Reducing Nitrous Oxide Emissions From Smallholder Farmer Agriculture Through Site Specific Nutrient Management

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For more information about PxD's 2022 Leaf Color Chart pilot project and analysis, including PxD's collaboration with IRRI to estimate GHG emissions, please email info@precisiondev.org. All errors are our own.

PxD PRECISION DEVELOPMENT

IGSD

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Initiative Overview

Precision Development (PxD) and the Institute for Governance & Sustainable Development (IGSD) are partnering on a unique initiative to collaboratively identify opportunities for innovation in climate change mitigation, particularly for the greenhouse gases most problematic in agricultural production, methane and nitrous oxide, as well as carbon dioxide. We are specifically focused on innovations with pertinence to the world's smallholder farmers, who farm most of the world's approximately 570 million farms. The Food and Agriculture Organization of the United Nations defines these smallholder farmers as "small-scale farmers, pastoralists, forest keepers, fishers who manage areas varying from less than one hectare to 10 hectares…(and) are characterized by family-focused motives such as favouring the stability of the farm household system, using mainly family labour for production and using part of the produce for family consumption." The majority of farms in the Global South, a term used to denote the regions of Asia, Latin America, Africa, and Oceania, are small and it is within this broad geography and smallholder farming context that we focus our climate change mitigation initiative.

This initiative includes four analytical pieces on the following opportunities for climate change mitigation by smallholder famers:

- carbon dioxide sequestration through enhanced rock weathering,
- carbon dioxide sequestration through conserving (keeping what is already present) or increasing (i.e., sequestering) the organic carbon storage in soils and plant biomass,
- nitrous oxide mitigation through precision nutrient management, and
- methane mitigation in dairy through improved livestock feeding practices.

In our initiative we are guided by the following principles:

Consider the tradeoffs: We aim to determine smallholder farmers' private returns from the adoption of new technologies or agricultural practices, as well as the societal return of such adoption as measured by gauging the impact of these innovations on our main outcome of interest in climate change mitigation, namely, reducing greenhouse gas (GHG) emissions.

Farmer welfare first: Smallholder farmers cannot be expected to pay the price for climate change mitigation. Climate change-related advisory should support livelihoods, especially as sustained adoption cannot occur without realized benefits for farmers. If it is difficult to understand *a priori* how a specific agricultural practice or technology might impact yields or income, we commit to exploring ways to compensate early adopters as payment for promoting the broader social benefit.

Replicate and scale: We aim to deliver impact at scale. We are particularly interested in low-cost climate change mitigation innovations with strong adoption potential, that can be customized to local contexts, and scaled throughout other regions with similar constraints or needs.

Our goal is to identify opportunities in agriculture with potential benefits for smallholder farmers, either directly or through compensation mechanisms for their environmental services, as well as for GHG mitigation. In identifying these opportunities, we will outline the evidence for impact on farmers' outcomes and on GHG-mitigation outcomes, as well as address challenges in building that evidence, particularly in outcome measurement methods. We will also address practical next steps to build a pathway to scale for the identified opportunities.

About Precision Development (PxD)

Precision Development (PxD) is a global non-profit organization that harnesses technology, data science, and behavioral economics to build digital services that empower people to change their own lives. We build low-cost information systems at scale to share knowledge with the world's poorest and most disadvantaged people. Our pioneering model of digital development is implemented in collaboration with partner organizations to maximize scale. We continuously experiment, iterate, and gather evidence on our impact to improve service delivery and demonstrate our value. Most of PxD's services deliver customized digital agricultural advisory to smallholder farmers, with more than 6 million users using these services in 2022. Given the many constraints facing these farmers, PxD is investigating the application of our platforms and core competencies to deliver advisory in new informational fields, including climate change adaptation and mitigation, as the effects of global warming ripple through the agriculture sector.

About the Institute for Governance & Sustainable Development (IGSD)

The Institute for Governance & Sustainable Development (IGSD) promotes just and sustainable societies, specifically through building resilience by accelerating fast climate change mitigation actions to slow near-term warming and self-reinforcing climate feedbacks, avoid catastrophic climate and societal tipping points, and limit global temperature increase to 1.5°C—or at least keep this temperature guardrail in sight. IGSD's latest research shows that decarbonization alone is insufficient to slow near-term warming to keep us below 1.5°C or even the more dangerous 2°C guardrail, and that the fastest and most effective strategy is to combine the marathon to zero out carbon dioxide (CO_2) emissions by decarbonizing the energy system with the sprint to rapidly cut non-CO_2 super climate pollutants, and to protect carbon sinks. The super climate pollutants include four short-lived climate pollutants (SLCPs)—methane (CH_4), hydrofluorocarbons (HFCs), black carbon soot, and tropospheric ozone (O_3)—as well as the longer-lived nitrous oxide (N_2O).

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Terminology

Global Warming Potential – Global Warming Potential (GWP) allows comparison of the potency of the warming impact of different gases relative to carbon dioxide over a given period of time. The GWP for a given gas is defined as how much energy "1 ton of the gas will absorb over a given period of time, relative to 1 ton of carbon dioxide."[1] Higher GWP means that an emission of that gas has a larger warming impact on the Earth compared with CO_2 over that time period.[2] Time periods of 100 years are commonly used to capture longer-term warming impacts, while a 20-year time period better captures warming impact in the near term.[3] The GWP of carbon dioxide is 1 by definition regardless of the time period used[4], whereas the GWP of nitrous oxide is 273 and of methane is 27-30 over a 100-year timescale.

Greenhouse Gas (GHG) Mitigation – The Intergovernmental Panel on Climate Change (IPCC) defines GHG mitigation as a "human intervention to reduce emissions or enhance the *sinks* of *greenhouse gases."*[5]

Nitrogen Use Efficiency (NUE) – Nitrogen use efficiency (NUE) in agriculture is a common metric to gauge nitrogen management. While there are many approaches for its calculation, at its most basic in the agricultural context, it is the ratio of crop nitrogen uptake to the total input of nitrogen fertilizer.[6] An NUE of 40% means that only 40% of nitrogen inputs are captured by the crop and incorporated into plant biomass, and the rest is lost to the environment. There are other common indices of nitrogen (N) management that focus on crop yield outcomes as a function of applied N,[7] including:

- agronomic efficiency of applied nitrogen [AE_N] (kg grain increase / (kg N applied – soil supplied N), which is the ratio of a farmer's yield increase and the amount of fertilizer applied at the field level, and

- the partial factor productivity of applied N (PFP_N) (kg grain / kg N applied), which is the ratio of a farmer's actual yields over the amount of nitrogen applied at the field level; partial factor productivity of applied N is typically the easiest efficiency metric to compute and most commonly used in studies.

Nitrogen Balance – Nitrogen balance (N balance) is another common metric to gauge nitrogen management in agriculture and has the advantage of being simple to calculate; it is therefore used in practical applications. It is calculated as "the difference between N inputs to, and N removed in products from, an agricultural system. At the spatial scale of a single production field, for example, N balance can be calculated from records of inorganic and organic nutrient applications and crop yield." This simple calculation for N balance can therefore be used as a "measure of the extent to which anthropogenic N supply exceeds crop needs."[8] This excess creates opportunities for nitrogen loss through pathways like nitrous oxide emissions.

Nitrification and Denitrification – Nitrogen is a critical nutrient in agriculture and is subject to many transformations, facilitated through microbial activity, in the nitrogen cycle. This cycle includes nitrification, which transforms nitrogen inputs into forms that are available to plants, and also into forms which can be lost (e.g., through leaching and nitrous oxide emissions), and includes denitrification, which transforms nitrogen into atmospheric forms (e.g., nitrous oxide emissions and elemental nitrogen, N_2).[9]

NPK – NPK represents the three major nutrients plants need to live—nitrogen, phosphorus, and potassium, respectively—and are the major ingredients, whether together or separately, in most types of synthetic fertilizer. NPK ratios, in that order, represent the proportion of nitrogen, phosphorus and potassium in a specific fertilizer.

SSNM and PNM – Site-specific Nutrient Management (SSNM) is often used interchangeably with Precision Nutrient Management (PNM) to describe the tailoring of nutrient management to field- and location-specific conditions, although the two terms differ slightly for which contexts they best describe. SSNM is most often used in the context of the Global South where many farmers are smallholders who lack access to expensive and advanced technology that can measure nutrients. As such, SSNM tools are generally less expensive and easier to use for a layperson, e.g., Leaf Color Charts, compared to PNM tools. PNM is most often refers to nutrient management in the Global North, and often involves cutting-edge technology, e.g., Adapt-N, to access the need for nutrients and subsequent yields. Given PxD's focus on the needs and contexts of smallholder farmers in the Global South, this paper will use SSNM as the primary term.

Yield-scaled GWP – Yield-scaled GWP is the ratio of GHG emissions, in CO_2 equivalents (CO_2-eq), per unit of crop yield. It is a common metric used in climate change mitigation literature.

1. Executive Summary

Nitrous oxide (N_2O) is both an ozone depleting substance that damages the stratospheric ozone layer and one of the most potent greenhouse gases (GHGs) contributing to global climate change. Nitrous oxide has a long lifespan in the atmosphere, in the order of hundreds of years, and its Global Warming Potential (GWP) over a 100-year time span is around 273 times that of carbon dioxide. Anthropogenic N_2O emissions over the past 150 years are responsible for about 0.09 degrees Celsius of warming out of the observed 1.1 degrees Celsius for 2010–2019, or about 10% of the warming caused by carbon dioxide.[10] Despite the significant effects of N_2O on global warming and the ozone layer, there has been less concerted international action on reduction of emissions of N_2O compared to other gases.

As with almost all GHG emissions linked to anthropogenic processes, N_2O emissions have increased significantly in recent decades. Agriculture is the main driver for these increases,[11] with up to 71% of the increase in emissions from the 1980s to 2007-2016 coming from direct agricultural emissions.[12] In particular, scientists have pointed to the use of nitrogen fertilizer as a key reason for the increasing N_2O atmospheric burden.[13] When nitrogen fertilizer is applied in excess or at the wrong time or place, its composite nitrogen becomes more susceptible to losses, for example through N_2O emissions.

Changing farmers' nitrogen fertilizer practices through an approach known as Site Specific Nutrient Management (SSNM) can make fertilizer application much more efficient and thus have a significant impact on N_2O mitigation. SSNM allows farmers to determine the precise amount and timing of nutrients that their plots require under growing conditions in a specific season and location. There is a strong evidence base for SSNM resulting in reduced nitrogen fertilizer usage, with one meta-analysis of 61 studies finding 10% less nitrogen fertilizer used with SSNM compared to farmer fertilizer practice. Concurrently, farmers saw average yield gains of 12%, as well as a 15% increase in gross return above fertilizer cost.[14]

To access SSNM recommendations, farmers who have more resources, like those in the Global North, can use physical tools like Soil Plant Analysis Development (SPAD) chlorophyll meters to assess the nutrient requirements of their crops or even install advanced software systems to monitor nutrient requirements in real time, i.e. Adapt-N. For smallholder farmers in the Global South, however, these kinds of tools are prohibitively expensive and complex to use. While some SSNM tools targeted for smallholder farmers have been developed and are comparatively less expensive and complex, e.g., the International Rice Research Institute's web-based Rice Crop Manager, their use to date is limited due to continued constraints around cost, complexity, and challenges to scale.

