Total Profits (USD)	Total Avoided Emissions (tCO$_2$e)
2013–2014	$88.30	0.02	191	$16,907	4
2014–2015	$59.48	0.23	425	$25,299	97
2015–2016	$27.02	0.07	600	$16,214	39
All Years	**$48.01[a]**	**0.11[b]**	**1,217[c]**	**$58,420[c]**	**141[c]**

Note: Based on 194 observations. Values are in U.S. 2015 dollars.

[a] This number is calculated by dividing Total Profits by Total Area from All Years.

[b] This number is a weighted average of the numbers in this column.

[c] This number is a total of the numbers in this column.

Table 7 Additional profits and avoided greenhouse gas emissions by year in Guanajuato (maize)

Year	Additional Profits (USD/ha)	Avoided Emissions (tCO$_2$e/ha)	Total Area (ha)	Total Profits (USD)	Total Avoided Emissions (tCO$_2$e)
2014	$272.48	−0.40	66	$17,878	−26
2015	$30.10	0.37	90	$2,703	33
All Years	**$132.43[a]**	**−0.08[b]**	**155[c]**	**$20,580[c]**	**7[c]**

Note: Based on 67 observations. Values are in U.S. 2015 dollars.

[a] This number is calculated by dividing Total Profits by Total Area from All Years.

[b] This number is a weighted average of the numbers in this column.

[c] This number is a total of the numbers in this column.

Table 8 Additional profits and avoided greenhouse gas emissions by year in Guanajuato (wheat)

Year	Additional Profits (USD/ha)	Avoided Emissions (tCO$_2$e/ha)	Total Area (ha)	Total Profits (USD)	Total Avoided Emissions (tCO$_2$e)
2013–2014	−$15.95	0.18	131	−$2,085	24
2014–2015	$138.71	0.51	85	$11,777	43
All Years	**$44.96[a]**	**0.37[b]**	**216[c]**	**$9,692[c]**	**67[c]**

Note: Based on 47 observations. Values are in U.S. 2015 dollars.

[a] This number is calculated by dividing Total Profits by Total Area from All Years.

[b] This number is a weighted average of the numbers in this column.

[c] This number is a total of the numbers in this column.

(b) whether deviations of fertilizer application rates from recommendations impact additional profits derived from the technology.

Two types of statistical tests were run to examine these issues. The first was a *t* test of yields to examine whether mean yields on the reference strips (where fertilizer was overapplied) were significantly higher than yields where the GreenSeeker recommendation was provided to the farmers. In the Yaqui and Mayo Valleys, yields on the reference strip were found to be higher by an average of 95 kg/ha, or equivalent to 1.4% of mean yields, and this difference is highly statistically significant (1% significance level, see Appendix Table A-4). The interpretation of this is that GreenSeeker users in the Yaqui and Mayo Valleys may have been sacrificing up to 1.4% of yields when they used the technology even though they were increasing profits from using the technology. This result is supportive of findings in previous studies that the maximum economic yield is lower than the maximum agronomic yield (Fischer et al., 2014; Fischer, 2015). This is likely an upper bound of what farmers are sacrificing because farmers were asked to purposely overapply the fertilizer on the reference strip rather than apply what they would have applied on their fields otherwise.

