Benefits and costs of nitrogen fertilizer management for climate change mitigation

Focus on India and Mexico

Working Paper No. 161

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

Rishi Basak

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Abstract

This report analyzes the costs and benefits of managing nitrogen fertilizer in ways that also reduce greenhouse gas emissions in cereal production (rice, wheat, and maize) in India and Mexico. The purpose of this work is to inform finance needed for low emissions agricultural development. For each agricultural mitigation practice identified, the corresponding potential emissions reduction and on-farm costs and benefits (e.g., operational costs, savings, or other benefits) are provided, based on available literature.

Keywords

Climate change; mitigation; fertilizer, nitrogen; rice; wheat; maize; greenhouse gas emissions; India; Mexico; low emissions development

About the authors

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Acronyms

BAU	Business-as-usual
BNI	Biological nitrification inhibition
CCAFS	CGIAR Research Program on Climate Change, Agriculture and Food Security
CH_4	Methane
CIMMYT	International Maize and Wheat Improvement Center
CO_2e	Carbon dioxide equivalent
CRF	Controlled-release fertilizers
GHG	Greenhouse gas
ha	Hectare
INUE	Internal nitrogen use efficiency
kg	Kilogram
IPCC	Intergovernmental Panel on Climate Change
LED	Low emissions development
Mt	Mega tonnes (1,000,000 tonnes)
N	Nitrogen
N_2O	Nitrous oxide
NPK	Nitrogen, phosphorus, potassium (ratio in fertilizer)
NUE	Nitrogen use efficiency
t	Metric tonne
UNFCCC	United Nations Framework Convention on Climate Change
$	United States dollar

Executive summary

This report analyzes the costs and benefits of managing nitrogen (N) fertilizer in ways that also reduce greenhouse gas (GHG) emissions in cereal production (rice, wheat, and maize) in India and Mexico. The purpose of this work is to inform climate finance for low emissions agricultural development. For each GHG-reducing practice identified, its corresponding emissions reduction potential and impact on farm-level costs and benefits (e.g., operational costs, savings, or other benefits) were summarized based on available literature. It should be noted that there is a lack of data on the GHG and economic impacts of several technologies in the academic literature. Results are summarized in table E-1.

Table E-1. Summary of farm-level outcomes from mitigation practices

Mitigation practice	Country	Outcomes			Data gaps	Win-Win?
		GHG emissions	Yield	Economics		
Fertilizer source						
Shift from urea to ammonium sulfate/nitrate		No data	Increase 5-11% (maize)	Cost prohibitive	GHG reduction potential	
		No data	Increase 11%, 0.760 metric tonnes/hectare (t/ha) (wheat) No data for maize	Cost prohibitive	GHG reduction potential	
Fertilizer rate						
Optimization of N fertilizer rate, based on assessment of N needs (e.g., using GreenSeeker)		Increase 3%, 0.016-0.061 tCO_2e/ha (wheat) 0.051-0.247 tCO_2e/ha (rice) No data for maize	Increase 10%, 0.2-0.530 t/ha (wheat) No change (rice) No data for maize	Increase net returns $159/ha (wheat) Increase cost $10-49/ha (rice) No data for maize	Impacts in maize	
		Increase 0.190 tCO_2e/ha (wheat) Increase 0.154 tCO_2e/ha (maize)	No change (wheat, maize)	Increase production costs $83/ha (wheat) $68/ha (maize)	Improve accuracy of GHG reduction potential	
Genotypic differences to inhibit the N cycle, etc.		No data	Increase 1-2%/ year (wheat)	Seeds made available for free Increase revenues	GHG reduction potential, current diffusion rate	
		No data Full adoption		No cost for seeds Increase revenues	GHG reduction potential	

Mitigation practice	Country	Outcomes			Data gaps	Win-Win?
		GHG emissions	Yield	Economics		
Application timing						
Applying fertilizer at planting, split dosage		No data	Increase 4%, 0.176 t/ha (wheat) No data for rice, maize	No data	GHG emissions, economics (wheat, rice, maize) Yield for rice, maize	
		Increase 89% N_2O and NO (wheat) No data for maize	No change (wheat) No data for maize	Cost saving equivalent to 12-17% after tax profits (wheat) No data for maize	Conversion to CO_2e, Overall business case for maize, How to eliminate barriers to adoption	
Controlled-release fertilizers		GHG emission reductions uncertain	0% to increase of 20%	Cost prohibitive	GHG impact	
		No data	No data	Cost prohibitive	GHG and yield impacts, cost-effective options	
Nitrification inhibitors		Increase 0-53% (rice, wheat) No data for maize	Decrease (rice, wheat) Increase 0.150-0.520 t (maize)	Chemical inhibitors are cost prohibitive (\$20-\$44/tCO_2e)	Neem oil costs and availability	
		No data	No data	Cost prohibitive	GHG and yield impacts	
Deep placement		Increase 4%, 0.108 tCO_2e/ha (rice)	No change (rice) No data for wheat, maize	\$29/t CO_2e Increase \$3/ha cost of production (rice)	Super granules and briquettes in Indian rice	
		No data	No data	No data	GHG, yield and economic impact	

*Symbol legend:

 Strong evidence that it reduces GHGs and improves livelihood of farmers

 Evidence that the technology may not reduce GHGs or be financially viable or that it lacks compelling evidence that it reduces emissions and/or improves livelihoods of farmers

 Further research required to determine impacts of the technology

Optical sensors, combined with decision tools for providing field-specific guidelines on nutrient management, are promising technologies for optimizing N efficiency. As table E-1 shows, optical sensors, such as the GreenSeeker, are also a promising technology for reducing GHG emissions in the agriculture sector in India and Mexico, especially if a solution can be found that allows farmers to avoid having to pay the full, up-front cost of the sensor. In India, rates of fertilizer application using optical sensors were found to have a GHG reduction potential of 0.016–0.247 tCO_2e/ha (0.135–2.500 $MtCO_2e$ nationwide). They could lead to important increases in yield (0.20–0.53 t/ha in wheat) and net returns ($159/ha in wheat), compared with farmers' practice. Benefits of this technology in India should be examined relative to other programs with similar goals, such as a planned Government of India Soil Health Card program. In Mexico, the GHG benefits of using optical sensors in wheat production are 0.190 tCO_2e/ha (0.0056–0.0504 $MtCO_2e$ nationwide). There is no change in yields beyond the business-as-usual yields from fertilizer; the financial benefits are $83/ha (production cost reduction). If similar GHG and financial benefits can be achieved in maize production, this technology could have even more significant results in Mexico, since over 7 million ha are under maize production there. A preliminary estimate of the technology's national-level impacts is summarized in table E-2.

Table E-2. Summary of national-level impacts of using optical sensors (e.g., GreenSeeker) for optimizing N efficiency

National impact	India	Mexico
Additional area using optical sensor for optimizing N efficiency in 5 years under business-as-usual (BAU) scenario	2.2 million ha (rice) 1.3 million ha (wheat)	370,000 ha (maize) 29,450 ha (wheat)
Additional area (over BAU) with optical sensor for optimizing N efficiency in 5 years with national-scale program	2.2–8.9 million ha (rice) 1.3–5.1 million ha (wheat)	370,000–1.5 million ha (maize) 29,000–118,000 ha (wheat)
Annual incremental (over BAU) GHG reductions from optical sensor in 5 years with national-scale program	0.100–2.200 $MtCO_2e$(rice) 0.021–0.314 $MtCO_2e$ (wheat)	0.0056–0.0224 $MtCO_2e$ (wheat) 0.057–0.228 $MtCO_2e$ (maize)
Annual incremental (over BAU) yield increase from optical sensor in 5 years with national-scale program	No change (rice) 0.3–2.7 Mega tonnes (Mt) (wheat)	No change (wheat)
Annual incremental (over BAU) fertilizer cost savings from optical sensor in 5 years with national-scale program	No data	$2.4–$9.8 million (wheat) $25–$101 million (maize)
Annual incremental (over BAU) increased net returns from optical sensor in 5 years with national-scale program	$242–$966 million (wheat)	No data

For Mexico, further studies should more precisely determine the GHG reduction potential of optimizing N application through the use of an optical sensor such as the GreenSeeker for wheat, since using the Intergovernmental Panel on Climate Change default emission factor may be too conservative. Additional research is also required to determine the GHG reduction potential of this technology in maize in Mexico. A study on how diffusion can be increased, including potential policy instruments that may increase incentives for adoption, would also prove useful for the development of future low emissions development policy and finance in Mexico. In India, data also are lacking on the GHG reduction potential from using optical sensors in maize, though research is currently underway at the International Maize and Wheat Improvement Center. An additional data gap in India is the yield improvement and financial viability of optical sensors in maize production.

Practice changes—including application timing, neem as a nitrification inhibitor, and deep placement—also show promise, though further research is required to build the business case. Field studies on fertilizer application timing, with measurement of GHG emissions and quantification of the financial benefits and costs, are needed before firm conclusions can be reached about the impacts of this technology in the Indian context. Similarly, neem oil may also be a promising technology as a nitrification inhibitor, as one study found that neem oil decreased GHG emissions by 11% for rice and 21% for wheat. An additional key question to determine neem oil's financial attractiveness is whether it would be available in sufficient amounts (and at a sufficiently low price) across India if neem coating of urea became a mainstream practice. This requires an in-depth study. It should be noted that the Government of India announced in January 2015 that it would require via regulatory mandate that 75% of the urea produced domestically be neem-coated. This will ensure broad diffusion across the country, but would also make neem-coated urea a less attractive technology in a national context as its GHG reduction benefits would not necessarily be considered additional for the purpose of performance-based payments. Finally, the deep placement of super granules may also be promising at reducing emissions in Indian rice production, as they have been found to be effective and profitable in Bangladesh. Although a 1985 study (Prasad & Singh 2015) found negative results in terms of the technology's GHG benefits, the study seems to have been strongly influenced by site selection. Further field studies, on a multitude of soil types in India, would need to be conducted before a more compelling business case can be developed.

Field studies need to go beyond agronomic impacts. It is recommended that future field studies include analysis of the cost-effectiveness of technologies, in addition to overall GHG impact (i.e., methane and nitrous oxide emissions from the crop, soil, and fuel use) and agronomic benefits. Special attention should be placed on economics of the technology, including labor costs under manual and mechanized approaches to application, labor costs to produce the fertilizer (in the case of briquettes produced on site or locally), and market availability of the technology (and any machinery required for its implementation, if applicable). Field studies related to technologies that entail increased traffic in fields (e.g., split fertilizer application) should also consider soil compaction and long-term impact on productivity. Having this more comprehensive suite of information would enable solid business cases to be built for technologies that have been demonstrated as having significant agronomic benefits.