Most smallholder farmers thus continue to rely on their own judgement or blanket nitrogen fertilizer recommendations, which can miss critical variations in soil and crop nitrogen needs. This inefficient use of nitrogen not only contributes to N_2O emissions, but also subjects farmers to nitrogen underuse, which leads to yield gaps, as well as overuse, which adversely affects farmer profits and contributes to water and land toxicity through other types of nitrogen losses. Offering farmers in the Global South an accessible and user-friendly way to use nitrogen more efficiently will thus not only help reduce the environmental impact of the use of nitrogen fertilizer in agriculture, but also improve farmers' productivity and profits. Addressing the precision nutrient management gap for smallholder farmers in the Global South is a critical priority for achieving both anti-poverty and climate change goals, especially as the use of nitrogen fertilizer in Global South countries rises[15] in coming years to meet increasing global food demands.

2. Nitrous Oxide Emissions in Agriculture

The agriculture, forestry, and land use sector (AFOLU) accounts for 82% of global anthropogenic N_2O emissions,[16] contributing approximately 1.8 Gt CO_2-eq per year between 2010 and 2019.[17] Nitrous oxide emission in agriculture originates primarily from nitrogen fertilizers, but animal manures and nitrogen fixation by legumes are also sources, as crop recovery of reactive nitrogen from the soil never reaches 100%. Some level of loss of reactive nitrogen to the environment from all nitrogen sources is thus inevitable. These losses take various forms, including nitrate leaching, gaseous losses from ammonia volatility, N_2O emissions, as well as inert forms (e.g., N_2 gas) that don't contribute to environmental degradation or global warming. The form and fate of nitrogen lost from crop production systems is mediated by many factors, including temperature, soil pH, soil hydrology, and the timing of nitrogen inputs with respect to the crop growth cycle. Minimizing these losses from crop production systems, particularly from the use of nitrogen fertilizer which drives anthropogenic N_2O emissions across the globe,[18] without jeopardizing crop productivity goals is key to N_2O mitigation.

Although N_2O emission from inefficient fertilizer-use is problematic in many geographies, fertilizer behavior in countries in East and South Asia is particularly concerning due to the low nitrogen use efficiencies (NUEs) in these geographies. Nitrogen use efficiency is a helpful measure to quantify the propensity for nitrogen loss in a given system, as it represents the fraction of applied nutrients that are recovered by a crop, usually at the time-scale of a single season. In China and India, NUEs are around 32% and 34%, respectively, compared with around 72% in the United States.[19] The low NUEs in many Global South geographies can be partly attributed to subsidy environments which distort nitrogen-fertilizer consumption.[20] For example, subsidies and price changes in India have favored nitrogen fertilizer consumption, especially in urea which is their main source of nitrogen. Urea prices are fixed by the government[21] and over the past three decades the nominal price of nitrogen has risen by only 4%, compared with a 7% nominal price increase for other key nutrients like potassium and phosphorus.[22]

Another reason nitrogen fertilizer behavior in Global South geographies is of particular concern is that many of the existing macronutrient ratios in these regions, commonly used as blanket fertilizer recommendations (BFR), are outdated and fail to meet the nutrient needs of crops. In India, the accepted macronutrient ratio has historically been 4 Nitrogen:2 Phosphorus:1 Potassium or 4N:2P:1K, despite lacking evidence that this ratio is applicable to most contexts within India. While the exact origins of the 4N:2P:1K ratio are largely unknown, most researchers attribute its nutrient balance calculations to pre-Green Revolution agricultural contexts. The 4N:2P:1K ratio therefore does not account for more recent changes in improved seed varieties, cropping systems, environmental or seasonal differences, soil fertility, and indigenous nutrient supply.[23]

In addition, blanket fertilizer recommendations by definition overlook the high variability in spatial soil-fertility and the variations between cropping systems, including differences in soil type, soil nutrient status, geographic location, input availability, and crop management practices.[24] As a response, the Government of India, in collaboration with the Indian Council of Agricultural Research (ICAR) and State Agricultural Universities (SAUs), developed recommended dose(s) of fertilizers (RDF) per state, although some of these RDFs still do not adequately account for the high heterogeneity in indigenous nutrient supply and other farm-level variations in the smallholder farmer context.[25]

One science-based approach to improve fertilizer efficiency and help reduce nitrogen losses in nitrogen fertilizer use, while closing yield gaps, is Site Specific Nutrient Management (SSNM). SSNM provides precise fertilizer recommendations based on field-specific conditions in a given cropping season, including the best time and place to apply nitrogen fertilizer[26], and allows for agricultural intensification without overshooting the amount of nitrogen needed.[27] Rather than applying nitrogen indiscriminately throughout a field or applying the right dose but at the wrong time in attempts to avoid yield penalties, farmers can use SSNM to apply the precise amount of nitrogen fertilizer their field requires. SSNM has been shown to either maintain or increase crop yields and can increase farmer profits by reducing the amount of money farmers spend on nitrogen fertilizer, in cases of overuse, or by getting more in productivity returns from a given level of fertilizer investment. More balanced nutrient management through SSNM also may lead to improved resistance to plant diseases and pests, as well as to healthier, more robust plants,[28] which can help make smallholder farmers more resilient to agricultural shocks.

3. Nitrous Oxide Mitigation through Site Specific Nutrient Management

Developed in the 1990s with the goal of increasing yields and optimizing resources of smallholder rice farmers in Asia, SSNM was created by the International Rice Research Institute (IRRI) and other collaborators in Asia.[29] The SSNM approach was expanded soon thereafter to include wheat and maize systems, and now includes nutrient management guidelines for numerous crops.

The basis of the SSNM approach builds on the principles of 4R Nutrient Stewardship: Right Product, Right Rate, Right Time, and Right Place:

1. **Right Product** encourages farmers to use the ideal sources (e.g., synthetic chemical fertilizers, organic fertilizers like organic compost, controlled release fertilizers which are designed to release nutrients gradually over a set period of time, etc.) that meet crop nutrient requirements, considering the indigenous nutrient availability and the characteristics of available products.
2. **Right Rate** refers to applying the correct quantity of fertilizer, which includes properly assessing plant demand and nutrient supply already present in the soil. Applying the correct amount of fertilizer leads to less environmental waste from excessive fertilizer application, and ensures that farmers get the most from their nutrient application.
3. **Right Time** ensures farmers optimize nutrient availability by applying fertilizers based on the crop demand and potential nutrient loss (erosion, leaching, etc.) during the cropping season.
4. **Right Place** encourages farmers to apply nutrients in the correct area at the ideal soil depth (according to soil type and topography) to minimize nutrient loss and to enhance plant nutrient uptake.[30]

SSNM is designed to help farmers balance nutrients present in the soil and apply optimized amounts of N, P, and K to maximize yields. Meeting nitrogen demand with nitrogen supply through SSNM allows for a reduction in global N_2O emissions by helping reduce nitrogen overuse and increasing nitrogen use efficiency (NUE).[31]

In contexts where nitrogen-based fertilizer prices have remained low, or farmers have sufficient capital, some farmers may apply more nitrogen in their fields than necessary because they want to prevent any nitrogen stress in their crops and the associated reduction in yields. However, when farmers add excess nitrogen to the soil, there is more nitrogen available than the nitrogen that will be taken up by the plant, and the nitrogen is therefore transformed into N_2O during microbial-led nitrification and denitrification.

In other instances, farmers do not necessarily overuse nitrogen-based fertilizers, but they may have applied nitrogen fertilizers at the wrong time and in the wrong place. This reduces the chances that plants can fully access the applied nitrogen, thereby creating more opportunities for nitrogen loss through N_2O emission. SSNM helps farmers place the nitrogen in such a way that the crop uptake is maximized, leaving a lower margin of unused nitrogen for microbial activity in nitrification and denitrification, and therefore reducing potential N_2O emissions.

In contexts where nitrogen fertilizer is more expensive or farmers lack financial resources to purchase the desired amount of fertilizer, underutilization of nitrogen fertilizer has led to lower productivity. Many smallholder farmers remain unable to assess the quantity, quality, and timeline of nitrogen-based fertilizer application for optimal productivity. By optimizing nitrogen application based on SSNM guidance in these underuse situations, farmers can work towards improved productivity without resorting to indiscriminate use of nitrogen fertilizers and overshooting the amount of nitrogen their crops require.

4. The Impact of SSNM on Farmer and Climate Change Mitigation Outcomes

There is a substantial evidence base demonstrating that the SSNM approach improves farmer yields and profits, especially in rice, wheat, and maize cropping systems in Asia and Africa, as well as improves crop nitrogen use efficiency, a key metric for how much nitrogen is subject to loss in a cropping system (Table 1 and Table 2).

In terms of farmer outcomes, SSNM has been shown to either maintain or increase crop yields, with almost no existing studies showing an average negative impact on yields compared to farmer fertilizer practice (FFP) or recommended doses of fertilizer (although this may be due to publication bias favoring positive, statistically significant results). SSNM also generates profits for farmers by helping them save money on fertilizer input costs through reduced nitrogen use and/or increases in yield, with various studies finding between 6 and 15% increases in returns (Table 1).

In addition to higher profits and yields, other benefits to farmers of balanced NPK nutrient application include improved plant disease resistance and more vigorous plant growth.[32] When there is a nutrient imbalance, specifically a surplus of nitrogen, vegetation can grow excessively and make crops more susceptible to pest and disease attacks as well as to lodging.[33] Lodging is when the stems of grain crops become bent during maturity, due to weather conditions like rain or hail, or weakness in the plant itself (for example, rice plant stems may be unable to support grain weight and may fall over),[34] and is a chronic constraint on productivity for farmers worldwide[35] as it makes grains difficult to harvest and reduces ultimate grain yield. Applying balanced nitrogen rates also allows for less use of pesticides, as plants are healthier and more robust to resist pest outbreaks.[36]

These plant health co-benefits of SSNM are important from the perspective of the smallholder farmer as the benefits help reduce the farmer's downside risk; this reduction can be just as attractive to farmers as an increase in profits or yields. These plant health co-benefits will become more pertinent in coming years as farmers in the Global South face the disproportionate effects of climate change, from extreme weather events to more frequent pest and disease outbreaks.