The second quantitative component of this study is an ordinary least squares (OLS) regression analysis to gauge the effects on profitability of over- or under-application of fertilizer compared to recommended rates. Only data from the Yaqui Valley were used in the analysis as this was the dataset with a large enough number of observations (631) to lend reliability to the results. This component of the analysis involves a two-pronged approach. The first is fitting a model to the data to examine the relationship between average profits and deviations from recommended fertilizer application rates. Then, asymmetry was inves-
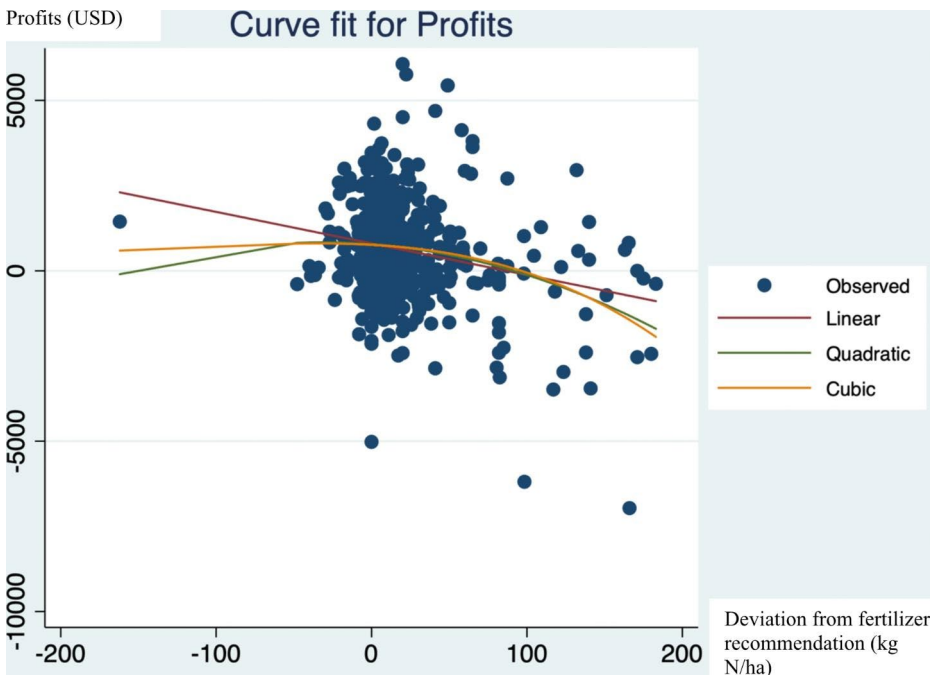

Fig. 1 Curve fit of the linear, quadratic, and cubic specifications of the regression of average profits on deviation of fertilizer rates

tigated for how average profits respond to positive and negative deviations from the recommended rates.

To examine the effect of deviations in fertilizer application rates from recommended levels on average profits, nonlinearity was tested in their relationship. Higher order polynomials were included in an OLS regression of average profits on deviations in N fertilizer applications and use the Wald test to test the significance of the quadratic and cubic terms. The null hypothesis was rejected for them being equal to zero and thus a quadratic and cubic form were used to examine which provides the best fit (measured by adjusted R^2). Results suggest that the quadratic model slightly out-performs the cubic specification and more significantly out-performs the linear form. All three fits of the model are displayed in Fig. 1.

As Fig. 1 shows, the quadratic functional form, which best fits the data, implies that average profits are maximized in the region around zero deviation from recommended fertilizer application rates. This suggests that deviations above or below the recommended rate will lower average profits.

The presence of potential asymmetry is further examined in how profits respond to positive and negative deviations form recommended application rates. Do profits fall more if fertilizer is under-applied or over-applied or is the response symmetrical? To address this question, average profits were regressed on positive and negative deviations and the model was estimated using OLS. Fertilizer deviations were interacted with two dummy variables: one takes a value of one if deviations are positive and zero otherwise, while the second takes a value of one for negative deviations and zero otherwise. The first interaction variable therefore depicts positive deviations while the second variable represents negative deviations. The list of regressors were completed with year dummy variables to account for time-varying factors. Table 9 displays the results.

The results of the regression analysis suggest that only positive deviations have statistically significant effects on average profits, while negative deviations do not significantly affect profits. This implies that adding fertilizer more than the recommended amount adds more to costs than revenues, thereby reducing profits. Additionally, the results indicate that negative deviations are not significant, which suggests that reducing fertilizer from the recommended amounts does not reduce profits significantly. Most negative deviations lie just below zero (see Fig. 1), meaning that farmers are not underapplying fertilizer by large amounts. It is, therefore, reasonable that the observed reductions in fertilizer application may not significantly lower yields, and hence revenues, in a way that would more than offset the reduction in associated fertilizer costs. This result may be different if there were more observations far to the left of zero deviations.