Introduction

This report contributes to the project "Financing Low Emissions Agriculture," led by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). The project aims to analyze financial options and gather empirical evidence to build business cases for supporting transitions to low emissions agriculture in developing countries. Ultimately the project seeks to inform investment in agricultural development and the mitigation of agricultural greenhouse gas (GHG) emissions. This report focuses on nitrogen (N) fertilizer management impacts on the mitigation of GHG emissions in cereal production (maize, rice, and wheat) in India and Mexico, countries with significant potential for growth in fertilizer-related emissions. The rationale for focusing the analysis on these three crops is that together they account for 60% of global N fertilizer use (Ladha et al. 2005). A companion report (Working Paper 160) is available on alternate wetting and drying as a GHG emissions mitigation strategy in paddy rice production in Vietnam and Bangladesh.

The report is organized as follows: The approach used to undertake this study is described, followed by a brief background section that provides an overview of agricultural production in India and Mexico, including size of the sector and its GHG impact. The third section describes several N fertilizer technologies, their emissions reduction potential, and corresponding implementation costs and benefits. The report concludes with comments and recommendations.

Approach

This report is based on a desk review of the grey and academic literature. It does not contain an exhaustive review of the agronomic studies, but merely a review of studies relevant to the project's main objective of starting to build business cases for technologies that can reduce GHGs while also yielding financial benefits to smallholder farmers, thereby increasing their food security. As such, most studies that were reviewed focused on the GHG and economic impacts of mitigation technologies. A two-stage screening process was used, as suggested by Loevinsohn et al. (2013). First, search keys were used in Google Scholar, and paper titles and abstracts of each article were reviewed for their relevance to this study. Studies were excluded if they were not:

- Written in English or French;[1]
- Focused on smallholder farmers in low or lower-middle income countries;
- Focused on N fertilizer management.

Papers that were retained were then screened to exclude those that did not provide data on key elements quantified in this study, namely:

- Costs of production (labor, other inputs);
- Benefits of production (yield, revenues);
- Specific mitigation technologies of interest;
- GHGs associated with the production, that is, impacts of both methane (CH_4) and nitrous oxide (N_2O), or overall carbon dioxide equivalent (CO_2e);
- Focus on maize, rice, or wheat;
- Results specifically for the Indian or Mexican context.

At least one of the elements above needed to be included in the study for it to be retained. Overall, more than 700 studies were reviewed, with 57 ultimately retained.

Alternative N fertilizer management technologies and practices that lead to reduced GHG emissions were compiled. For each GHG-reducing technology identified, the author documented its corresponding emissions reduction potential and financial impact (e.g., implementation costs including labor, fertilizer, and fuel, savings, other benefits[2]), where information could be found.

As the objective of this project is to estimate the costs and benefits for the most promising technologies, results from multiple studies were used to fill in information gaps. For instance, one study may have provided data on the GHG reduction potential of a given agricultural practice but did not contain information on the corresponding cost of adoption. Results from another study (or studies) were therefore required to determine the cost of adoption. Yet another study may have been required to determine the cost per metric tonne (t) of emissions reduced, via a process of "triangulation." In many instances, insufficient information was available to determine the full costs and/or benefits of adoption.

An essential element for the development of national impact estimates is the diffusion rate of the technology under a business-as-usual (BAU) scenario. This was then compared with a case in which an effective low emissions development (LED) program could be established to

[1] The contractor hired to undertake the analytical work for this project was able to review technical documentation in English and French only.

[2] Unfortunately, none of the studies retained included information on social or environmental co-benefits beyond GHG reductions.

incentivize farmers to adopt the new practices. As scant information could be found in the literature on current or potential diffusion rates of N fertilizer management technologies, a credible range for the diffusion rate of these technologies was determined using an expert survey approach. Using information gathered from the expert survey and information found in the literature on the diffusion of agricultural technologies, three scenarios were developed to estimate the national-level impacts of N fertilizer management technology adoption:

1. BAU scenario: impacts of the given technologies in the absence of further efforts by LED programs to encourage adoption.
2. Conservative scenario: impacts of the given technologies if efforts by the global community to encourage adoption lead to negligible uptake.
3. Aggressive adoption scenario: impacts of the given technologies if LED programs invest in aggressive diffusion efforts.

All financial amounts included in this study are in 2014 United States dollars (USD), unless stated otherwise.

Background

This section provides an overview of the agriculture sector for the Indian and Mexican markets, including size of the market and GHG emissions.

Cereals are a staple food in India, supplying over 60% of the Indians' protein intake and using 63% of the country's fertilizer (Chanda 2008). In 2012, India produced 157,800,000 mega tonnes (Mt) of paddy rice and 94,880,000 Mt of wheat (FAOSTAT). Paddy rice had a total cropped area of 44.7 million ha, with 24 million ha irrigated. Wheat was cropped on 25.7 million ha (89% irrigated), whereas maize is grown on 6.6 million ha, only 1.5 million ha of which is irrigated, for a total annual production of 22.3 Mt (FAOSTAT).

Fertilizer use in rice production is 37%, 24% for wheat, and 2% for maize (Chanda 2008). Fertilizer use varies significantly in India. Farmers in rain-fed areas apply very little fertilizer due to the high uncertainty of crop yield or lack of available inputs. Most fertilizer is therefore used in India's irrigated agriculture. In irrigated areas, the nitrogen, phosphorus, potassium (NPK) ratio was 4.8:2.3:1 in 2011, close to the recommended agronomic dose (Mujeri et al. 2012, Kumar 2011). According to the FAO, irrigated paddy rice in India uses 0.103 t/ha of N fertilizer, whereas irrigated wheat and maize use 0.106 and 0.060 t/ha, respectively. The N recovery efficiency for wheat is relatively low: 18% recovery (0.145 t/ha) under unfavorable weather and 49% (0.123 t/ha) under favorable weather (Cassman et al. 2002).

According to India's 2012 submission to the United Nations Framework Convention on Climate Change (UNFCCC) (GoI 2012), its agriculture sector was responsible for emitting 355.6 $MtCO_2e$/year in 2000 (see Figure 1), 27% of national emissions (1,301.2 mega tons of carbon dioxide equivalent—$MtCO_2e$). Rice cultivation alone emitted 74.4 $MtCO_2e$, whereas emissions from soils were responsible for 57.8 $MtCO_2e$. Enteric fermentation, crop residues, and manure management were responsible for 211.4, 6.9, and 5.1 $MtCO_2e$, respectively (see figs. 1 and 2).

In 2011, Mexico produced 22.1 million t of maize, 3.6 million t of wheat, and 173,000 t of rice (FAO 2015).

Mexican agriculture accounted for 12.3% of national GHG emissions in 2010: 92.2 $MtCO_2e$ in 2010 (see Figure 1) in agriculture compared with the national total of 748.3 $MtCO_2e$, according to the country's fifth national communication to the UNFCCC (GoM 2012). Agricultural soils accounted for 50.4% of agriculture emissions, followed by enteric fermentation (41.2%) and manure management (8.2%). Rice cultivation and in-situ burning of agricultural residues together accounted for less than 1% of the sector's emissions (see figs. 1 and 2).

Mexican farmers used almost half a million tons of N fertilizer in 2005 (GoM 2009). Of 32.6 million ha of agricultural land, maize covers 7.4 million ha, wheat 589,015 ha, and rice under 100,000 ha. In 2008, approximately 6.5 million ha of the country's agricultural land was irrigated (CONAGUA 2008).

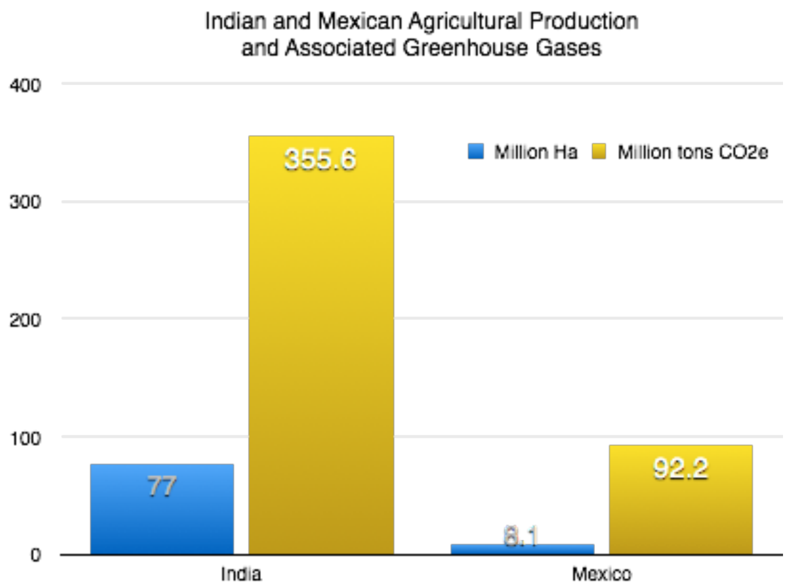

Figure 1. Indian and Mexican agricultural production and associated GHG emissions.

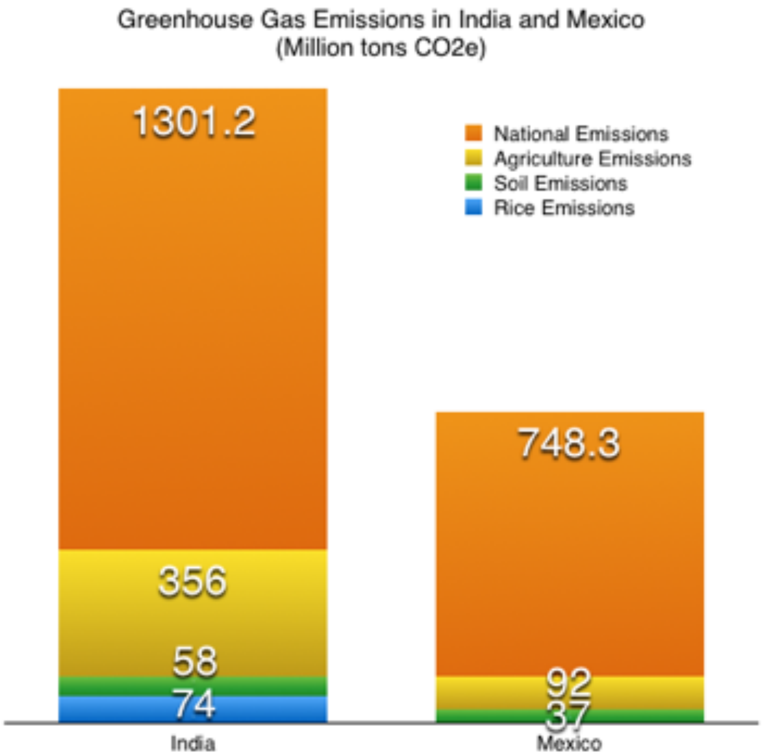

Figure 2. National GHG emissions in India and Mexico.