Table 1: Impacts on Yields, Farmer Profits, Nitrogen Application, and NUE of the SSNM Approach

Study	**SSNM Approach**	**Study Type**	**Geography**	**Impact Evidence on Yields**	**Impact Evidence on Farmer Profits**	**Nitrogen (N) Fertilizer Application and Nitrogen Use Efficiency (NUE)**
Dobermann et al., 2002	A modification of the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model	On-farm experiments (n=179) to test validity of SSNM approach on irrigated rice	China, India, Indonesia, Thailand, the Philippines, and Vietnam (eight irrigated rice domains in Asia)	7-11% increase in rice yields*	12% increase of total average net return* across all sites and four successive rice crops	4% decrease in average N fertilizer application rate
Chivenge et al., 2021	Various approaches across included studies	Meta-analysis of 61 studies on maize, rice, and wheat; most studies were on-farm, with five studies conducted on station	Indonesia, Ghana, Bangladesh, the Philippines, India, Nepal, China, Vietnam, Senegal, Thailand, and Burkina Faso (8 Asian countries and 3 African countries)	12% increase in grain yields across all crops* Higher yield gains in rice in Africa (24%) compared to South Asia (10%)*	15% increase in profits*	10% decrease in N fertilizer application* Increased NUE across studies
Wang et al., 2007	Customized SSNM recommendation developed at Zhejiang University in collaboration with IRRI	Multiple rounds of on-farm trials (n=61) from 1998-2004 in rice systems	China (Zhejiang province)	0.5 t/ha increase in average grain yield across seasons and years*	10% increase in gross return above fertilizer costs*	30-50% decrease in N fertilizer application (~61 kg/ha)* AE_N increased by 80%*
Chivenge et al., 2022	Various approaches across included studies	Literature review and discussion of history of SSNM in SSA for rice, maize, and cassava production. Authors discuss findings from other studies, and conduct a small meta-analysis from eight studies on rice and maize systems in SSA	Sub-Saharan Africa (SSA), including studies in Mali, Burkina Faso, Senegal, Ghana, South Africa, Nigeria, Ethiopia, and Tanzania	24%* and 11%** increase in grain yield for rice and 69%* and 4%** increase in grain yield for maize	6% increase in gross return above fertilizer costs.** Authors point out that profit gains were smaller for maize than for rice.	28% higher NUE* 19% higher NUE**

* compared to farmer fertilizer practice (FFP)
** compared to a recommended dose of fertilizer (RDF) / blanket fertilizer recommendations (BFR) / state recommendations (SR)

In terms of climate change mitigation outcomes, growing evidence finds SSNM can lower N_2O emissions and the global warming potential of agricultural activities compared to farmer fertilizer practice or even state fertilizer recommendations (Table 2). In cases of nitrogen overuse, SSNM lowers nitrogen fertilizer application rates and provides farmers with an application schedule to optimize nitrogen uptake. These effects often lead to higher: agronomic efficiency of nitrogen (AE_N), recovery efficiency of nitrogen (RE_N), and partial factor productivity of nitrogen (PFP_N). However, very few studies assess N_2O emissions in on-farm trials with farmers managing cultivation practices. Some on-farm trials calculate improvements in NUE, but very few calculate N_2O emissions, given the difficulty in calculating N_2O or GHG emissions (as discussed in the next section). Future studies must explore both the climate benefits of SSNM tools, and, specifically, the farmer-focused barriers to adoption and implementation of SSNM.

Table 2: SSNM Impacts on Nitrogen Fertilizer Application, NUE, and Nitrous Oxide Emissions

Study	SSNM Approach	Study Type	Geography	Nitrogen (N) Fertilizer Application Rate	Nitrogen Use Efficiency (NUE), AE_N, RE_N, PFP_N	N2O Emissions / Global Warming Potential (GWP)
Gupta et al., 2022	Leaf Color Chart (LCC)	University experimental farm using a randomized block design with 13 treatments	Punjab, India	Farmers only used 60% of the recommended N but had comparable cotton yields.**	AE_N and RE_N appeared to be comparable between LCC and soil-test based recommendations.**	LCC-based N application lowered N_2O emissions by 66.8%.**
Pampolino et al., 2007	LCC	On-farm trials (n>120)	Southern India, the Philippines, and southern Vietnam	N fertilizer use decreased by 10% in the Philippines and 14% in Vietnam.* N fertilizer application rates were similar or higher between SSNM and FFP, depending on the site in India.* Grain yields increased significantly in all three countries across all sites.*	NUE increased with SSNM* PFP of N increased by 21% in the Philippines and 26% in Vietnam*	Averaged across the Philippines and Vietnam, yield scaled GWP decreased by 56 kg CO_2-eq (carbon dioxide equivalent) Mg^{-1} grain, or a 22% reduction in CO_2-eq per unit of rice produced. In India, SSNM was able to increase yield with the same or increased rate of fertilizer N without additional N_2O emission per unit of grain yield or fertilizer used.
Sapkota et al., 2014	Nutrient Expert & GreenSeeker	On-farm trials over two consecutive years (n=15, with each farmer having a complete set of 5 nutrient management treatments randomized separately under two tillage methods)	Haryana, India	SSNM fertilizer applications used, on average, more N in 2010-2011 than FFP and SR used, but less N in 2011-2012. SSNM-based applications used less P on average and more K than FFP and SR. On average, SSNM recommendations increased grain yield and biomass yield by 5% and 3%, respectively over state recommendation and by 14% and 9%, respectively over farmer's practice.	No difference in PFP of N between SSNM recommendations and state recommendation, but significant difference between SSNM recommendations and farmers' practice.	In the case of nutrient management strategies (averaged over tillage methods), estimated N_2O emission was the highest under FFP and lowest under one of the SSNM management treatments, the NE:GS system.
Zhang et al., 2018	Nutrient Expert	On-farm trials (n=315)	Northcentral China (Shanxi, Hebei, Shandong, and Henan Provinces)	SSNM decreased N and P inputs by 41.4% and 30.1%, respectively.* SSNM increased K inputs by 51.5%.*	SSNM increased AEN by 70.0%* and 13.3%,** and increased RE_N by 73.8* and 13.3%.** SSNM also increased the PFP of N by 58.5%* and 22.2%.**	SSNM-based applications decreased total N_2O emissions by 54.8%* and 26.3%.** SSNM also reduced total GHG emissions by 44.8%* and 22.9%** and GHG emission intensity by 45.8%* and 22.0%.**
Huang et al., 2021	Nutrient Expert	Two 9-year field experiments	Northcentral and Northeast China (Hebei and Jilin Provinces)	21.4% and 25.6% reduction in N application rate in summer and spring maize, respectively.*	21.8% and 16.0% reduction in reactive nitrogen (Nr) losses in summer and spring maize, respectively.*	18.4% and 20.9% reduction in GHG emissions in summer and spring maize, respectively.* 24.8% and 21.4% reduction in N footprints in summer and spring maize, respectively.* 30.3% and 22.9% reduction in the N-derived N footprints in summer and spring maize, respectively.*
Sapkota et al., 2021	Nutrient Expert	On-farm trials (n=1594)	Indo-Gangetic Plains (IGP), India	18% reduction of N application in rice-wheat systems. Average N application decreased by 10% in Eastern IGP and 25% in Western IGP.*	Study reports improved NUE in rice and wheat.*	2.5% reduction of GWP in rice and 12-20% reduction of GWP in wheat from SSNM.*

* compared to farmer fertilizer practice (FFP)
** compared to soil-test based N recommendations

It is important to keep in mind, however, that most of the literature on SSNM revolves around experimental research farms or on-farm trials with heavy researcher involvement rather than on-farm trials under farmer management. In addition, the vast majority of studies evaluate the efficacy of SSNM in rice, wheat, and maize cropping systems in Asia. Research in Africa remains limited, with only a few studies focusing on rice production. For example, Chivenge et al. (2021) provide an overview of existing literature in an expansive meta-analysis of SSNM with 61 studies, yet only three were situated in Africa. For many of the on-farm trials discussed, crop management practices were determined by researchers and are not observations of how farmers would realistically implement SSNM recommendations, which raises questions about the applicability of these results to real life scenarios. Farmers may face resource constraints (if SSNM advises higher doses of fertilizer than FFP) or may not adopt all practices simultaneously. In six recent on-farm farmer-led impact studies, SSNM has shown yield increases ranging from 2% to 17% and profit increases from 4% to 48% for both rice and maize crops, but the range of productivity and profitability suggest that further research is needed to be able to predict SSNM impacts adequately.[37]

Measuring Nitrous Oxide Emissions

Nitrous oxide fluxes, as in most greenhouse gases, can be difficult to monitor and measure. Accounting for GHG emissions is a field unto itself and there are various standards and approaches which companies and governments use to understand their contribution to global climate change. However, measuring and monitoring emissions over time is critical for climate change mitigation efforts, especially in smallholder farmer contexts. Measurement helps to ensure emission reductions actually occur, and opens pathways for farmer compensation for their verified climate change mitigation activities. There are three types of estimates of greenhouse gas emissions, based on IPCC classifications, each with a specific methodological complexity and associated accuracy.[38]

Tier 1

Tier 1 emissions estimates are the most basic and use IPCC default emission factors, which are representative values connecting specific activities with amounts of emissions produced. For example, there are emissions factors associated with different agricultural activities, e.g., rice cultivation. Tier 1 emissions factors are global and do not differ by region, so it’s important to keep in mind its estimates come with a high level of uncertainty. In reality, emission rates for different agricultural activities can differ considerably based on differing landscape conditions, but Tier 1 estimates will ignore those differences.

At its most basic, Tier 1 calculations involve multiplying the emission factor for an activity by the rate at which the activity is occurring (in the case of agriculture, this is hectares of land under cultivation). Tier 1 estimates therefore require the least specific inputs as they do not include any context-specific information. While Tier 1 estimations are the simplest emissions calculations for practitioners to use, they are best placed neither for precise measurement nor for measurement of changes in emissions arising from how an activity is done. Rather, they are best for providing a high-level overview of GHG emissions from a specific activity.[39]

Tier 2

Tier 2 emissions estimates use empirical models to build region-specific emission calculations, rather than the default emissions factors in Tier 1 estimates. Although Tier 2 estimations are more precise than Tier 1 estimates, they still lack important nuances about the cropping system, as broad assumptions are still made around factors affecting emissions. Examples of Tier 2 empirical models include carbon calculators like the Climate Change, Agriculture and Food Security – Mitigation Option Tool (CCAFS-MOT) or the Cool Farm Tool (CFT). These calculators can estimate direct and indirect carbon dioxide equivalent emissions from different agricultural and agronomic activities within a cropping system—fertilization, mechanization, irrigation, or even off-farm activities like post-harvesting processes or transport—and the estimates will differ based on geography. For example, the CCAFS-MOT is an Excel-based tool which allows users to input information about a specific field or cropping system and receive GHG emissions estimates in carbon dioxide equivalent per hectare and carbon dioxide equivalent per unit of product.