Table 9 OLS regression results of average profits on positive and negative deviations of fertilizer application rates from recommended levels

Variable	Estimate	Robust standard error
Positive deviations	-8.72 ***	3.19
Negative deviations	0.89	3.79
Constant	-333.59	380.87

Note: Other variables included in the models are year dummy variables. Robust standard errors between parentheses. Significance levels: *** p<.01.

Discussion

The GreenSeeker Handheld, as a fertilizer use efficiency technology, has provided significant profits for farmers in three regions of Mexico. Scaling average estimated GreenSeeker profits to the state level would mean $11.6 million per year in additional profits and 57,600 tCO_2e of avoided emissions for wheat farmers in Sonora, $4.2 million per year in additional profits and 31,900 tCO_2e of avoided emissions for wheat farmers in Baja California. Scaling estimates up to the national level would mean $29.4 million per year in additional profits and 176,400 tCO2e of avoided emissions to wheat farmers in Mexico (data from Guanajuato was not scaled up due to the relative fewer observations and smaller farmer area under GreenSeeker). Estimates of profitability do not account for subsidies provided for the technicians to go to the field to take the readings or set up the test strips or for farmers' opportunity costs if they took time to set up the test strips. However, technicians are paid approximately 60 pesos per hectare, much less that the average increase in profitability/ha that is being reported here.

Although GreenSeeker has led to higher profits and lower GHG emissions, on average, where it has been applied, it is not yet sustainable in the absence of external support for the costs of the GreenSeeker operator to travel to the sites, collect data, and provide recommendations to the farmer. The reasons for this are multifactorial and related to the technology subsidies as well as behavioral, market, and other factors (Lapidus et al., 2017). It costs farmers to overapply, but it is a risk management strategy for them. If you have certain weather conditions that lead to high fertilizer runoff, for instance, there would not be enough N available for their crops if they do not apply excess fertilizer. Recommendations for more efficient fertilizer use could be accompanied by crop insurance for yield shortfalls associated with following N BMPs or other public measures to mitigate increased yield risk. The study does not go into the other market and institutional dynamics affecting adoption and disadoption of the technology, which are also important but are the subject of other manuscripts and represent opportunities for future research (Lapidus et al., 2017; Matson, 2012).

Furthermore, profits have varied significantly over time and space. Farmers may experience large profits one year and lower profits the next, or one farmer may experience profits, but a neighbor does not. In the 2014–2015 growing season, when temperatures were unseasonably warm, profits in the Yaqui and Mayo Valleys were negative because many GreenSeeker farmers overapplied fertilizer in an unsuccessful attempt to counteract lower expected yields. This negative outcome is not a result of the technology but reveals limitations in the benefits that can be achieved in the absence of strategies to (1) increase confidence in the recommendations under alternative conditions and (2) improve risk management available to farmers such that their incomes are less variable year-to-year and they can focus more on the potential benefits for average returns over time. In addition, farmers are not currently able to capture any of the value of the environmental benefits associated with more efficient fertilizer use. Climate policy providing incentives for GHG mitigation, for instance, is likely to make use of N management technologies such as GreenSeeker considerably more attractive to farmers. With climate change and higher expected temperatures, GreenSeeker has the potential to help farmers increase profits to offset lower yields, but these benefits depend on whether farmers follow the application recommendation.

Several key physical factors were tested to determine how they influence the effectiveness of GreenSeeker. As evidenced by the 2014–2015 growing season, profits were found to

be significantly less when farmers deviate from the GreenSeeker application recommendation. The econometric analysis further reaffirms this finding, which supports the hypothesis that profits could have been even higher if farmers had followed the recommendation for their fields.