Characterization of GHG-reducing technologies

There are several N fertilizer management technologies that can be adopted to reduce GHG emissions[3] from cereal production. Emissions are generally related to the efficiency in plant N uptake, with the "mantra"/principle in the literature and in the practitioner community being "right source at the right rate, at the right time and with the right placement."

In addition to fertilizer management practices, uptake of N by crops is influenced by genotype (plant/cultivar characteristics) and specific site conditions (climate, topography, and soil characteristics). As Jing et al. (2008) point out, the contribution of each of these factors is not well documented. In fact, Jing and his colleagues undertook a study focusing on three rice varieties at eight locations in Asia and found a very complex set of interactions:

[3] Figures for GHG emissions found in the literature were not on a full life-cycle basis, except for the work by Sapkota et al. (2014). Most studies only accounted for some of the GHGs emitted on site (i.e., scope 1 emissions). For instance, no study disaggregated the GHG emissions associated with fertilizer production (scope 3), emissions associated with electricity used for water pumping (scope 2), or fuel required to power equipment (scope 1). Emissions associated with fertilizer production have been minimized in Europe with alternative production systems. Fertilizer production in India and Mexico was not within the scope of this study, as such. The extent to which less GHG-intensive fertilizer production methods exist in these countries has not been assessed.

> Environmental factors contributed differentially to yield, N uptake, and internal nitrogen use efficiency (INUE), and their contributions were modified by N management. Indigenous soil N supplies affected yield and INUE more strongly than weather conditions at low fertilizer N rates, but its influence was less pronounced at higher fertilizer N rates. Under both, low and high fertilizer N rates, indigenous soil N supply affected N uptake more than weather conditions did. Temperature contributed more than radiation to the variation in yield, N uptake, and INUE. Results suggest that N fertilizer management should take into account indigenous soil N supply, while temperature is the major factor in the selection of genotypes and sowing dates in maximizing rice yield.

For the purposes of this study, we clustered and prioritized technologies into the following categories, which include management practices and technologies related to genotypic differences:

- Fertilizer source
  - Urea vs. ammonium sulfate/nitrate
- Fertilizer rate
  - Using sensors, such as the GreenSeeker
  - Genotypic differences
- Application timing
  - Applying fertilizer at planting
  - Controlled-release fertilizers
  - Nitrification inhibitors
- Fertilizer placement
  - Deep placement

This is by no means an exhaustive list. The technologies chosen for further analysis of their economic potential as GHG mitigation options are based on feedback received from scientists within the CGIAR system, mainly based on expert knowledge of the technologies' agronomic and GHG reduction potentials.

The following subsections characterize the technologies, including their implementation benefits and costs, where information could be found.[4] Results are described on a per-hectare basis for India and Mexico, then used to generate preliminary estimates of the implementation impacts at the national level for both countries.

[4] This was done for maize, rice, and wheat in India, and only for maize and wheat in Mexico, as rice production is not significant there.

Fertilizer source

Globally, urea and ammonium sulfate are the two main sources of N fertilizer for flooded (lowland) rice (Fageria et al. 2003). Urea is the standard N fertilizer source for maize, rice, and wheat in most developing countries as its low cost and ease of use make it attractive. It is an effective fertilizer for flooded soils in rice production when applied and managed properly, but can lead to significant N loss via ammonia volatilization when applied at the surface and the field is not flooded immediately (Wilson 2003). For instance, Norman et al. (1997) found that delaying flooding 5–10 days after application led to a 20–25% loss, with a corresponding yield decrease of 12–23%. As such, replacing urea with other sources of N that would volatilize less would help reduce GHG emissions.

Shift from urea to ammonium sulfate/nitrate

Many agronomic studies have demonstrated that ammonium sulfate and nitrate can lead to yield increases, compared with urea. Following are illustrative examples. Bufogle et al. (1998) found that ammonium sulfate led to a slight yield increase (8.54 t/ha vs. 8.47 t/ha) in a field study of flooded rice production in Louisiana. Abbasi et al. (2012) found that ammonium nitrate increased yields 8–11%, whereas ammonium sulfate led to increased yields of 5–10% in a field experiment with rain-fed maize in a hilly region of Pakistan. Similarly, Ortiz-Monasterio (2000) found that applying ammonium sulfate instead of urea led to a 10.9% increase in yield (0.76 t/ha) in a field study on the impact of different fertilizers on wheat yield in Mexico. Unfortunately, none of these studies examined the cost of implementation nor measured the GHG emissions differential in applying these different fertilizers.

Dillon et al. (2012) point out that although ammonium sulfate is an effective fertilizer, its use leads to higher operating costs because it has a lower concentration of N than does urea. Additionally, ammonium nitrate is a more expensive N source, and its production is likely to decline, at least in the United States over the next decade (Kallenbach and Massie 2000), which would raise its price further.

On the basis of the literature, these two urea substitutes would not be promising GHG reduction technologies because they would increase the cost of production for smallholder farmers, unless cheaper sources can be found. Further studies could be undertaken to determine how ammonium sulfate and nitrate can be made cheaper to farmers in developing countries (e.g., via local production, using subsidies, or by taxing urea).

Fertilizer rate

As fertilizers are subsidized in many countries, including India, there is an incentive for farmers to over-use them. Dwivedi et al. (2001), through a survey of fertilizer use in Uttar

Pradesh, found that almost a third of rice–wheat farmers applied as much as 0.18 t/ha of N fertilizer, compared with the local recommendation of 0.12 t/ha.

Although Mexican farmers have been paying the full market price for fertilizers since 1992 (FAO 2006), there is evidence of over-application (Ortiz-Monasterio, pers. comm. 2015a). Optimizing the fertilizer application rate can help to reduce N loss and GHG emissions. This can be achieved via better diagnostics of agronomic needs and through plant genotypic differences that can help improve the uptake of N.

Optimization of N fertilizer rate based on assessment of N needs

Handheld optical crop sensors are user-friendly devices that enable diagnosis of crop health and nutrient needs.[5] Optical crop sensors evaluate crop conditions by shining specific wavelengths of light (e.g., red and near-infrared) at crop leaves and measuring the type and intensity of the light wavelengths reflected back to the sensors. Healthy plants absorb more red light and reflect larger amounts of near-infrared light than unhealthy plants. These reflectance characteristics are used to develop vegetative indices such as the Normalized Difference Vegetation Index to assess plant health. Using a N-rich strip, the sensor establishes a N-sufficient reference area in the field. Other areas of the field then are compared to the strip to make fertilizer rate recommendations (Nowatzki nd). Although less precise than more sophisticated tractor-mounted optical crop sensors, the low cost of handheld sensors makes them an attractive technology in developing countries.[6]

The agronomic benefits of optical sensors have been demonstrated in several countries. For instance, Li et al. (2009), through 10 field experiments in four different locations in China, found that using an optical sensor to apply optimal doses of fertilizer in winter wheat led to significant improvements in nitrogen use efficiency (NUE): 61% versus 13% from farmers' practice involving uniform application of fertilizer. On a per-hectare basis, this represented 0.305 t of N saved, with an apparent N loss reduced by 0.201 t/ha. Tubaña et al. (2008) showed that determination of optimal N rates using the GreenSeeker could improve NUE in maize by 15% (from 56% NUE to 65%). This aligns with results in Raun et al. (2002, 2005), who also reported a 15% increase in NUE due to the use of an optical sensor in wheat.

[5] There are several other diagnostics tools, including chlorophyll meters (e.g., Hydro-N-Tester, SPAD, atLEAF) and leaf color charts, in addition to costlier methods such as remote sensing.

[6] For example, the Crop Circle ACS-430 Active Crop Canopy Sensor is $9,381, the CropScan Multispectral Radiometer is $7,592, the OptRx crop sensor is $5,075 for a complete one-sensor kit: $5,075, whereas the CropSpec Topcon is $18,000 (Nowatzki nd).

More germane to the CCAFS project on financing low emissions agriculture, Sapkota et al. (2014) undertook a study comparing the impact of technologies on wheat yields and GHG emissions on farms in seven districts of Haryana, India. One technology tested was the GreenSeeker optical sensor, alone and combined with the use of Nutrient Expert (a computer-based tool that provides fertilizer recommendations with or without soil-testing data). **They found that the optical sensor and Nutrient Expert, when used together, led to a GHG reduction of 0.196 tCO_2e/ha, compared with farmers' practice (10% reduction).**[7] The GHG emissions were estimated using the Cool Farm Tool model and represent the full life cycle (i.e., they include emissions from the soil, as well as the production and transportation of inputs such as fertilizer and even emissions from fuel production, transportation, and use). Unfortunately, the study did not report disaggregated scope 1 emissions.[8] Brock et al. (2012) found that production and transportation of fertilizer were responsible for 30% of life-cycle emissions in wheat production, whereas production, transportation, and use of diesel for farm machinery accounted for 16% of emissions. They found that the emissions from N fertilizer applied to the crop consisted of 26% of life-cycle emissions. As these results were for New South Wales, it can safely be assumed that the GHG emissions associated with fuel is much larger than in the Indian context, where there is little to no mechanization. It would therefore also be safe to assume that the scope 1 emissions associated with the Sapkota et al. (2014) results would be at least 30%. As such, we can be confident that **reduced on-site GHG emissions stemming from optimized N application rates determined by an optical sensor alone would be at least 0.016 tCO_2e/ha, whereas emissions from the joint use of the optical sensor and Nutrient Expert could lead to a GHG reduction of 0.061 tCO_2e/ha,** compared with farmers' practice. Furthermore, the use of the optical sensor led to an **increase in net returns of $159/ha**, compared with the use of Nutrient Expert alone (45% increase). When the optical sensor and Nutrient Expert were used together, net returns increased by $249/ha (94% increase), compared with farmers' practice.

Similarly, Singh et al. (2015) conducted a field study using the GreenSeeker optical sensor on 19 rice farms in northwestern India and Punjab. They found that the sensor-guided N fertilizer applications led to greater recovery efficiency (6–22% compared with farmers' practice) with no loss in rice yield. In 6 out of the 19 sites, farmers were applying 0.092–0.180 kg of N/ha but producing significantly less rice than under optical sensor-based applications, which were 0.075–0.097 t of N/ha (0.017–0.083 less t/ha). Unfortunately, the Singh et al. study did not

[7] Yield-scaled results were 0.113 t per t of wheat produced.