These Tier 2 models can be used to detect changes in emissions due to changes in farming activities, as users can customize their input of activity information. Some of the Tier 2 carbon calculators even integrate decision support tools, so users can receive feedback on how to lower GHG emissions given their inputted activities. Tier 2 estimations, however, require a knowledgeable user trained in the use of the empirical model.

Tier 3

Tier 3 emissions estimations are the most complex, but also the most precise. They involve either process-based models, which replicate the various biological and chemical processes occurring in the field, or direct measurement techniques, to arrive at estimations. Tier 3 estimates are typically used by researchers or academics, as the use of process-based models or direct measurement require specialized education and/or technology.

- Process-based models combine empirical equations, estimated by laboratory experimentation, with well-known theoretical axioms and laws of soil physics and biogeochemistry, to create dynamic models able to simulate the different processes involved in nitrogen and carbon cycling. They require calibration and parametrization to evaluate the model using observable data, which is obtained through field experiments. This calibration and parametrization step is especially critical when using a process-based model for a new crop or agroecological zone. Examples of process-based models include Century, Daycent, and DNDC which are all commonly used by researchers to simulate GHG emissions. The advantage of using process-based models is that an unlimited number of scenarios and contexts can be simulated,[40] including in various future climate scenarios, and simulations can be a relatively inexpensive alternative to direct GHG measurements. However, the evaluation and validation of these models are still dependent on field data, and the calibration of soil models can be a time-demanding task which requires technical knowledge and detailed soil, crop, and weather data.

- Direct measurements in fields use technologies such as static closed chambers or eddy covariance towers, which can directly measure emissions in a variety of cropping systems.

Static closed chambers can be installed in crop fields to capture the soil-atmosphere gas exchange and quantify gas emissions rates. Eddy covariance towers, which look similar to meteorological stations, use sensors to measure the GHG emissions in the air at different heights. Direct measurements of GHG fluxes—compared to models—provide the most accurate estimation, but their use can be expensive and time demanding. For example, in India, the use of eddy covariance towers requires both governmental approval and collaboration with specific research centers and/or state agricultural universities. In addition, both static closed chambers and eddy covariance towers require specially trained users as they most accurately estimate emissions if samples are correctly taken and managed. The rate of error is high if researchers do not have an adequate level of knowledge to implement direct measurement technologies properly.

GHG Emissions Estimation for Practitioners

Tier 3 approaches may provide the most accurate emission estimates, but they require specially trained expert users—i.e., scientists specializing in GHG emission measurement—and can have other high barriers, like cost and governmental regulation. Tier 1 calculations, while simple to use, are not able to calculate changes in emissions resulting from changes in how the activities are performed. Tier 2 calculations, therefore, may be best placed among the existing options for practitioners in smallholder farmer contexts to calculate emissions and how emissions change due to an implemented program.

For example, the CCAFS-MOT and CFT are promising tools which practitioners can be trained to use in measuring N_2O and other GHG emissions, and which avoid high barriers like cost or specialized knowledge. It is important to keep in mind, however, that carbon calculators like CCAFS-MOT and CFT are both relatively new tools that have been developed in the last decade. While preliminary results in South Asia are promising, CCAFS-MOT and CFT have not yet been sufficiently deployed and tested in broader geographical and ecological contexts. Further testing and calibration of CCAFS-MOT and CFT in diverse contexts are necessary so that estimates can be applicable in diverse smallholder contexts across Asia and Africa. Nevertheless, given that all current GHG estimation methods involve a tradeoff between accuracy and ease of use, as well as being costly and time-consuming, these existing Tier 2 calculators are best placed for practitioner use.

5. Challenges and Opportunities in Scaling Site Specific Nutrient Management Approaches

When the 4R principles, which form the conceptual framework of SSNM, were first introduced in 1988 by the International Plant Nutrition Institute, [41] researchers were met with the challenge of tangibly applying the SSNM concept in a smallholder farmer context in low- and middle-income countries (LMICs) in the Global South. The main approach scientists first used was to generate desired nutrient quantity and application guidelines using a regression model, known as QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) which calculates the input nitrogen (N), phosphorous (P), and potassium (K) needed to obtain target yields for a given plot.[42] This approach requires advanced calculations, an understanding of soil properties, detailed information about a farmer's inputs and previous yields, as well as a soil nutrient profile of the plot. The soil tests and on-farm nutrient trials to obtain some of the required input data are also expensive and time-consuming, all of which makes SSNM adoption at scale amongst smallholder farmers extremely challenging.

In response, a number of international organizations created tools that allow farmers to access and apply SSNM principles themselves. A number of digital and physical decision support tools are now available to provide nutrient management in a comparatively simple manner. Examples of physical tools include chlorophyll meters (a portable diagnostic tool to measure the relative chlorophyll content of leaves), GreenSeekers (a portable sensor to measure the Normalized Difference Vegetation Index (NDVI) of plants),[43] and Leaf Color Charts (a plastic, ruler-shaped strip containing several panels in a range of green shades used to estimate the nitrogen content of a crop). The readings from these physical tools can all be used to calculate the nitrogen needs of crops. Most physical tools, however, are prohibitively expensive for smallholder farmers (e.g. ~USD 800 for a GreenSeeker and ~USD 3,000 for a chlorophyll meter as of the time of writing). Examples of digital tools include the web- and app-based Rice Crop Manager, Nutrient Expert, and RiceAdvice which allow farmers to input information specific to their plot to obtain nutrient recommendations.

In Table 3 we highlight the tools that have the most relevance for direct smallholder farmer use, primarily excluding expensive physical decision support tools. All highlighted tools have evidence of their potential to lower N_2O emissions while simultaneously boosting farmer productivity and profitability, if adopted (for an in-depth review of the evidence on each highlighted tool, see Appendix 1). Their wide-scale adoption by farmers, however, has yet to occur, which indicates that, apart from cost, significant barriers to adoption remain. For example, web- and app-based tools require a knowledgeable user who can navigate the input data required. Meanwhile, while Leaf Color Charts are affordable (~USD 1 each), they require expensive physical distribution and training to reach farmers.

Another barrier discussed in the literature is a lack of supporting systems to assist SSNM adoption, such as internet connectivity for web- and app-based tools, and well-functioning agricultural extension services to properly disseminate, market, and train farmers on available tools.[44] For example, farmers may not have reliable internet access, smartphones, nor the ICT literacy needed to use existing web- and app-based tools. These digital tools may also not adequately account for context specific fertilizer issues like availability and cost of recommended fertilizer types and amounts.[45] SSNM adoption to date is thus limited due to the cost, complexity, and challenges to scale of the available decision support tools.

Table 3: Physical and Digital SSNM Tools

SSNM Tool	Tool Overview	Development	Crops and Geographies	Price
Leaf Color Chart (LCC)	The LCC is a physical tool consisting of four to eight plastic color panels ranging from yellow-green to dark green, which farmers use to assess the greenness of leaves on different plants in their fields. Based on the results of the LCC visual analysis, farmers are able to calculate if their crops have absorbed enough N and how much N-based fertilizer they need to apply to maximize yields.	LCCs were first developed for rice by the International Rice Research Institute (IRRI) and Philippine Rice Research Institute (PhilRice).	LCCs have been calibrated for crops including rice, maize, wheat, sugarcane, potato, cassava, cotton, and other vegetables in geographies across Asia and Africa.	LCCs generally cost about USD 1, but differ slightly in cost in different geographies. For PxD's LCC pilot project in Gujarat, LCCs cost 180 INR, or about USD 2.25.
Rice Crop Manager (RCM)	Rice Crop Manager (RCM) is a free web-based decision support tool for nutrient management of rice, and is available through a computer, tablet, or smartphone via Windows, Android, and Linux. On the RCM tool, farmers answer approximately 30 questions about the cropping system, farm conditions, and farmer practices. Based on the farmer's information, the RCM tool provides a customized one-page printout with nutrient management advice.	In 2008, IRRI created a nutrient management tool called Nutrient Manager for Rice. In 2013, IRRI renamed the tool Rice Crop Manager and added nutrient management advice through the SSNM framework.	RCM can be used for rice and rice-wheat cropping systems (Bangladesh, India, Indonesia, and the Philippines).	RCM software is free, but users must have access to a computer, tablet, or smartphone and internet connection, or access to agricultural extension agents with internet access.
Nutrient Expert (NE)	Nutrient Expert (NE) is a computer-based decision support tool for nutrient management. NE allows farmers to enter information about their current crop management practices, previous yields, environmental conditions, and available inputs. Nutrient Expert utilizes the principles of SSNM and the QUEFTS model, but allows farmers to input less specific information and still receive specialized nutrient management guidance.	NE was developed by the International Maize and Wheat Improvement Center (CIMMYT) and the International Plant Nutrition Institute (IPNI) in 2013.	NE is calibrated for 23 crops, including maize (China, India, Indonesia, the Philippines, Vietnam, Kenya, Zimbabwe, Ethiopia, and Nigeria), rice (China and India), wheat (China, India, Nepal, Bangladesh, Algeria, Morocco, and Tunisia), soybean (China), and a variety of fruits and vegetables.	NE is free software, but users must have access to a computer, tablet, or smartphone, and internet connection, or access to agricultural extension agents with internet access.
RiceAdvice	RiceAdvice is an android-based decision support tool for nutrient management of rice. Farmers put information into the tool about cultivation practices, including sowing date, fertilizer type, and price information. Two additional versions of RiceAdvice exist: RiceAdvice Lite and RiceAdvice-WeedManager.	RiceAdvice was developed by the Africa Rice Center (AfricaRice) in 2013 and released in 2016.	RiceAdvice is used in Benin, Burkina Faso, Ghana, Mali, Nigeria, and Senegal, with ongoing testing in 16 other African countries.	RiceAdvice is free but users need access to a smartphone and internet to use the technology.

Despite robust evidence that SSNM decision support tools (Appendix 1) can significantly impact yields, profits, and N_2O emissions at the farm level, the current scope of SNNM operationalization has not yet been able to scale its adoption. One issue is that, while SSNM tools may be appropriate for certain agroecological zones, they may need to be calibrated to other zones for optimal use. For example, farmers using Nutrient Expert in mountainous regions of Nepal obtained lower rice yields than their lowland counterparts, due to calibration issues.[46] Even rule-of-thumb tools like Leaf Colors Charts may need calibration if used outside the agroecological zones where they were originally developed. For example, the LCC that PxD used in its pilot project in Gujarat, India was developed for Punjab, India. A calibration needs assessment showed that there was probably a low need to calibrate the LCC for farmers in Gujarat due to small differences in optimal recommendations between the two locations. However, the available literature to answer this question empirically is sparse, and questions remain on what degree of difference between agroecological zones will start affecting farmer outcomes and necessitate calibration and customization. Using a structural approach to identify relevant defining characteristics of agroecological zones for different cropping systems, and using rigorous agronomic trials within groups of these characteristics to understand how much these factors must change to justify the cost of calibration and customization for SSNM tools, will help answer this question.