These results suggest that technology adoption for the GreenSeeker Handheld will largely depend on producers' willingness to follow the recommendation. To realize the economic and environmental benefits that this paper demonstrates, a strategy for adoption will have to account for farmers' preferences, mentality, attitudes, risk aversion, and demographics. Their openness to question assumptions of how much N fertilizer their crops need will be a key factor in how widely the technology will be used and accepted. In addition, partnerships with key actors within each region's agricultural knowledge systems are essential for successful diffusion and adoption (Basak, 2016).

Conclusions

This study provides empirical evidence from on-farm data on fertilizer application rates and yields and data for how a fertilizer use efficiency technology has both improved profits and provided environmental benefits to farmers in three different regions of Mexico. Results suggest that these dual benefits were realized for wheat in Sonora in 7 of 9 years, in Baja California in 4 of 4 years, and in Guanajuato in 1 of 2 years. Although the technology is not yet self-sustainable in the absence of public subsidies, efforts are underway to continue transferring the technology and to develop new remote sensing tools that use similar sensors and could lead to these dual benefits in the future.

Appendix Tables:

Table A.1 Yaqui Valley wheat and fertilizer prices (MXN)

Year	Wheat Price[a] (pesos/kg)	Fertilizer Price[b] (pesos/kg N)
2007–2008	4.1	10.6
2008–2009	3.4	16.6
2009–2010	3.0	12.9
2010–2011	3.9	12.4
2011–2012	3.9	18.5
2012–2013	3.8	16.7
2013–2014	3.7	13.7
2014–2015	4.6	13.2

[a] Prices informed by CIMMYT

[b] Average price of urea and NH_4 (ammonium sulfate)

Table A.2 Baja California wheat and fertilizer prices (MXN)

Year	Wheat Price[a] (pesos/kg)	Fertilizer Price[b] (pesos/kg N)
2012–2013	3.7	15.2

Table A.2 Baja California wheat and fertilizer prices (MXN)

Year	Wheat Price[a] (pesos/kg)	Fertilizer Price[b] (pesos/kg N)
2013–2014	3.4	13.2
2014–2015	4.5	14.1
2015–2016	3.7	15.4

[a] Prices informed by CIMMYT

[b] Weighted average prices of urea (25%), NH_4 (ammonium sulfate)(25%), and ammonia (50%)

Table A.3 Guanajuato crop and fertilizer prices (MXN)

Year	Wheat Price[a] (pesos/kg)	Barley Price[a] (pesos/kg)	Maize Price[a] (pesos/kg)	Fertilizer Price[b] (pesos/kg N)
2012–2013	N/A	N/A	N/A	N/A
2013–2014	3.8	3.5	3.6	14.8
2014–2015	3.6	3.7	3.6	15.6
2015–2016	N/A	4.5	N/A	16.8

[a] Prices informed by CIMMYT

[b] Average price of urea and NH_4 (ammonium sulfate)

Table A.4 Yield difference between reference strip and farmer fields in the Yaqui Valley

Variable	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf. Interval]	
Rich strip yield	1,003	7,033.9	35.0	1,109.6	6,965.1	7,102.7
Sensor yield	1,003	6,937.9	33.6	1,065.7	6,871.9	7,003.9
mean(diff)=mean(Rich_Strip_Yield−Sensor_Yield)					t=10.7	

Ho: mean(diff)=0 degrees of freedom=1002

Ha: mean(diff)<0 Ha: mean(diff) != 0 Ha: mean(diff)>0

Pr(T<t)=1.0000 Pr(|T| > |t|)=0.0000 Pr(T>t)=0.0000

Availability of data material, and code. The datasets and code generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflicts of interest/Competing interest The authors declare that they have no conflict of interest.

Ethics approvals No approvals or waivers were required for this manuscript.

Consent to participate and consent for publication All authors agreed with the content and gave explicit consent to submit and obtained consent from the responsible authorities at the institute/organization where the work has been carried out.

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