[8] Scope 1 emissions are direct emissions produced on site (e.g., through the direct burning of fuel). They are crucial to climate finance per accepted GHG accounting protocols, as climate finance mechanisms count reductions caused by the project/program from scope 1 emissions.

include GHG or financial impact information. However, using the IPCC's 1% emission factor (i.e., 1% of N applied is converted to N_20), the GHG reduction associated with the fertilizer saved is **0.051–0.247 tCO_2e/ha**[9] (soil only, not full life cycle). The fertilizer represented $10.03–$48.97 at the market price for urea.[10]

No studies could be found on the use of optical sensors in Indian maize.

The Government of India announced a "Soil Health Card" scheme in February 2015,[11] whereby farmers will be given a soil nutrient status for their land, accompanied by advice on fertilizer use. The government estimates that 140 million Soil Health Cards will be issued over the next three years.[12] If most farmers have an up-to-date diagnostic of their farmland's soil quality and corresponding agronomic advice, the incremental benefits of using optical sensors would be reduced, assuming that the diagnostics on the Soil Health Cards and the advice provided by the Ministry of Agriculture would be comprehensive, timely, and optimal.

In Mexico, Ortiz-Monasterio et al. (2014) found that the use of optical sensors to determine optimal N rates reduced N fertilizer use by 0.068 t/ha in wheat production, for a savings of $83/ha (7% of total production costs). The estimated GHG reduction associated with the fertilizer use reduction is 0.190 tCO_2e/ha.[13] Similarly, Ortiz-Monasterio (pers. comm. 2015a) and his colleagues undertook a different study in 2014, in Guanajuato, Mexico, to assess the impact of using optical sensors to optimize N application rates in maize production. On the basis of 17 evaluations in farmers' fields, they found that farmers could save 0.055 t of N fertilizer/ha using the sensor in maize while maintaining the same yield, thus **saving $68/ha in fertilizer**. Although GHG emissions were not measured in this study, using the IPCC's emission factor provides an estimate of **0.154 tCO_2e/ha that would be reduced**. Ortiz-Monasterio and his colleagues are repeating the study in 2015.

[9] 1 kg N_2O = 298 kg CO_2e. 17 kg x 0.01 = 0.17 kg N_2O; 0.17 kg N_2O x 298 = 51 kg CO_2e. 83 kg x 0.01 = 0.83 kg N_2O; 0.83 kg N_2O x 298 = 247 kg CO_2e.

[10] Using a urea price of $273/t (http://www.indexmundi.com/commodities/?commodity=urea), with 46% N content, equals $0.59/kg of N. $0.59 x 17 = $10.03; $0.59 x 83 = $48.97 (in current US dollars).

[11] See soilhealth.dac.gov.in/Content/FAQ/FAQ_Final_English.docx and the Prime Minister's news release: http://pmindia.gov.in/en/news_updates/pm-launches-soil-health-card-scheme-presents-krishi-karman-awards-from-suratgarh-rajasthan/

[12] Assuming each card represents 1 ha of farmland, this would mean 90% of India's 154 million ha of cultivated land would be assessed in three years.

[13] Using the IPCC's 1% conversion factor. That is, 1% of N applied is converted to N_2O. The emission factor of 1 kg N_2O = 298 kg CO_2e. New research suggests that in temperate regions, the 1% "rule" does not apply, as it was found that N_2O production is nonlinear and exponential. The more N is applied beyond the agronomic level, the more N_2O is produced. Dr. Ortiz-Monasterio and some of his colleagues will be analyzing this N–N_2O relationship for the tropics and subtropics over the next two years (pers. comm. 2015a).

Costs for optical sensors, such as the GreenSeeker handheld unit that costs $550, can thus be reimbursed in less than 10 months for an 8-ha farm.[14] The Mexican government offers a 50% tax rebate on the purchase of optical sensors, which increases its affordability and would reduce the simple payback period[15] to 5 months. According to Ortiz-Monasterio (pers. comm. 2015a), there is also a maintenance cost to be considered and need for recalibration in some instances. The recalibration cost is $200–$250, and it has been done once during a 12-year period (under $21/year, annualized).

Ortiz-Monasterio's team (pers. comm. 2015a) has made efforts to diffuse this technology across Mexico by providing private and government farm advisors and farm cooperatives with handheld units and training. Farm advisors in turn provide optical sensor readings and interpretation services to farmers. Ortiz-Monasterio (ibid.) estimated that the penetration rate is below 5%[16] after 10 years of diffusion efforts.[17]

On the basis of the literature, handheld optical sensors are a promising technology for GHG reductions in the agriculture sector in developing countries, especially if farmers do not have to pay the full up-front cost of the technology. This could be achieved through a subsidy program, a cost-sharing scheme with neighboring farmers or farmers' cooperatives, or even via a pay-for-service scheme whereby a third party would charge to undertake sensor readings in the field and provide fertilizer application recommendations. According to Ortiz-Monasterio (ibid.), it takes about 2–3 hours to train farm advisors to use the unit and interpret its results, which is not a significant investment. The application (Android phone or PC) paired with the device makes it easy to use and interpret results. However, as discussed in McCullough and Matson (2011), partnerships with key actors within the local agricultural knowledge system are essential to successful diffusion.

In India, an analysis should be undertaken to determine how the recent Government of India Soil Health Cards program could be used to expand and complement efforts to promote the adoption of optical sensors for GHG reductions. More importantly, careful thought should be put into how an LED policy and financing package could be designed to ensure that emissions

[14] The 8-ha figure is the average farm size in Mexico (Salinas Álvarez 2006, Puyana and Romero 2008).

[15] The simple payback calculation is the expected period of time it takes for the initial cash outflow of an investment (e.g., the cost of the GreenSeeker device) to be recovered from the cash inflows generated by the investment (e.g., savings from lower fertilizer use).

[16] The GreenSeeker (or other sensor) has been used on 5% of the land in the areas where CIMMYT has expended diffusion efforts (i.e., in the state of Guanajuato, the Yaqui Valley, and the Mexicali Valley).

[17] Although the GreenSeeker has only been available for the last two years, other sensors have been tested and diffused over the last decade.

reduced through the use of optical sensors could still be considered additional (e.g., by including the Soil Health Cards program as part of the mix of policy instruments within the LED program).

In Mexico, further studies should be undertaken to more precisely determine the technology's GHG reduction potential in wheat and to determine its GHG reduction potential in maize. There is also a lack of data on the technology's GHG reduction potential in Indian maize. Other data gaps include the yield improvement and financial viability of the technology in Mexican and Indian maize production. A study on how diffusion can be increased, including potential policy instruments that may increase incentives for adoption, could also prove useful for the development of future LED policy and finance in Mexico.

Optimizing N use via genotypic differences

Breeding to improve the genetic properties[18] of plants can be done using techniques that impact the plant, cell, or DNA levels. Breeding ranges from conventional methods such as hybridization to genetic engineering (BATS 1995). Breeding for improved NUE[19] leads to plants absorbing fertilizers more efficiently, which reduces N_2O emissions in addition to improving yields (compared with the varieties used by smallholder farmers in developing countries).

Reynolds and Borlaug (2006), in a retrospective paper on the impact of modern wheat varieties in the developing world, including India and Mexico, referenced research showing that yield increases through improved varieties have averaged over 1% per year between 1965 and 1995 in irrigated regions (Byerlee and Moya 1993, Lantican et al. 2005) and over 2% in more marginal environments such as semi-arid and heat-stressed environments (Lantican et al. 2002, Trethowan et al. 2002). Semi-dwarf wheat cultivars were found to outperform old, tall cultivars grown in northwestern Mexico by over 2 t/ha (Fischer et al. 1998). Ortiz-Monasterio et al. (1997) assessed the genetic progress in wheat yield and NUE of germplasm released in Mexico and found that NUE increased from 26% to 42% between 1950 and 1985 (annual improvement of 1.4%). It must be noted that these yield increases from improved varieties are not solely from NUE; other key drivers of increased yield are drought and

[18] One important distinction with this technology is that each variety is in fact a different technology and is developed for specific agronomic conditions. This makes it difficult to make broad recommendations for adoption.

[19] NUE is defined as the yield of grain per unit of available nitrogen in the soil (Moll et al. 1982).

disease resistance, for instance. Also of note is that none of these papers discussed neither the GHG implications of these improved varieties nor their financial impacts.[20]

For rice varieties, Zheng et al. (2014), in a meta-analysis of 27 papers, found significant differences in GHG emissions between indica and japonica rice grown in China. Emissions (CH_4 and N_2O) from indica rice were 6.7 tCO_2e/ha compared with 5.1 tCO_2e for japonica rice. Indica rice was also found to be more GHG-intensive once adjusted for yield. Yield-scaled emissions for indica varieties were 1.1 tCO_2e/t rice produced, whereas japonica was 0.7 tCO_2e. Although India grows both japonica and indica varieties, consumer preferences and perceptions may limit the potential of less GHG-intensive japonica rice in India.[21]

Hirel et al. (2007, p. 2370) pointed out that, "(a)lthough it is well known that there is some genetic variability in maximum N uptake in rice (Borrell et al. 1998) and wheat (Le Gouis et al. 2000), the physiological and genetic basis for such variability has never been thoroughly investigated (Lemaire et al. 1996)."

DoVale et al. (2012, p. 53) made a similar point and offered some hope for future prospects. They state that, "While methods for understanding the mechanisms of remobilization and utilization of N during grain development are still not defined, once discovered, they will significantly increase NUE in crop species." Research on the improvement of NUE via genetically modified crops has been hampered by the difficulty of field-testing in various regions, including Europe. Additionally, much of the research being done by the private sector is not in the public domain (Hirel et al. 2011).

The over-expression of glutamine synthetase (GS1) in transgenic rice improved its NUE (Brauer et al. 2011). Similarly, Habash et al. (2001) found that over-expression of the GS1 gene from the French bean increased NUE and yield by 20% in wheat (Habash et al. 2001) and the over-expression of a native gene encoding GS1 (Gln1-3) of maize improved yield of the transgenic maize by 30% (Martin et al. 2006).

Grooms (2012) stated that crop varieties with the NUE trait were being developed in the private sector and showing promising results. Research trials for these NUE crops, including maize and rice, showed they can produce yields as much as 15% more than crops without the trait. Grooms stated that NUE crops are expected to reach the market before 2020. Hirel et al.