There is also a large need for research to explore why and how farmers adopt different fertilizer management practices. Currently, there are limited studies to assess farmer uptake and decision making around SSNM tools. Evidence suggests that farmers may need to develop deeper trust in SSNM decision support tools before fully following nutrient management advice, even when initial reactions to the tool appear positive.[47] In cases of nitrogen overuse, farmers may be cautious in trusting SSNM guidance and may be hesitant to decrease their fertilizer application amount, especially if this advice contradicts FFP or RDF practices. In cases where farmers underutilize fertilizers, there may be multiple barriers to adoption outside of the farmer's immediate control, such as financial, credit, or input access constraints.

PxD Leaf Color Chart Pilot Project

To advance ways to scale SSNM adoption, in 2022, PxD conducted a pilot project with the existing decision support tool that is easiest to use: Leaf Color Charts. Farmers with minimal background knowledge of scientific processes can use an LCC, and its panels that range in the shade of green, to obtain customized and precise nitrogen fertilizer recommendations. However, the distribution of physical LCCs to farmers remains a challenge to widespread scale. PxD's pilot project thus focused on testing different LCC distribution pathways to understand how to increase its availability and usage.

PxD tested LCCs in Gujarat, India in the cotton cropping system. Cotton is one of India's most important commercial crops and requires several fertilizer applications, creating an ideal opportunity for a nitrogen fertilizer intervention. PxD piloted a light-touch intervention to encourage the use of LCCs with 830 cotton farmers and tested several different in-person distribution channels: (i) direct distribution by PxD staff, (ii) distribution by a partner non-governmental organization (NGO), (iii) distribution by local agro-dealers in an area, and (iv) distribution by LCC beneficiary farmers to their peers.

While this pilot project was designed to generate insights on barriers to adoption of LCCs, and to elicit farmer feedback, PxD also gathered indicative data on the intervention's impact on farmer and climate change mitigation outcomes (for an in-depth description of PxD's pilot project and analysis, see Appendix 2).

- Overall, PxD saw wide use of the tool, as more than half of the cotton farmers who received an LCC reported using the tool.

- PxD observed that distribution by agro-dealers and distribution by peer farmers, of LCCs accompanied by a context-specific instruction booklet, are especially promising distribution channels for LCCs in terms of the potential effect on farmer nitrogen use, LCC adoption, digital engagement, and accurate recall of LCC usage instructions.

- Calibration of existing LCCs for different locations is a critical product-development step. PxD piloted an LCC originally calibrated for a different Indian state, as PxD had found that the locations are close enough agroecologically so that the differences in nitrogen recommendations between the two were small and probably did not require the calibration to be Gujarat-specific. Further work, however, is required to understand the degree of differences in agroecological zones that will necessitate calibration and customization of LCCs from one location to another.

- PxD's end-of-the-season survey provides strong support for the theory of change that LCCs substantially reduce the use of nitrogen fertilizers without reducing yields. The farmers who received LCCs, on average, reported applying 35% less nitrogen fertilizers, and harvesting 11% more cotton, than those who did not receive LCCs. Among farmers who reported using the LCC (55% of the treatment group), average nitrogen fertilizer use was 64% less and yields 20% higher than those who did not.

- As a result of decreased nitrogen fertilizer use, based on PxD's previous data on the average cost of production of cotton in Gujarat, as described in Cole & Fernando (2021), PxD estimates farmers will experience at least a 4.3% decrease in their cost of production per acre if they receive an LCC compared to farmers who do not receive an LCC.

- Using a CGIAR customized version of the mini–Cool Farm Tool greenhouse gas calculator, PxD finds that this decrease in nitrogen use means farmers who received LCCs, on average, decreased greenhouse gas emissions by 0.3 metric tonnes CO_2-eq per hectare in a given cotton season compared to farmers who did not receive LCC's. These results are an average over everyone in the treatment group who used and did not use LCCs. Restricting the estimate to those who report using the LCC (55% of the treatment group), the tool's impact is a 0.55 metric tonnes CO_2-eq per hectare decline in total greenhouse gas emissions. It is important to keep in mind that emissions estimations from calculators like the Cool Farm Tool, by nature, come with a certain amount of uncertainty as they use general emissions factors and other generalized assumptions about greenhouse gas fluxes.

Another pathway to scale LCCs which PxD did not test, but merits additional research, is digital LCCs. Digital LCCs would be easy to use, compared to existing web and app-based tools which require complex inputs, and could leapfrog the distribution challenges of physical LCCs by using a distribution channel already in many farmers' pockets—a smartphone. While smartphone ownership in the smallholder farmer context is not yet widespread, ownership trends are increasing at a fast pace. For example, in India the rural and urban smartphone ownership gap is steadily narrowing with more than 30% of rural Indians owning smartphones compared to more than 50% of urban Indians in 2021. However, few examples of digital LCCs exist (for a list of existing examples, see Appendix 1), so there is little information on their ability to provide accurate nutrient management recommendations in real world settings, especially compared to physical LCCs. There is also a lack of evidence on how farmers interact with the tool and its levers for behavior change. Digital LCCs have high potential to scale due to the cost-effectiveness of digital communication, but additional research on the many logistical and operational questions which remain must occur in order to tap into that potential.

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To scale the SSNM approach, it will be critical to further develop the science of SSNM tools as well as the logistics of tool usage. Understanding the contextual fertilizer landscape as well as co-developing SSNM tools with the end user—farmers—in mind can help address some of these issues and should be a priority for those working with smallholder farmers and in sustainable development. Providing farmers with a way to use nitrogen more efficiently will not only help reduce the environmental impact of the use of nitrogen fertilizer in agriculture, but also improve farmers' productivity and profits. Addressing the precision nutrient gap can thus provide a win-win for both climate and antipoverty goals by helping farmers to use a critical farming input sustainably.

Appendix 1: SSNM Tool Landscape

A. Leaf Color Charts (LCCs)

An LCC—a plastic, ruler-shaped strip containing several panels in a range of the shade of green—is a low-cost, rule-of-thumb tool that has the advantage of being relatively easy to use and requires only a limited background knowledge of scientific processes, soil nutrient composition, and previous years' yields. There is substantial evidence that LCCs help farmers make real-time decisions on the efficient use of nitrogen fertilizers. A number of on-farm studies have demonstrated LCCs' benefits for productivity and profitability for rice, wheat, maize, and cotton (Table 4). In several studies, farmers obtained slightly higher yields, but with significantly less nitrogen applied, and thus saved money from the lower cost of inputs and decreased negative environmental impacts (Islam et al. 2007; Singh et al. 2007; Peng et al. 2010 in Table 4). Other studies assessing the impact of LCCs on experimental research farms also found positive effects from their use in maize, wheat, and cotton value chains (Bhatia et al. 2012; Singh et al. 2020 in Table 4). While there has been significant effort to create LCCs for South and Southeast Asian geographies, more testing and calibration, as well as on-farm trials, need to be conducted to create suitable LCCs for sub-Saharan African geographies.

Table 4: Impact Evidence of LCCs on Farmer and Environmental Outcomes

Study	**Study Type**	**Geography**	**Impact on Productivity**	**Impact on Farmer Profits**	**Impact on Fertilizer Application**
Islam et al., 2007	On-farm trials (n=388)	West Bengal, India	LCC adopters obtained slightly higher yields than non–adopters: 50 kg per ha additional paddy in the pre-kharif, 60 kg per ha in the kharif and 90 kg per ha in the boro seasons.*	Additional profits from yields were USD 6.80, USD 8.2, & USD 12.3 per ha in pre-kharif, kharif and boro seasons, respectively. The cost saving on fertilizer in monetary terms is USD 9.2 per ha in the boro, USD 6.6 per ha in the pre-kharif and USD 5.9 per ha in kharif season. The LCC adopters reduced insecticide sprays by 50%, which was significantly lower than the number of sprays they used to apply before the adoption of LCC (t = 30.32**, df = 147) as well as the number of sprays of those who did not adopt the LCC. Economic benefit of LCC adoption from reduced nitrogen fertilizer use, insecticide use, and increased yields taken together is estimated at USD 19.0 per ha in pre-kharif, USD 19.7 per ha in kharif and USD 27.0 per ha in boro season.*	Fertilizer N application was significantly reduced by 21% (31 kg N per ha or 68 kg urea per) in the boro season followed by 19.5% (23 kg N per ha or 49 kg urea per ha) in the pre-kharif season and 17% (20 kg N per ha or 44 kg urea per ha) in the kharif season.*
Pasuquin et al., 2014	On-farm (n=65)	Indonesia, Vietnam, and the Philippines	13% increase in maize yields (1.0 t/ha)*	A 15% increase in profits (USD 167/ha/crop) per season*	10% decrease in N fertilizer application* (~27kg/ha); NUE increased by 42%

Singh et al., 2020	Research farms at PAU	Punjab, India	LCC-use increased maize yields by 6-10% at LCC≤5.***	N/A	LCC-based N application lowered N_2O emissions by 7.3-7.8% at LCC≤5.***
Peng et al., 2010	On-farm trials (n=144)	China	5% increase in rice yields (7.08 t/ha to 7.47 t/ha)* 3% increase in rice yields with SSNM compared to fixed rate N treatments (7.45 t/ha to 7.69 t/ha)	N/A	32% decrease in N application* (from 195 kg/ha to 133 kg/ha) 29% decrease in N application compared to fixed rate N treatments (161 kg/ha to 120 kg/ha) Improved agronomic NUE by 61% and partial factor productivity of N by 43%*
Varinder-pal-Singh et al., 2007	On-farm trials (n=350)	Punjab, India	Rice yields were almost identical between FFP and LCC.	N/A	Decreased N fertilizer use by an average of 25%. LCC-based application required 36 kg/ha less N fertilizer on average. Increased NUE from 48 to 65 kg grain / kg N at LCC≤4 Increased PFP from 48.0 to 64.7 kg grain per kg applied N in rice
Pampolino et al., 2007	On-farm trials (n>120)	Southern India, the Philippines, and southern Vietnam	Rice yields increased by 17% and 2-10% in India and the Philippines, respectively (0.8 t/ha and 0.3 t/ha).* Rice yields in Vietnam were similar but increased slightly (0.2 t/ha).*	Farmer profits from using LCCs were USD 34/ha/yr, USD 106/ha/yr, and USD 168/ha/yr in Vietnam, the Philippines, and India, respectively.	N fertilizer use decreased by 10% in the Philippines and 14% in Vietnam.* N fertilizer application rates were similar or higher between SSNM and FFP, depending on the site in India.* Averaged across the Philippines and Vietnam, yield scaled GWP decreased by 56 kg CO_2-eq (carbon dioxide equivalent) Mg-1 grain, or a 22% reduction in CO_2-eq per unit of rice produced. In India, SSNM was able to increase yield with the same or increased rate of fertilizer N without additional N_2O emission per unit of grain yield or fertilizer used.
Bhatia et al., 2012	Experimental farm at ICAR	New Delhi, India	At LCC≤4, rice and wheat yields increased 12% and 14%, respectively, and at LCC≤5, rice and wheat yields increased 24% and 25%, respectively.**	N/A	LCC-based N application either the same as conventional application or increased by 30 kg/ha** N_2O emissions decreased by 7-16% and by 9-18% for rice and wheat, respectively.**
Gupta et al., 2022	Research farmers at PAU	Punjab, India	Cotton farmers were able to produce comparable yields with less N.	Similar yields with lower input costs will increase profits.	Farmers only used 60% of the recommended N but had comparable cotton yields. LCC-based N application lowered N_2O emissions by 66.8%.***