[20] The cost of adoption to the farmer, however, can safely be assumed to be minimal as the seeds for varieties developed by CIMMYT are distributed free of charge to more than 700 partner organizations in almost every country across the globe.

[21] Kovach et al. (2009) challenged the traditional assumption that the fragrance trait found in India's beloved basmati rice arose in the indica varietal group when they demonstrated that basmati-like accessions were almost genetically identical to the ancestral japonica haplotype.

(2011) also noted that improving NUE through genetic engineering (or marker-assisted breeding) was in its early stages, though “little information is currently released from both the private and public sector in consideration of the potential economic value of crop NUE improvement” (p. 1469).

Another promising area is breeding for biological nitrification inhibition (BNI).[22] BNI can be enhanced using conventional methods and molecular genetics (Subbarao et al. 2012). For instance, Subbarao et al. (2007) successfully introduced and expressed genes from a wild cereal that had high production of BNI in cultivated wheat. Indeed, Ortiz et al. (2008), among others, mentioned this technology as a potential mitigation solution. In a recent article, Subbarao et al. (2015) discussed the feasibility of breeding for BNI in major crops to improve NUE and reduce N_2O emissions. They expressed optimism about the technology’s potential.

Ortiz-Monasterio (pers. comm. 2015b) stated that an adoption rate of close to 100% in Mexico exists for most (non-genetically modified) N-efficient varieties due to the user-friendliness of the technology. Thus, no capacity is needed to increase adoption of the technology, and there are no disruptive changes to farming practices. Users simply plant new seeds. The high adoption rate is also due to the very high level of credibility and trust associated with varieties developed at the International Maize and Wheat Improvement Center (CIMMYT). McCullough and Matson (2011) confirmed this in a study on the knowledge system for agricultural development in the Yaqui Valley, Sonora, Mexico. Information found in MAIZE and WHEAT CGIAR Research Program documents (submitted in the context of the CGIAR Strategic Results Framework commitments) shows that maize germplasm developed by CIMMYT has been diffused in 108 countries, reaching 98% of all the poor who live in maize-growing areas. Similarly, wheat germplasm developed by CIMMYT has been diffused in 114 countries, reaching 99% of all the poor who live in wheat-growing areas (Lantican et al. 2015).

On the basis of available information, it is not possible to determine the costs and benefits of adopting more N-efficient maize, rice, and wheat varieties (either genetically modified or developed via more traditional plant breeding methods) as a GHG mitigation strategy. Further field studies would need to be undertaken to assess the GHG benefits of the varieties in India and Mexico, as well as the technology’s financial impact.

[22] Certain plants can suppress soil-nitrification by releasing inhibitors from roots, a phenomenon termed biological nitrification inhibition (Subbarao et al. 2009).

Application timing

N fertilizer applied at the optimal time will maximize the plant's N uptake, reducing the amount of fertilizer needed without decreasing yield and decreasing N_2O emissions. As a general rule, fertilizer should not be applied prior to planting, but during the initial crop development phase, at planting time or shortly thereafter (Flynn 2009).

Applying fertilizer at planting, split dosage

There are many studies on the agronomic benefits of improving fertilizer application timing in India. For instance, Krishnakumari et al. (2000), in a field trial near Delhi, found that splitting N fertilizer application in three doses increased wheat yield by 4% (0.176 t/ha) in light-textured soils. Unfortunately, information on the corresponding cost of implementation and the GHG benefits was not included in the study. Kaur et al. (2010) found similar results in a field study of wheat NUE in Haryana, India. They observed a 4.1% increase in grain yield when fertilizer was applied in the following three doses: 45% at sowing, 50% at first irrigation, and 5% as foliar application. No studies were found on the GHG and financial benefits of adopting this technology in India.

Matson et al. (1998), in a field study of Mexican wheat production, found that applying 33% of fertilizer at pre-planting, 0% at planting, and 67% after planting led to a 5% increase in N gas emissions (N_2O plus nitric oxide). In the same study, the authors also found that applying 28% less fertilizer (0.180 t N/ha, with 33% at planting and 67% six weeks after planting) left yields unchanged, yet offered cost-savings equivalent to 12–17% of net profits,[23] in addition to reducing N gas emissions by 89% compared with farmers' practice. Ortiz-Monasterio (2000), in a field study on the impact of different fertilizer application times on wheat yields in Mexico, found that applying 33% of the urea fertilizer at the time of sowing and two-thirds at Zadoks growth stage 30 (Z-30) led to a 7.6% increase in yield (0.53 t/ha), compared with applying two-thirds at sowing and one-third at Z-30.

Ortiz-Monasterio and Naylor (2000) found that wheat farmers in the Yaqui Valley of Mexico applied 75% of N fertilizer a month prior to planting. In a field study using five sites in the Yaqui Valley, they found that for a low rate of N fertilizer application (i.e., 0.075 t/ha), applying 33% of N fertilizer at planting and the remainder at six weeks after planting (so-called 0-33-66 application) led to a 20% increase in yield (1.032 t/ha), compared with farmers' practice of applying 75% at pre-planting and 25% six weeks after planting (i.e., a 75-0-25 application). For heavier applications of N (i.e., 0.300 t/ha), the 0-33-66 method brought

[23] Profit is gross returns minus costs of production. Net profit is profit after taxes.

about a 3% yield increase (0.182 t/ha). The authors also calculated that the optimum economic fertilizer application rate (i.e., the rate at which it is most profitable to the farmer, considering yield impact and fertilizer cost) for the 0-33-66 practice was 0.210 t/ha. At this rate, farmers could apply 0.068 t less of N than with the 75-0-25 application, saving the farmer almost $40/ha.[24]

According to Ortiz-Monasterio (pers. comm. 2015a), current fertilizer application timing in Mexico's Yaqui Valley remains suboptimal: farmers continue to apply at pre-planting, then irrigate and then plant 18 days later. Also, farmers tend to over-apply urea at pre-planting in case there is fertilizer loss due to rain at planting, which leads to further N losses (about 30% of N is lost in this fashion). Although CIMMYT has been informing farmers and farmers' cooperatives for more than 10 years about improved application timing benefits, there has been little uptake. Ortiz-Monasterio posits that the lack of adoption is because the technology would require disruptive changes in farming methods: fertilizing at planting slows down operations, which are done via large farming equipment.

On the basis of available information for India, splitting the N fertilizer application into three doses is shown to have yield benefits. However, it is unclear if this practice is economical, as no information could be found on the corresponding cost of this split application in terms of additional labor, machinery, and fuel,[25] compared with fewer applications. The GHG emissions reductions due to split application are also unclear, including the GHG impact of the fuel required for an additional application. In Mexico, there are clear and significant GHG reduction benefits and cost savings that can be achieved through reduced fertilizer usage and split fertilizer application. However, there is strong reluctance to change fertilizer application practices, which may hinder the adoption of this technology in Mexico.

Further field studies with quantification components on the technology's GHG emissions, cost of production,[26] profitability, and long-term impacts, including the soil compaction due to increased traffic on the fields associated with splitting fertilizer application in three doses versus one or two,[27] are needed for maize, rice, and wheat in India. In Mexico, further studies should be conducted on the technology's yield improvement and financial viability in maize,

[24] Using a urea price of $273/t (http://www.indexmundi.com/commodities/?commodity=urea), with 46% N content, equals $0.59/kg/N. $0.59 x 68 = $39.91.

[25] There is little to no mechanization on Indian smallholder farms; this impact would thus be negligible in the near future.

[26] For instance, how much more does it cost in labor, fuel, and equipment rental to split fertilizer application in three doses versus one or two?

[27] Studies, such as Gunjal and Raghavan (1986) and Gunjal et al. (1987), have shown that soil compaction can lead to significant economic losses.

as well as the overall scope 1 emission reduction potential (crop, soil, and fuel use) in CO_2e of the adoption of this technology in wheat and maize. A study on how to address barriers to adoption, including potential policy instruments that may increase incentives for adoption, could also prove useful for the development of future LED policy and finance in Mexico.

Controlled-release fertilizers

Controlled-release fertilizers (CRF) are "fertilizers that contain a plant nutrient in a form the plant cannot immediately absorb. Uptake is delayed after application, so that CRFs provide the plant with available nutrients for a longer time" (Liu et al. 2014, p. 2). As such, they lead to a decrease in wasted fertilizer and a corresponding reduction of N_2O emissions.

Only two studies were found on the impact of CRF in Indian agriculture, and both studies focused on rice production. Wassmann and Pathak (2007) used TechnoGAS, a spreadsheet model, to estimate the yield, net revenues, and CO_2e/ha. Pathak (2010) also used a modeling approach to determine the cost, net revenue, and GHG emissions from the use of CRF, compared with conventional practice. Both studies found that adopting CRF led to a decrease in net revenues. The two studies conflict in terms of the yield and GHG emissions associated with the technology: Wassmann and Pathak found that CRF led to an increase in yield of 20% and an increase in emissions of 0.14 tCO_2e/ha. Pathak's model, on the other hand, found yield unchanged and a slight decrease in emissions (0.20 tCO_2e/ha).

No studies could be found on the effectiveness, GHG reduction potential, or the economics of CRF in Mexico. According to Ortiz-Monasterio (pers. comm. 2015b), adoption of CRF is negligible in Mexico, as they are cost-prohibitive for smallholder farmers.

When casting the net more broadly, findings on studies on the impact of CRF in other countries include the following: (1) CRF and slow-release fertilizers tend to be cost-prohibitive for smallholder farmers and are used mostly in horticulture and for turf fertilization (IHS 2015). (2) The price of CRF can vary anywhere from three to eight times the cost of standard fertilizer (Little 2010). Little conducted a modeling exercise assuming a yield increase of 6.5% through the use of CRF in sub-Saharan Africa. Results showed an increase in net revenues, even though they assumed that the CRF costs three times that of conventional fertilizer.

Li et al. (2004) studied the effects of CRF on N_2O emissions from paddy fields in China. They found that N_2O emissions from CRF ranged from a 28% reduction to an increase of 12%.

Field studies with quantification of GHG emissions, cost of production, and profitability are needed to discern the potential of CRF as a GHG mitigation measure in India. Field studies should focus on the lowest-cost CRF, as these are most likely to be promising in low-income countries. Cost considerations include the price of fertilizer, the cost of coating (i.e., if the fertilizer needs to be coated by farmers themselves, this entails a labor cost), and the cost of application (i.e., via machinery[28] and/or labor).

Nitrification Inhibitors

Nitrification inhibitors delay nitrification by eliminating the Nitrosomonas bacteria (Mullen and Lentz 2011). They prevent soil microorganisms from converting soil ammonium to soil nitrate, which would otherwise be converted into N_2O (La Grange and Rawnsley 2010). Sturm et al. (1994) found that certain nitrification inhibitors can result in the killing of soil bacteria, leading to undesirable impacts to the natural agro-ecosystem. Parkin and Hatfield (2014) found the effects of nitrification inhibitors on N_2O emissions to be mixed. Through a field study undertaken on maize in Iowa, they found no difference in N_2O emissions among fertilizer types (including polymer-coated urea and urease containing AgrotainPlus, a nitrification stabilizer). Furthermore, they found that nitrification inhibitors might be "of limited value in regions where N_2O emissions are episodic and stimulated primarily by rainfall events" (p. 8). Thus, nitrification inhibitors were found to be not promising for rain-fed crops. It must also be noted that the effectiveness of nitrification inhibitors can be influenced by fertilizer placement: Jat et al. (2012) found that a surface application of fertilizer treated with nitrification inhibitors was ineffective in drier and warmer climates.

Several studies have been conducted on the effectiveness of nitrification inhibitors and their GHG reduction potential in India. Malla et al. (2005) undertook a field study that examined the effect of neem-coated[29] urea in the production of wheat and rice. They found that it could decrease GHG emissions by 0.127 tCO_2e/ha—a 13% reduction for the rice-wheat system, compared with urea alone. They also assessed the GHG reduction potential of several other inhibitors and found that the most effective were urea combined with coated calcium-carbide (reduction of 0.184 tCO_2e/ha for the rice–wheat system) and dicyandiamide (reduction of 0.131 tCO_2e/ha). The study found that these inhibitors also led to the following changes in rice and wheat yields:

- Neem oil-coated urea: rice and wheat yield reduced by 0.190 t/ha;
- Urea, combined with coated calcium-carbide: rice yield increased by 0.070 t/ha, wheat yield reduced by 0.080 t/ha;
- Dicyandiamide: rice yield decreased by 0.180 t/ha, wheat yield increased by 0.110 t/ha.

[28] As mentioned above, there is little to no mechanization on Indian smallholder farms, so this impact would be negligible in the near future.

[29] Neem oil is pressed from the fruits and seeds of the Indian neem tree (*Azadirachta indica*). The neem tree has been introduced in tropical countries (see en.wikipedia.org/wiki/Neem_oil).

The Malla et al. (2005) study did not include figures on financial costs and benefits.

Kumar et al. (2010) analyzed the impact of varying the thickness of neem oil coating on urea fertilizer used to grow lowland irrigated rice at the Research Farm of Indian Agricultural Research Institute in New Delhi. They found that the amount of oil applied affected yield and N uptake, and concluded that applying neem oil at 1 g/kg of urea led to the greatest yield increase. Implementation costs (cost of neem oil and labor costs to coat the urea) and GHG implications were not within the scope of this study.

Majumdar et al. (2000) conducted a field experiment in Delhi, India, to assess the effectiveness of inhibitors on N_2O emissions from irrigated rice. Unlike Malla et al. (2005), Majumdar and colleagues found that **N_2O emissions from neem-coated urea were not significantly different from urea alone, but urea treated with dicyandiamide reduced N_2O emissions by 18%, compared with regular urea fertilizer**. Ghosh et al. (2003), in a field study in New Delhi, also found that dicyandiamide reduced N_2O emissions from irrigated rice between 10% and 53%. No information in any of these studies was available to determine the cost-effectiveness of dicyandiamide as a GHG mitigation strategy.

Wassmann and Pathak (2007) modeled the impact of nitrification inhibitors in rice-based agriculture in Haryana, India. They found that nitrification inhibitors would lead to a 5% reduction in GHGs, a 10% increase in yield, and a slight decrease in net revenue ($4.53/ha). The practice would therefore have a cost of $20/t$CO_2$e reduced. Pathak (2010), also via a model, estimated that fertilizer input could be reduced by 17% without reducing rice yields in Haryana by using nitrification/urease inhibitors, causing a corresponding 7% decrease in GHG emissions. The cost of production was estimated to be only slightly higher than conventional practice ($8.35/ha) and net revenues 1% lower. Pathak's results translate to a cost of $44.40/t of CO_2e reduced, which is significant.

Sharma and Prasad (1995) analyzed the impact of neem and dicyandiamide on NUE in maize–wheat cropping systems in a two-year field experiment. They found that neem-coated urea increased maize yield by 0.520 t/ha compared with prilled urea, whereas dicyandiamide increased yield by 0.150 t/ha. They also found the application of neem-coated urea increased the yield of the succeeding wheat crop by 0.290 t/ha more than the treatment with dicyandiamide. Singh and Shivay (2003) examined the effect of coating prilled urea with neem on rice yield in a single field experiment, finding that neem coating increased rice yield by 4–6%. Kumar and Shivay (2009), in a single field experiment in New Delhi, found that neem-coated urea led to an increase in rice yield of 9.5–15% (0.430–0.690 t/ha). Unfortunately, no financial or GHG data were included in the above papers.

Prasad (2008) found that although nitrification and urease inhibitors were already in use in the United States, Japan, and Europe, their high cost made them uneconomical in India. More recently, Jat et al. (2014), in a chapter on nutrient management in wheat systems, stated that chemicals retarding urea hydrolysis and nitrification were little used in South Asia due to high cost and inadequate availability. Ortiz-Monasterio (pers. comm. 2015b) also stated that the high cost of nitrification inhibitors is a key barrier to adoption in Mexico, even though the technology would offer significant benefits in terms of ease of use and improvements in application timing.

Research seems to indicate that **chemical nitrification inhibitors would not be a win-win in India or Mexico at this time**, as their higher cost outweighs the benefits in increased yields. Neem may be a promising nitrification inhibitor in rice and maize in India, as there is evidence that it reduces GHGs and can lead to significant yield increases. However, it is unclear if neem would be available in sufficient amounts and at a sufficiently low price across India if neem coating of urea became a mainstream practice.[30] This would require further study. Note that the Government of India announced in January 2015 that it would require, via regulatory mandate, that 75% of the urea produced domestically be neem-coated (GoI 2015). Further analysis is needed of how this regulatory mandate could complement future agriculture sector mitigation initiatives in India.

Fertilizer placement

Fertilizer can be applied at soil surface (in a band, broadcast as top-dressing or side-dressing, and even foliar applications), subsurface (placing fertilizer at varying depths under the soil surface, sometimes in briquette or pellet form), and fertigation (applying in liquid form, via irrigation system). Each placement has advantages and disadvantages, depending on the fertilizer, the crop, and other factors. For instance, applying anhydrous ammonia via fertigation is not advisable because it can lead to clogging under certain circumstances (UoH nd). Note, too, that N placement is influenced by myriad factors (see box 1).

[30] According to Tinghui et al. (2001), there were 18 million neem trees in India in the early 2000s. It is unclear if this would be sufficient to supply neem oil for all fertilizer application in India.

Box 1: "Wheat nutrition and fertilizer requirements: Nitrogen" by Agriculture and Forestry Department of Alberta

Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop1273

The method of placement and time of application can have significant effects on the efficiency of N fertilizer by increasing yield and/or protein. Application methods include:

- Drilling in with the seed
- Sideband placement
- Banding into soil prior to seeding
- Broadcast and incorporated into the soil
- Broadcast without incorporation
- Pocket or nest fertilizer
- Foliar application

A number of factors influence the magnitude of wheat response to N fertilizer and its placement. These include:

- Rate of fertilizer—the higher the rate, the less impact placement will have.
- Test levels—the higher the soil test level, the less impact placement will have.
- The higher the rainfall, the less impact placement has.
- Ammonium nitrate is less sensitive than urea-based fertilizer to placement. Anhydrous ammonia (NH_3) has to be banded.
- Crop rotation—legumes in rotation with cereals can reduce the impact of placement.

Deep Placement

One study was found on the GHG and economic impacts of N deep placement in India. Pathak (2010), using the InfoNitro model, found that by improving fertilizer placement fertilizer could be decreased by 9% without reducing rice yield in Haryana. This is associated with corresponding decrease in GHGs of 4.2% (0.108 t/ha), a cost of production increase of $3.09/ha, and a net revenue decrease of $3.13/ha. This translates to a cost of $28.95/t$CO_2$e reduced, which is significant.

Other studies describe benefits of N deep placement strategies, even if their focus was not on the technology's GHG mitigation potential. For instance:

Briquettes

Daftardar et al. (1996) assessed the effectiveness of urea briquettes in rice in Maharashtra State, India. They used diammonium phosphate urea briquettes, deep-placed by hand on the day of transplanting.[31] The technology improved yields by almost 62% (1.6 t/ha), and the authors found that the benefit/cost ratio (value of additional grain and straw yields, divided by all additional variable costs, including labor) was between 5 and 8.5.

A field study conducted by Singh et al. (1989) in India determined that urea briquettes were effective in increasing lowland rice yield compared with prilled urea. Placement at a depth of 3–4 cm was significantly better than surface application or placement at a depth of 0–1 cm. Moreover, the researchers found that spacing of 30 cm between briquettes led to better results than spacing at 60–90 cm, and that a single application 10 days after transplanting performed as well as two applications (at 10 days after transplanting and at panicle initiation). They did not discuss financial benefits or costs.

Savant et al. (1992) conducted field trials in the Philippines and India on pillow-shaped urea briquettes deep-placed by an applicator and by hand immediately after rice transplanting. They found that briquettes led to an increased yield of 0.2–1.5 t/ha (a 5–83% increase). No cost data were included in this study.

Bowen et al. (2005), in on-farm trials in Bangladesh, found that deep-point placement of urea briquettes in boro rice production reduced N use by 53%, compared with farmers' practice. The yield benefit of deep placement briquettes was greater than 0.7 t of grain/ha in over 75% of the cases and greater than 1.4 t in 25% of the cases. The financial impacts of this technology were not within the scope of the study.

Islam et al. (2011) found that NPK briquettes used in tidal-flooded soil during the boro rice season in Bangladesh could save 0.033 t of N/ha, compared with urea. No implementation cost comparison was included.

Super granules

Katyal et al. (1985) analyzed the NUE of urea super granules, sulfur-coated urea, conventional urea, and ammonium sulfate in wetland rice in Punjab, India. They found that N loss was 46–50% for urea and ammonium sulfate, whereas sulfur-coated urea losses were 27–38%. Urea super granules led to the greatest N loss, at 78%. The authors explain that this significant loss was likely due to the site's high percolation rate, not typical of most rice-growing areas.