* compared to farmer fertilizer practice (FFP)
** compared to a recommended dose of fertilizer (RDF) / blanket fertilizer recommendations (BFR)
*** compared to soil-test based N recommendations

LCCs function as alternative physical tools to optical sensors, such as the Soil Plant Analysis Development (SPAD) meter or the GreenSeeker. Both SPAD and GreenSeeker are handheld crop sensors that assess crop health and allow farmers to have an accurate reading of nitrogen content in crop leaves. The high cost of SPAD and GreenSeeker (~USD 500 or more each) makes these technologies cost prohibitive for individual farmer use in many LMIC contexts. Farmer cooperatives or NGOs (non-governmental organizations) may be able to purchase chlorophyll meters for communal use, but scalability remains a challenge. Comparatively, LCCs are inexpensive (LCCs generally cost about USD 1) and easy to use without the need for internet connectivity and mobile phones.[48] Studies comparing chlorophyll meters and LCCs have shown that LCCs often lead to comparable yield increases in comparison to farmer practice and provide an accurate measurement of nitrogen leaf concentration in both rice and maize.[49]

However, LCCs still require farmers to calculate their nitrogen application based upon the LCCs' readings. While calculations are relatively easy, basic numeracy and simple instructions on LCC operation are necessary prior to use. In addition, some farmers have noted difficulty in assessing LCC color via the naked eye, and reported that the colors may fade over time with use or sun damage.[50] Despite being low cost, LCC adoption has not been as high as researchers predicted given their strong research results.

Future research should explore the moderate rate of adoption and implementation of LCCs. One study by the CGIAR, a global research partnership for a food-secure future, on willingness to pay (WTP) for climate smart agricultural technologies, with Indian farmers in a rice-wheat cropping system, ranks LCC WTP medium-low in comparison to other options.[51] In on-farm research trials of LCCs in rice production in Bangladesh, Islam et al. (2007) find that farmers were much more likely to adopt LCCs once they saw the yield and profit gains of their neighbors who were experimenting with LCCs. Farmers often started using LCC-based nutrient management in one section of their fields (about half of their land holdings) and would expand to their other farm plots as the technology proved effective. Younger, more educated farmers were much more likely to adopt LCCs and those farmers with less farming experience were also more comfortable trying LCCs to improve nutrient management practices.[52]

Digital LCCs are under development to both scale the existing technology and improve calibration in specific contexts for a wider range of crops and cropping systems. BaiKhao (meaning rice leaf in Thai) is a version of a digital LCC for rice production in Thailand, that remains under calibration.[53] The Philippine Rice Research Institute (PhilRice) has also developed a digital LCC for rice production called the Leaf Color Computing Application (PhilRice LCC App).[54] Several other ongoing projects are trying to digitize LCCs so that a smartphone would be able to scan and assess nitrogen applications and provide farmers with nutrient management guidance, without having to conduct their own calculations based on LCC readings; an example is Yara International's digital LCC within its FarmCare app.[55]

In an effort to make SSNM easier and more accessible to farmers, other digital tools have been developed to measure and calculate nitrogen applications based on a farmer's input data rather than on leaf color assessments. Decision support tools such as Rice Crop Manager (RCM), Nutrient Expert (NE), or RiceAdvice allow farmers to apply SSNM principles in their specific context without requiring numerous or detailed pieces of information that can be prohibitive. Unlike LCCs, these digital tools are free to download and use as long as the farmer has access to a computer or smartphone, and the ability to access the internet (or access these services through an agricultural extension agent).[56]

B. Rice Crop Manager (RCM)

Rice Crop Manager (RCM) is a web and app-based platform that provides customized nutrient management recommendations for rice farmers in Asia. The International Rice Research Institute, which developed the tool in coordination with partners, claims that through use of the tool farmers in India and the Philippines increased yields by an average of 0.5 and 0.4 tons per crop per hectare, respectively, which translates to an added net benefit increase of about USD 100/ha/cropping season for Filipino farmers and USD 150/ha/cropping season for Indian farmers.[57] On-farm trials with farmers applying nutrient management practices based on RCM also suggest how the tool increases productivity and profitability of farmers (Table 5).

Table 5: Impact Evidence of RCM on Farmer and Environmental Outcomes

Study	**Study Type**	**Geography**	**Impact on Productivity**	**Impact on Farmer Profits**	**Impact on Fertilizer Application**
Banayo et al., 2018	On-farm trials (n=93)	Northern Philippines	RCM increased rice yield by 6% (0.26 t/ha).*	Farmer profits increased by USD 154/ha.*	Fertilizer use decreased by 12%.*
Sharma et al., 2019	On-farm trials (n= 209)	Odisha, India	Rice yields were higher with RCM by 0.3-0.8 t/ha* and by 0.2-0.4 t/ha.**	Added net benefit was higher in RCM than FFP or BFR. By switching from FFP or BFR to RCM, the probability of earning at least USD 25/ha more was 79% and 32%, respectively.	N application was higher in RCM by 18–26 kg/ha.** RCM fertilizer application range (54–143 kg/ha) was much smaller than FFP (14–252 kg/ha).* RCM reduced P and K application as well.*

* compared to farmer fertilizer practice (FFP)
** compared to a recommended dose of fertilizer (RDF) or blanket fertilizer recommendation (BFR)

However, as with LCCs, adoption rates are lower than ideal, given the demonstrated benefits of using RCM. In the Philippines, RCM guidance failed to account for other ongoing projects or national initiatives, leading to confusing advice and mixed messages for farmers.[58] In addition, research from a series of interviews with Filipino farmers attributes barriers to adoption and implementation of RCM to social system issues, such as the lack of farmer resources, overstretched agricultural extension services, low ICT connectivity, and overlapping nutrient management advice.[59] These results suggest that widespread adoption of RCM (and other similar SSNM technologies) will succeed in contexts where farmers have adequate resources and sufficient social systems in place, but may not be as beneficial in contexts that lack these existing structures.

C. Nutrient Expert (NE)

Nutrient Expert is a computer-based site-specific nutrient management tool used for wheat, rice, maize, and twenty other crops in fourteen countries.[60] Like many other SSNM tools, NE allows farmers to calculate nutrient management from an online tool rather than having to calculate NPK applications using QUEFTS. Farmers' input into NE is information related to their environment (water availability and soil properties) and their practices (current yield and available inputs). Nutrient Expert has some of the most robust impact evidence of SSNM tools to date, which, like LCCs and RCM, show the productivity, profitability, and N_2O emission benefits of scaling this technology. Research on NE shows yield and profit increases in wheat, maize, and rice cropping systems in China, Nepal, Indonesia, the Philippines, and India over both FFP and RDF (Table 6).[61] Other studies in the Indo-Gangetic Plains also conclude that NE leads to lower GHG emissions in rice and wheat production compared to farmer practices.[62]

Other studies in India, the Philippines, and Indonesia noted mixed results on increasing or decreasing fertilizer quantity, but led to higher comparable yield increases.[63]

Table 6: Impact Evidence of NE on Farmer and Environmental Outcomes

Study	**Study Type**	**Geography**	**Impact on Productivity**	**Impact on Farmer Profits**	**Impact on Fertilizer Application**
Zhang et al., 2018	On-farm trials (n=315)	North-central China (Shanxi, Hebei, Shandong, and Henan Provinces)	NE increased yields from 7.9 Mg/ha with FFP to 8.1 Mg/ha (but with an average N fertilizer reduction of 279 kg/ha to 164 kg/ha).*	Fertilizer cost was lower with NE by USD 84/ha* and USD 40/ha.** Net return from NE ranged from 0.1–10.7%.	NE decreased N input by 41.4%, decreased P input by 30.1%, and increased K input by 51.5%.* NE-based N application decreased N_2O emissions by 54.8%* and 26.3%.** GHG emissions decreased by 44.8%* and 22.9%.**
Huang et al., 2021	Two 9-year field experiments	Northcentral and Northeast China (Hebei and Jilin Provinces)	NE increased maize yields by 3.9% and 6.9% (7.4 t/ha and 11.5 t/ha) in summer and spring maize systems, respectively.*	N/A	NE decreased N application by 21.4% and 25.6% in summer and spring maize, respectively.* NE-based fertilizer application led to 18.4% to 20.9% reduction in GHG emissions in summer and spring maize, respectively.*
Sapkota et al., 2021	On-farm trials (n=1594)	Indo-Gangetic Plains, India	Over 80% of farmers saw increased yields, with average yield increases of ~4% and ~5% for rice and wheat, respectively.*	Approximately half of farmers had higher total fertilizer costs, and half of the farmers reduced costs. Revenue from yield increased by ~5% and ~7% for wheat and rice, respectively.*	NE-based fertilizer management reduced N application by ~18% in rice-wheat systems (10% in EIGP and 25% in WIGP).* NE-based fertilizer application reduced GWP by 2.5% and 12–20% in rice and wheat, respectively.*

* compared to farmer fertilizer practice (FFP)
** compared to soil-test based N recommendations

D. RiceAdvice

RiceAdvice is an android-based decision support tool for nutrient management of rice cultivation in sub-Saharan Africa. Rice Advice is currently used in Benin, Burkina Faso, Ghana, Mali, Nigeria, and Senegal, with ongoing testing in 16 other African countries. Although RiceAdvice is fairly new, farmers report yield gains between 0.6 and 1.8 t/ha and higher profits of USD 100- 200 per ha.[64] In on-farm research from 368 farmers in Kano State, Nigeria, over 90% of surveyed farmers decreased nitrogen application by over 25%, and approximately 84% saw rice yield increases of 25% or more (Table 7). All farmers saw profitability increase by more than 25% (Table 7). However, less than a quarter of surveyed farmers owned an android phone, meaning that smartphone ownership and ICT literacy will pose a major challenge to scaling RiceAdvice. Another study in Kano state showed that farmers who used RiceAdvice saw yield increases of 7% and profit increases of 10% (Table 7). However, when farmers received their recommended fertilizer amount based on RiceAdvice calculations, yields and profits increased by 20% and 23% over FFP, respectively (Table 7). These results point to adoption and implementation challenges of SSNM tools in contexts where farmers do not have access to the desired quality and quantity of fertilizers to maximize yields. To date, studies have not assessed the impact of RiceAdvice on N-use efficiency or N_2O emissions.