Rahman and Barmon (2014) examined the economics of deep placement of urea super granules in Bangladesh and found this technology to be profitable for rice growers in the local

[31] Note that the improved timing of fertilizer application may have a confounding effect, which was not controlled for in this study.

context. Their modeling suggested that although adopting this technology would be slightly more labor intensive ($28/ha more in labor cost) but would increase profitability by $243/ha.

A field experiment undertaken by Prasad and Singh (1985) in India from1981 to 1983 found that urea super granules had no yield benefits for spring wheat compared with prilled urea.

Although in most instances the literature points to an agronomic advantage of using various forms of deep placement, the scant amount of information on the technology's implementation costs and GHG benefits for India and Mexico makes it difficult to build a solid business case at this time. Future field studies should include an analysis of the cost-effectiveness of deep placement technologies, as well at the overall GHG impact (i.e., CH_4 and N_2O emissions) and agronomic benefits. Special attention should be placed on the labor costs under manual and mechanized approaches to application and the cost to produce the fertilizer itself in the case of briquettes produced on site or locally.

Other placement methods

Pathak (2010), using the InfoNitro model, found that fertilizer could be decreased by 17% without reducing rice yield in Haryana via foliar application of fertilizer. This comes with a corresponding decrease in GHG emissions of 7.3% (0.188 t/ha), a cost of production increase of $5.61/ha and a net revenue decrease of $5.64/ha. This translates to a cost of $30.00/t$CO_2$e reduced.

No studies were found on the effects of banding on GHG emissions and economics, although several studies looked at the technology's agronomic impacts. For instance, Ortiz-Monasterio and Naylor (2000) found that banding did not affect the N recovery in wheat in Mexico, compared with the farmers' practice of broadcasting. Mashingaidze et al. (2012) conducted field experiments in Zimbabwe to assess the impact of fertilizer placement on maize yield, and found that application via banding led to greater yields compared with spot placement and broadcasting. The effect was not statistically significant, however.

No studies were found on the economic and GHG impacts of "broadcast incorporated," which entails broadcasting fertilizer (by hand or mechanical spreader) and then incorporating the fertilizer into the soil via manual or mechanical methods (e.g., plowing). Agronomic studies have demonstrated that this technology reduces N losses compared with hand broadcasting without incorporation. For instance, Fillery et al. (1984) undertook six experiments at two field locations on ammonia volatilization after urea application to flooded rice in the Philippines, and found that ammonia volatilization loss was only 13% after urea incorporation. It should be noted that broadcast incorporation requires more labor (or equipment, in the case of plowing) and results in non-uniform application (Cornell University nd).

There are also several other fertilizer placement methods, such as injection, fertigation, side-banding, mid-row banding, and other similar mechanized approaches.[32] Although these reduce losses through precise and subsurface application of N, they are capital intensive (i.e., they require specialized equipment that is expensive and not necessarily available locally) (Cornell University nd). As such, they would likely not be promising for most smallholder farmers.

Jat (pers. comm. 2015) asserted that fertilizer placement will likely play a key role in increasing NUE in cereal production in India in the future, based on observations about the increased attention on mechanization and increased mechanization of planting operations (seed-cum-fertilizer drilling), which would facilitate the wider adoption of improved fertilizer placement. He also stated that the Government of India is promoting micro-irrigation, which will also help farmers adopt fertigation (injecting of fertilizer with water through micro-irrigation).

Table 1 summarizes farm-level outcomes from different mitigation practices discussed in this paper.

Table 1. Summary of farm-level outcomes from mitigation practices

Mitigation practice	Country	Outcomes			Data gaps	Win-Win?
		GHG emissions	Yield	Economics		
Fertilizer source						
Shift from urea to ammonium sulfate/nitrate		No data	Increase 5-11% (maize)	Cost prohibitive	GHG reduction potential	
		No data	Increase 11%, 0.76 t/ha (wheat) No data for maize	Cost prohibitive	GHG reduction potential	
Fertilizer rate						
Optimization of N fertilizer rate, based on assessment of N needs (e.g., using GreenSeeker)		Increase 3%, 0.016-0.061 tCO_2e/ha (wheat) 0.051-0.247 tCO_2e/ha (rice) No data for maize	Increase 10%, 0.20-0.53 t/ha (wheat) No change (rice) No data for maize	Increase net returns $159/ha (wheat) Increase cost $10-49/ha (rice) No data for maize	Impacts in maize	
		Increase 0.19 tCO_2e/ha (wheat) Increase 0.154 tCO_2e/ha (maize)	No change (wheat, maize)	Increase production costs $83/ha (wheat) $68/ha (maize)	Improve accuracy of GHG reduction potential	
Genotypic differences to inhibit the N cycle, etc.		No data	Increase 1-2% per year (wheat)	Seeds made available for free Increase revenues	GHG reduction potential, current diffusion rate	

[32] For details on these and many more application methods, please see the Northeast Region Certified Crop Adviser Study Resources at Cornell University: http://nrcca.cals.cornell.edu/nutrient/CA4/CA0434.php

Mitigation practice	Country	Outcomes			Data gaps	Win-Win?
		GHG emissions	Yield	Economics		
		No data Full adoption		No cost for seeds Increase revenues	GHG reduction potential	
Application timing						
Applying fertilizer at planting, split dosage		No data	Increase 4%, 0.176 t/ha (wheat) No data for rice, maize	No data	GHG emissions, economics (wheat, rice, maize) Yield for rice, maize	
		Increase 89% N_2O and NO (wheat) No data for maize	No change (wheat) No data for maize	Cost saving equivalent to 12-17% after tax profits (wheat) No data for maize	Conversion to CO_2e Overall business case for maize, How to eliminate barriers to adoption	
Controlled-release fertilizers		GHG emission reductions uncertain	0% to increase of 20%	Cost prohibitive	GHG impact	
		No data	No data	Cost prohibitive	GHG and yield impacts, cost-effective options	
Nitrification inhibitors		Increase 0-53% (rice, wheat) No data for maize	Decrease (rice, wheat) Increase 0.150-0.520 t (maize)	Chemical inhibitors are cost prohibitive ($20-$44/tCO_2e)	Neem oil costs and availability	
		No data	No data	Cost prohibitive	GHG and yield impacts	
Deep placement		Increase 4%, 0.108 tCO_2e/ha (rice)	No change (rice) No data for wheat, maize	$29/t CO_2e Increase $3/ha cost of production (rice)	Super granules and briquettes in Indian rice	
		No data	No data	No data	GHG, yield and economic impact	

*Symbol legend:

- Strong evidence that it reduces GHGs and improves livelihood of farmers

- Evidence that the technology may not reduce GHGs or be financially viable or that it lacks compelling evidence that it reduces emissions and/or improves livelihoods of farmers

- Further research required to determine impacts of the technology

Estimating national-level impacts

To estimate national-level impacts using the cost and benefit information of optical sensors, one must consider financial incentives and barriers to adoption. It is important to note that the costs and benefits (and profitability) of the technology are only one part of the picture: adoption will also depend on policy incentives, technical support, and farmers' capacity, for instance.

Financial incentives

The key financial incentive for the adoption of the GreenSeeker and other optical sensors is the technology's potential to increase profit[33] or net returns, achieved via increased yield and reduced fertilizer use. The GreenSeeker and other optical sensors can lead to improved *wheat* yields of 0.500 t/ha in India. The improved wheat yields, combined with reduced fertilizer use, were found to increase farmers' net returns by $188/ha. The input cost savings associated with the reduced amount of fertilizer applied in *rice* fields would save farmers in India $10–$49/ha. In Mexico, research found that the GreenSeeker can reduce fertilizer use without affecting *wheat* yield (Ortiz-Monasterioet al. 2014), saving farmers $83/ha.

Barriers to adoption

To shed light on the barriers to the adoption of the GreenSeeker and other optical sensors in India and Mexico, an expert survey was conducted. Experts were asked what is preventing farmers from adopting this technology. Responses for India included access to information, lack of business concept in agriculture, and cost involved in the technology (for smallholder farmers).

To explore potential ways to remove the above-stated barriers, experts were also asked what would be required in a nationally appropriate mitigation action to help increase the adoption of this technology. The responses for India included provision of service providers in the farming communities, better extension of the technologies, and government subsidy on these environmentally friendly technologies.

It may be worthwhile for CCAFS to undertake or commission a study on the specific barriers to adoption to N fertilizer management technologies, including optical sensors. Study results would help in the development of strategies to remove these barriers and increase the chances of success for eventual LED programs and climate finance that may include such mitigation technologies. The relatively high up-front cost of optical sensors (for smallholder farmers in developing countries) warrants special consideration as a key barrier to adoption (Sapkota pers. comm. 2015). Various institutional arrangements and policy instruments, including subsidies, may be effective at reducing this specific barrier.

[33] Profit is gross returns minus costs of production, before taxes. Gross returns are the total revenues received from the sale of the crop before any deductions or allowances, as for rent, cost of goods sold, taxes, and so on. The terms "total revenues," "gross returns," and "gross revenues" are synonymous.

Developing scenarios

In the absence of specific evidence in the literature and survey results on diffusion rates and barriers to adoption, this study has used a scenario-based approach to estimate the national-level impacts of the adoption of optical sensors.

- For the BAU scenario, a 1% diffusion rate is used (i.e., an additional 1% of the total growing area each year would use optical sensors to improve the N fertilizer application rate). This is based on feedback received in the expert survey conducted for alternate wetting and drying of paddy rice and for optical sensors.
- A conservative scenario of 2% diffusion per year is based on feedback received in the expert survey we conducted on paddy rice and is in line with Bockel and Touchemoulin (2011)[34] and Lampayan et al. (2015). It is slightly lower than the lower-bound value estimated as part of the expert survey on optical sensors.[35]
- An aggressive diffusion scenario of 5% per year would require significant resources to mobilize stakeholders to ensure a high level of adoption in most growing regions in the two countries.[36] This aligns with the feedback received by the single respondent[37] to the expert survey we conducted for optical sensors, and is significantly lower than the aggressive scenario used for the diffusion in paddy rice.

Note that significantly higher diffusion rates have been observed for other types of agricultural technologies in developing countries. For instance, in the early 2000s, zero-tillage diffused at a rate of over 150% in the Indo-Gangetic Plains, according to Erenstein (2010). Similarly, the diffusion rate for new wheat varieties in India during the mid-1980s was 28%, according to a study by Azeem et al. (1989). The "off-the-shelf" nature of these technologies increases the ease of uptake and explains their high diffusion rate, compared with the more knowledge-intensive technologies such as optical sensors.

Total land area where technology is adopted

Less than 2% of the farmers have adopted optical sensors in India according to expert opinion. At a 2–5% diffusion rate, the total land area where optical sensors are used could

[34] Their modeling assumes a 10% increase in diffusion of climate-smart agricultural practices over a 6-year period (1.6%/year).

[35] The respondent estimated a lower-bound adoption rate of 4%/year could be achieved.

[36] For instance, the Nationally Appropriate Mitigation Action for the rice sector in the Philippines is targeting 100% of farmers cultivating irrigated rice. As such, plans are to train 150 irrigation officers and allocate $16 million over 6 years for training and management. (See http://procurement-notices.undp.org/view_file.cfm?doc_id=34218 for details.)

[37] The respondent estimated that an upper-bound adoption rate of 5%/year could be achieved.

increase by 2.2–8.9 million ha for rice and 1.3–5.1 million ha for wheat over the next five years, compared with the BAU scenario.

In Mexico, the total land area where optical sensors are currently used is 370,000 ha for maize and 29,450 ha for wheat (Ortiz-Monasterio pers. comm. 2015a).[38] At a 2–5% diffusion rate, the total land area where the technology is adopted could increase 370,000–1,480,000 ha for maize and 29,000–118,000 ha for wheat over the next five years, compared with the BAU scenario.

National GHG reductions

Materiality is an important consideration, especially in the context of climate finance and development of LED policies. As such, determining the GHG reduction potential of the technology if mainstreamed across India and Mexico is key to assess whether this technology is, on its own or as part of a broader suite of technologies, promising enough to attract financing support, either domestically or internationally.

National GHG reductions stemming from the adoption of optical sensors would amount to **0.135–2.500 $MtCO_2e$ in India** (wheat and rice combined). Adoption of this technology could lead to a decrease in GHGs of **0.063–0.250 $MtCO_2e$ in Mexico** (wheat and maize combined). The range in GHG reductions is based on the adoption rate (from conservative to aggressive) and the range of GHG reduction potential at the farm level found in the literature.

National yield impacts

Extrapolating from the credible range of yield impacts from the technology's adoption in the studies found, an additional 0.257–2.700 Mt of wheat grain would be produced annually by 2020 across India (above the BAU scenario). In Mexico, yields would remain unchanged, as there is already an over-application of fertilizer.

National economic benefits generated

On the basis of the credible range of economic benefits of the technology found in the literature and on the potential diffusion rates chosen for our scenarios, the implementation of optical sensors could increase net revenues for wheat farmers across India by $242–$966 million,[39] and $110–$438 million in fertilizer cost savings could be realized in Indian rice production. Implementation of the technology in Mexico could generate fertilizer cost savings of $27–$111 million per year in wheat production.

[38] This is based on a 5% adoption rate.

[39] This assumes the additional crops produced are sold, as opposed to consumed by the farm household.

Table 2 summarizes these and other national-level impacts from the use of optical sensors for optimizing N efficiency.

Table 2. Summary of national-level impacts of using optical sensors (e.g., GreenSeeker) for optimizing N efficiency

National impact	India	Mexico
Additional area using optical sensor for optimizing N efficiency in 5 years under the BAU scenario	2.2 million ha (rice) 1.3 million ha (wheat)	370,000 ha (maize) 29,450 ha (wheat)
Additional area (over BAU) with optical sensor for optimizing N efficiency in 5 years with national-scale program	2.2–8.9 million ha (rice) 1.3–5.1 million ha (wheat)	370,000–1.5 million ha (maize) 29,000–118,000 ha (wheat)
Annual incremental (over BAU) GHG reductions from optical sensor in 5 years with national-scale program	0.100–2.200 $MtCO_2e$(rice) 0.021–0.314 $MtCO_2e$ (wheat)	0.0056–0.0224 $MtCO_2e$ (wheat) 0.057–0.228 $MtCO_2e$ (maize)
Annual incremental (over BAU) yield increase from optical sensor in 5 years with national-scale program	No change (rice) 0.3–2.7 Mt (wheat)	No change (wheat)
Annual incremental (over BAU) fertilizer cost savings from optical sensor in 5 years with national-scale program	No data	$2.4–$9.8 million (wheat) $25–$101 million (maize)
Annual incremental (over BAU) increased net returns from optical sensor in 5 years with national-scale program	$242–$966 million (wheat)	No data

Conclusions and recommendations

The literature related to the mitigation technologies included in this report overwhelmingly focus on agronomic benefits. Very few studies analyze their GHG and economic impacts, making it difficult to build the business case for such technologies. The main exception is optical sensors.

Optical sensors

On the basis of the available information in the literature, optimizing N rates with optical sensors such as the GreenSeeker seems to be a promising technology for GHG reductions in the agriculture sector in India and Mexico, especially if solutions can be found that allow farmers to not have to pay the full up-front cost of the sensor purchase. Given these costs, the technology is now more appropriate for larger farmers who use significant amounts of fertilizer. In India, optical sensors were found to have a GHG reduction potential of 0.016–0.247 tCO_2e/ha (0.135–2.500 $MtCO_2e$ nationwide), and they could lead to important increases in yield (0.200–0.530 t/ha in wheat) and net returns ($159/ha in wheat). A recent Government of India policy to assess soil nutrient status on most farms across the country, accompanied by advice on fertilizer use (the Soil Health Cards program), could be used to expand and complement efforts to promote the adoption of optical sensors for GHG reductions. In Mexico, the GHG benefits of using this technology in wheat production are 0.190 tCO_2e/ha and 0.154 tCO_2e/ha in maize (0.063–0.250 $MtCO_2e$ across the country for wheat and maize combined), whereas the financial benefits to farmers are $68 and $83/ha (through reductions in fertilizer costs) in wheat and maize, respectively.

More research should be undertaken to determine the scope 1 emissions reduction potential of optical sensors in Indian wheat and maize production. Also, careful analyses of the recent Government of India Soil Health Cards program and how future LED policy and finance should be designed to ensure complementarity of efforts (e.g., by including the Soil Health Cards program as part of the mix of climate policy instruments). For Mexico, further studies should be undertaken to more precisely determine optical sensors' GHG reduction potential in wheat and maize, as using the IPCC default emission factor may be too conservative. There is also a lack of data on the technology's GHG reduction potential in Indian maize. An additional data gap is the yield improvement and financial viability of the technology in Indian maize production. A study on the specific barriers to adoption should be undertaken to find strategies to remove these barriers and increase the chances of success for LED programs that may include such mitigation technologies. The scope of the study on barriers should include analysis of various institutional arrangements and policy instruments, including subsidies.

Application timing

Further field studies on fertilizer application timing, with measurement of the GHG emissions and quantification of the financial benefits and costs, would need to be undertaken before any firm conclusions can be reached on how promising this technology is in the Indian context.

Neem as a nitrification inhibitor

Similarly, neem oil may also be a promising technology as a nitrification inhibitor, as it was found to decrease GHG emissions by 11% for rice and 21% for wheat in one study (Sharma & Prasad 1995). However, in the case of neem, the key question remaining to determine its financial attractiveness is whether it would be available sustainably in sufficient amounts (and at a sufficiently low price) across India if neem coating of urea became a mainstream practice. This would require an in-depth study that is beyond the scope of this report. However, the question may be moot as the Government of India announced in January 2015 that it would require, via regulatory mandate, that 75% of the urea produced domestically be neem-coated (Government of India 2015). This will ensure broad diffusion across the country.

Deep placement

The deep placement of super granules may also be promising for reducing emissions in Indian rice production, as the technology has been found to be effective and profitable in Bangladesh. Although the 1985 study by Katyal et al. found negative results in terms of the technology's GHG benefits, the study seems to have been strongly influenced by their site selection. Further field studies, on a multitude of soil types in India, would need to be conducted before a more compelling business case can be developed.

Going beyond agronomic impacts

It is recommended that future field studies include an analysis of the economic impacts of technologies, in addition to the overall GHG impacts (i.e., CH_4 and N_2O, overall scope 1 emissions reduction potential including crop, soil, and fuel use in CO_2e) and agronomic benefits. Special attention should be placed on:

- Capital costs associated with any equipment required to adopt specific technologies;
- Labor costs under manual and mechanized approaches to application and labor costs to produce the fertilizer (in the case of briquettes produced on site or locally);
- Market availability for the technology (and any machinery[40] required for its implementation).

Economic impacts should be analyzed over the short-, medium-, and longer-term to determine how the costs and benefits vary over time. This would enable better assessment of specific financing instruments and requirements (e.g., if most costs associated with adoption are up-front costs, and financial benefits can be reaped early on by farmers, short-term credit could be an appropriate solution) and may better capture unintended consequences of technologies. For example, field studies may include an assessment of soil compaction and its long-term impact on productivity for technologies that entail increased field traffic such as split fertilizer application.

Future field studies should include measurements of positive and negative externalities associated with these technologies, such as adaptation benefits, water pollution impacts, and the provision of other ecosystem services. Having this more comprehensive suite of economic, social, and environmental information is crucial for building solid business cases for technologies that have demonstrated significant agronomic benefits.

In terms of analytics required for implementation, efforts should determine how to more cost-effectively implement the technologies and in what regions and specific conditions

[40] Although there is little to no mechanization on Indian smallholder farms at the current time, this is not the case in Mexico.

(agronomic, economic, and institutional) under which technologies are most financially promising. Moreover, detailed documentation is needed of the specific barriers to implementation and likely mitigation measures to alleviate or eliminate these barriers.

Going beyond farm-level analysis

This report focused on farm-level benefits and costs of N fertilizer management technologies. To develop a credible proposal for future LED policy and finance, a number of broader national impacts and implementation issues will also need to be analyzed, including:

- What are the resources required to upscale the technologies? Information dissemination? Capacity building? Partnership building?
- How can implementation of an LED project or program be done most effectively? By bundling technologies and policy instruments? By aligning with existing and proposed government priorities?
- What are the roles of and the impacts on government? This includes an analysis of policy instruments the government can put in place to support LED objectives. Should they use irrigation fees, regulations, or integration within a broader technical assistance program? What are the fiscal impacts of the implementation of an LED program? Is it loss of revenue from irrigation fees or reduced need to invest in irrigation infrastructure?

Also important is the development of a solid sector profile (e.g., number of farmers, number of ha under production, specific locations of farmers, water fees, current agricultural practices, current and expected yields and estimated GHGs, and water usage associated with their current production). This profile would serve to develop the baseline and BAU scenario, which would help to improve the robustness of the monitoring, reporting, and verification system accompanying an eventual LED program with climate finance.

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