Table 7: Impact Evidence of RiceAdvice on Farmer and Environmental Outcomes

Study	Study Type	Geography	Impact on Productivity	Impact on Farmer Profits	Impact on Fertilizer Application
Arouna et. al., 2021	Randomized control trial (n=700)	Kano State, Nigeria	7% increase in rice yields without 100% fertilizer subsidy*; 20% increase in rice yields with 100% fertilizer subsidy*	10% increase in profits without 100% fertilizer subsidy*; 23% increase in profits with 100% fertilizer subsidy*	With or without the fertilizer subsidy, fertilizer quantity used remained roughly the same.* However they tended to change the type of fertilizer used, decreasing NPK fertilizer use and maintaining or even increasing urea use.
Zossou et al., 2020	Semi-structured interviews, multi-stakeholder workshop, and in-depth interviews (n=368)	Kano State, Nigeria	84% of surveyed farmers saw rice yields increase 25% or more compared with before use of RiceAdvice	All farmers saw an increase in income of more than 25% compared with before use of RiceAdvice	90% of surveyed farmers decreased N application by over 25% compared with before use of RiceAdvice

* compared to recommended dose of fertilizer (RDF) / blanket fertilizer recommendation (BFR)

Appendix 2: PxD Leaf Color Chart Pilot Project Details

A. Pilot Project Objectives

Urea, the primary nitrogen fertilizer in India, is heavily subsidized and accounts for about 70% of India's total fertilizer subsidies. The subsidy on urea contributes to its overuse, leading to adverse environmental impacts like increased N_2O emissions and nitrate leaching, which increases soil and water toxicity. With increasing global urea prices, the Indian government is also spending significantly more on fertilizer subsidies.

A Leaf Color Chart (LCC) is a plastic, ruler-shaped strip containing several panels that range in the shade of green. Analysis from Islam and Beg (2020) demonstrated that LCCs could be a low-cost, rule-of-thumb tool to help farmers make real-time decisions on the efficient use of nitrogen fertilizers, and to increase profits in a setting where the government subsidizes such fertilizers. Islam and Beg (2020) assessed LCCs in the rice value chain, but LCCs can be applicable across value chains as long as they are appropriately calibrated and validated. However, LCCs are not widely available for any crop; there is correspondingly limited use of LCCs amongst smallholder farmers in India.

Cotton is one of India's most important commercial crops and requires several fertilizer applications, creating an ideal opportunity for LCC intervention. PxD implemented a project for cotton farmers in Gujarat, India, with the overall objective of exploring how to increase the availability and usefulness of LCCs in this context to improve farmers' decision-making on appropriate nitrogen use. PxD's pilot project contributes to the sparse literature on LCC impacts on farmer fertilizer management in the cotton value chain.

This pilot project aimed to:

1. Assess the appropriateness of the available cotton LCC for farmers in Gujarat with a **calibration and validation needs** assessment survey;
2. Identify the **critical barriers** to accessing, adoption of, and sustained use of LCCs;
3. Explore potential **distribution channels** to identify at least one viable and scalable delivery model of cotton LCCs to smallholder farmers;
4. Develop LCC **training materials and digital voice advisory** using human-centered design to support the effective use of LCCs, and pilot these materials with ~400 cotton farmers in two districts of Gujarat;
5. Gather insights on the effects of LCC on **key farmer outcomes** (nitrogen application quantities and yield), and the mechanisms of impact; and
6. Review the feasibility of **digital** LCCs.

B. Overview of Pilot Activities

Calibration and validation need assessment survey: PxD used the only commercially available physical LCC for cotton, produced by an Indian company, Nitrogen Parameters and developed by researchers at Punjab Agricultural University through agronomic trials in Punjab (Shankar et.al., 2019). Researchers typically develop LCCs for one location and crop variety; the LCCs often require calibration when scaled to another context (Shukla et al., 2004). To investigate if PxD needed to calibrate the LCC developed in Punjab for optimal recommendations for farmers in Gujarat, the project team consulted with several soil and LCC experts, such as from the International Rice Research Institute. The project team then conducted a calibration needs assessment survey with about 150 plots from mid-August to end-September 2022. During this calibration needs assessment survey, PxD collected nitrogen concentration readings from the leaves of 10 plants in each plot using a SPAD chlorophyll meter, and compared the SPAD readings to the corresponding closest LCC panel value of the leaves.

Scoping activities: In April and June 2022, PxD conducted a series of scoping surveys with farmers and agro-dealers in four districts of Gujarat. The surveys aimed to understand farmers' baseline nitrogen fertilizer use, and if their usage differed according to the farmer's socio-economic background, as well as according to the agro-dealer behavior, including which nitrogen fertilizers they typically stock and what kind of nitrogen fertilizer recommendations they provide farmers. The project team also collected qualitative feedback on agro-dealers and farmers' initial reactions to the LCC.

LCC distribution: PxD randomly assigned four types of LCC distribution methods at the village level, stratified by the district in which the village is and whether PxD's service penetration rate in the village is above or below the median. PxD assigned treatment randomly to infer results clearly and at the village level, as a few distribution types had a risk of spillovers. However, PxD aimed the pilot project at providing only preliminary insights on the efficacy of the different distribution channels, to rule out mechanisms that are unlikely to work and to gather qualitative insights on whether and how farmers use the tool. With only 32 villages in the pilot project, *ex-ante*, the project team do not have sufficient statistical power in the study to detect significant differences.

During May 2022, PxD tested the following LCC distribution mechanisms, as shown in Figure 1:

- PxD's staff distributed LCCs directly to 231 farmers by visiting farmers door-to-door; staff also ensured the accurate training of farmers on LCC usage.

- PxD partnered with a non-governmental organization, a local foundation with an extensive network of cotton farmers that they regularly interact with in-person, to distribute LCCs. PxD used a train-the-trainers model to ensure the foundation's staff could train farmers on LCC usage properly. The foundation distributed LCCs to 115 farmers and trained them during their village meetings.

- PxD's staff trained four agro-dealers to distribute LCCs to their customers since we confirmed through our scoping activities that agro-dealers are a primary source of information about the application of nitrogen fertilizer, for farmers. The agro-dealers distributed LCCs to 22 farmers.

- PxD distributed LCCs to 19 farmers and asked each of these farmers to distribute two additional LCCs to their peers. Thirty-one farmers in these villages received an LCC from their peers in the village. Through the pilot project, PxD also followed up with 412 control farmers who did not receive the LCC.

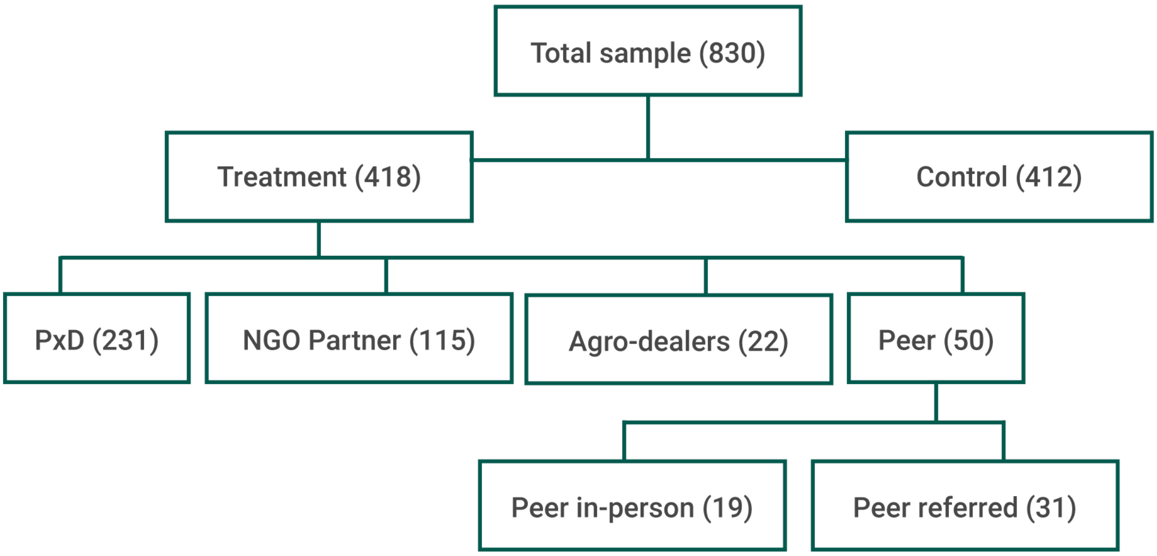

Figure 1: Treatment and control distribution arms of PxD's 2022 LCC pilot project in Gujarat, India

LCC training materials and digital advisory: PxD agronomists created an additional context-specific instruction booklet on LCC usage, which we provided to all farmers who received LCCs in our pilot project. PxD also created and delivered content over the phone to all farmers who received LCCs, to offer behavioral nudges on how and when to use LCCs. PxD sent these messages every week from the start of the sowing period in Gujarat, for three weeks.

Measuring nitrogen fertilizer use and other farming outcomes: PxD conducted a phone midline survey during August and September 2022, in-person focus group discussions and qualitative interviews during October 2022, and an in-person end-of-season survey during November 2022 to January 2023, to understand if LCC recipients changed their nitrogen use patterns, as well as the impact of nitrogen use on other farming outcomes.

Exploration of digital LCCs: Digital LCCs, which can provide accurate, real-time calculations and assessments, have the potential to leapfrog many of the distributional and usability challenges of physical LCCs by leveraging a distribution channel already in farmers' pockets—a smartphone. Digital LCCs are an emerging technology, and there are only a few examples of existing prototypes, including Yara

International's partnership with IRRI to develop rice and wheat digital LCCs within Yara's FarmCare app, as well as the BaiKhao app in Thailand, an Android-based digital LCC app in China, and the PhilRice LCC app in the Philippines. To assess whether PxD should pursue digital LCCs as a product offering on our services, PxD connected with the Yara/IRRI team to learn more about digital LCC creation requirements, and about any emerging evidence about the potential of digital LCCs to help scale LCC usage. These learning calls occurred toward the end of the pilot project timeframe in October 2022.

C. Insights from Pilot Activities

Insights form calibration and validation needs assessment survey: While the cotton LCC developed for Punjab does differ from what the LCC developed for Gujarat would ideally recommend, the differences in recommendations are small.

To understand LCC calibration needs, PxD estimated the linear relationship between the values of the SPAD chlorophyll meter reading and LCC panel using the data from the calibration needs assessment survey in Gujarat. PxD then compared this estimated linear relationship with the linear relationship between the two estimated for Punjab in Shankar, Gupta, and Singh (2019). The two relationships are close, but the urea recommendations in the Punjab LCC may be lower than optimal for Gujarat. However, as PxD did not observe a decrease in yield for those in the LCC treatment group who report using it, the difference in optimal recommendations is possibly slight, and the additional costs of precise calibration with further field testing and increased production costs are unlikely to make a substantial difference in actual farmer outcomes.

Insights from scoping activities: Overuse of nitrogen fertilizer is prevalent amongst Gujarat cotton farmers due to both social and environmental factors.

Farmers typically rely on their own and other farmers' experience, and on agro-dealers to determine how and when to use nitrogen fertilizers. Farmers typically use their accumulated judgment to assess the greenness of their crop or compare the greenness of their crop to other farmers' crops to determine whether their own crop requires more nitrogen, similar to the LCC concept. The peer comparison behavior often leads to competition for the "healthier" looking plant and thus to excessive nitrogen use.

According to the government's urea recommendation and the maximum urea recommended by presently available LCCs, any farmer applying more urea than 100 kg/acre is overusing nitrogen, regardless of the baseline soil quality. PxD finds that at least 28% of the farmers are overusing urea by this standard; this is not accounting for farmers whose optimal urea requirement, given the soil quality of their field, is less than the maximum of 100 kg/acre.

Feedback during the scoping surveys suggests that poorer farmers know they are probably underusing nitrogen fertilizers rather than overusing them. Their willingness to use an LCC was low as they did not see a clear benefit from its use. However, there are existing rice LCCs that inform the farmer of both the additional nitrogen needed for a given leaf color and the expected yield from applying it. A cotton LCC that similarly describes both the cost and benefit of their behavior change may be a more helpful tool to optimize poorer farmers' nitrogen use.

Insights from the various distribution methods: The most effective, scalable distribution channels for LCC adoption and accurate recall of LCC usage instructions are distribution by agro-dealers and by peer farmers.

Relative to the benchmark in-person distribution by PxD staff, distribution by agro-dealers and peer farmers showed promise for LCC adoption. Partnering with an NGO was not very successful, although our partner could distribute large quantities of LCC compared with other indirect channels. Qualitative surveys reveal that farmers who received LCCs from the NGO partner were less likely to recall having received the LCC, and had extremely poor recall of how to use the tool. In comparison, 93% of the farmers who received LCCs through PxD, agro-dealers or peer farmers recalled receiving the LCC, with 82% having it at the end of the pilot project (self-reported), and 54% using it during the season (self-reported). Farmers who received an LCC from the partnering NGO had the lowest engagement with the digital extension service as well (average LCC call pick-up rates of 60%) compared to those who received LCCs from PxD, peer farmers or agro-dealers (average LCC call pick-up rates of 75 to 85%). From both the quantitative data and qualitative surveys, we find that farmers who received LCCs from agro-dealers and peer farmers had higher average nitrogen use and are more educated at baseline than those receiving LCCs directly from PxD. This pattern suggests that local agents such as agro-dealers and farmers may be more effective at identifying and reaching farmers who are more likely to use and benefit from the LCCs, such as those who can read, those with high nitrogen use patterns, or those who are more willing to try new technologies.

Insights from LCC training materials and digital advisory: LCC instructions tailored to the farmer's specific context, e.g., local measurement units, make the tool more approachable and usable.

When PxD tested context-specific materials during scoping, PxD found that farmers with the complementary booklet of context-specific instructions were 10% more willing to use the tool than farmers who only had the instructions at the back of the LCC. The average ease of understanding rating was 4.5 out of 5 for farmers with the booklet compared to 3.9 out of 5 for farmers without the booklet. PxD experimentally varied the use of the booklet to explain the LCC with only a small number of farmers (52) during scoping, and the results were not statistically significant. However, due to the booklet's qualitative success during scoping, PxD disseminated these context-specific booklets to all farmers who received LCCs in the pilot project.

Measuring nitrogen use and other farming outcomes: Cotton farmers who received an LCC used 15% less nitrogen on average. The effect is driven by decreases in fertilizer use by those farmers who were overusing it at baseline.

PxD finds that cotton farmers who received an LCC used 35% less nitrogen on average than those who did not. For farmers who report using the LCC (55% of the treatment group), PxD finds a 64% decrease in nitrogen use, which is statistically significant. PxD also finds a smaller positive and statistically insignificant effect on yield. For farmers who received the LCC, PxD found an 11% increase in average yields compared with those who did not and, for farmers who used the LCC, PxD found a 20% increase in average yields compared to those who did not. Similar to Islam and Beg (2020), PxD interprets these results to indicate LCCs can lead to a reduction in nitrogen use without negative effects on yield.

As a result of decreased nitrogen fertilizer use, based on PxD's previous data on the average cost of production of cotton in Gujarat, as described in Cole and Fernando (2021), PxD estimates these results will translate to a decline of at least 4.3% in the cost of production per acre from the direct reduction in the use of urea if farmers receive an LCC. Restricting the estimate to those who report using the LCC, the estimated lower bound of reduction in cost of production is 7.8%. The decrease in nitrogen is at least in-part because farmers who received the LCC delay the first application to later crop stages when the plant absorbs more nitrogen than in earlier stages, which decreases wastage.

PxD partnered with scientists at the International Rice Research Institute to use a CGIAR customized version of the mini–Cool Farm Tool (CFT) greenhouse gas calculator to estimate changes in greenhouse gas emissions at the farm level from PxD's LCC intervention. The CFT found that, for farmers who received LCCs, on average, greenhouse gas emissions decreased by 0.3 metric tonnes CO_2-eq per hectare in a given cotton season compared to farmers who did not receive them. These results are an average over everyone in the treatment group who used and did not use LCCs. Restricting the estimate to those who report using the LCC (55% of the treatment group), the tool's impact is an estimated 0.55 metric tonnes CO_2-eq per hectare decline in total greenhouse gas emissions. It is important to keep in mind, however, that emissions estimations from calculators like the Cool Farm Tool, by nature, come with a certain amount of uncertainty as they use general emissions factors and other assumptions about greenhouse gas fluxes.

Insights on digital LCCs: Digital LCCs can be a cost-effective way to scale LCC use, but there are many logistical and operational questions which must be addressed in order to tap into their potential.

Preliminary findings from existing digital LCCs point to the successful calibration of digital LCC tools. Their accuracy in determining leaf color levels is between 85 and 96%, a range comparable to that of chlorophyll meters, which are a standard measurement tool for leaf color levels (Tao et al., 2020). There is still room for improvement in calibration and testing, as varying light conditions and camera quality in farmers' fields could negatively affect the quality of the digital LCC's nutrient management recommendations (Tao et al., 2020). However, due to the emerging nature of digital LCCs, there is little information on their ability to provide accurate nutrient management recommendations in real-world settings (including differences in lighting, camera pixel quality, and image angle, among other factors), especially compared with physical LCCs. There is also limited information on how farmers interact with the tool, and its leverage for behavior change.

For more information about PxD's Leaf Color Chart pilot project and our analysis, including data replication files, please reach out at info@precisiondev.org.

References

1 Environmental Protection Agency, *Understanding Global Warming Potentials*, (*last visited* 18 December 2022). ("The Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2).").

2 Environmental Protection Agency, *Understanding Global Warming Potentials*, (*last visited* 18 December 2022). ("The larger the GWP, the more that a given gas warms the Earth compared to CO2 over that time period. The time period usually used for GWPs is 100 years.").

3 Environmental Protection Agency, *Understanding Global Warming Potentials*, (*last visited* 18 December 2022). ("For example, the 20-year GWP is sometimes used as an alternative to the 100-year GWP. Just like the 100-year GWP is based on the energy absorbed by a gas over 100 years, the 20-year GWP is based on the energy absorbed over 20 years. This 20-year GWP prioritizes gases with shorter lifetimes, because it does not consider impacts that happen more than 20 years after the emissions occur. Because all GWPs are calculated relative to CO_2, GWPs based on a shorter timeframe will be larger for gases with lifetimes shorter than that of CO_2, and smaller for gases with lifetimes longer than CO_2. For example, for CH_4, which has a short lifetime, the 100-year GWP of 27–30 is much less than the 20-year GWP of 81–83. For CF_4, with a lifetime of 50,000 years, the 100-year GWP of 7380 is larger than the 20-year GWP of 5300.").

4 Environmental Protection Agency, *Understanding Global Warming Potentials*, (*last visited* 18 December 2022). ("CO_2, by definition, has a GWP of 1 regardless of the time period used, because it is the gas being used as the reference.").

5 Intergovernmental Panel on Climate Change (2018) *Annex I: Glossary* in Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, Masson-Delmotte, V., et al. (eds.), 541–562, 554 ("Mitigation (of climate change) A human intervention to reduce emissions or enhance the *sinks* of *greenhouse gases*.").

6 United States Department of Agricultural and Natural Resources Conservation Service (2007) Nutrient Management Technical Note No. 6: Nitrogen Efficiency and Management, 3 ("Nitrogen use efficiency is defined as the ratio of the crop nitrogen uptake, to the total input of nitrogen fertilizer.")

7 Dobermann A. R. (2005) Nitrogen Use Efficiency – State of the Art, Agronomy & Horticulture - Faculty Publications 316: 1–16 (See Table 1).

8 McLellan E. L., Cassman K. G., Eagle A. J., Woodbury P. B., Sela S., Tonitto C., Marjerison R. D., & van Es H. M. (2018) *The Nitrogen Balancing Act: Tracking the Environmental Performance of Food Production*, BioScience 68(3): 194–203, 195 ("Nitrogen balance is defined as the difference between N inputs to, and N removed in products from, an agricultural system. At the spatial scale of a single production field, for example, N balance can be calculated from records of inorganic and organic nutrient applications and crop yield…Nitrogen balance for a field, as defined above, is a measure of the extent to which anthropogenic N supply exceeds crop needs.").

9 Robertson G. P. & Groffman P. M. (2015) Nitrogen Transformations, in Soil Microbiology, Ecology and Biochemistry: 421–446, 422 ("(1) N mineralization, which is the conversion of organic-N to inorganic forms; (2) N immobilization, which is the uptake or assimilation of inorganic N forms by

microbes and other soil organisms; (3) nitrification, which is the conversion of ammonium (NH+4) to nitrite (NO2) and then nitrate (NO3); and (4) denitrification, which is the conversion of nitrate to nitrous oxide (N2O) and to dinitrogen gas (N2).”).

10 Figure SPM.2 in Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., et al. (eds.).

11 Nabuurs, G. et. al. (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)*, in Climate Change 2022: Mitigation of Climate Change, Angers, D. & Ravindranath, N.H. (eds.), (“A recent comprehensive review confirms agriculture as the principal driver of the growing atmospheric N_2O concentration (Tian et al. 2020). The latest FAOSTAT data (FAO 2020b, 2021a) document a 25% increase in AFOLU N_2O emissions between 1990 and 2019, with the average share from agriculture remaining approximately the same (96%).”).

12 Tian, H., et al. (2020) *A Comprehensive Quantification of Global Nitrous Oxide Sources and Sinks*, Nature 586: 248–256, 249 (“Up to 87% of this increase results from direct emission from agriculture (71%) and indirect emission from anthropogenic nitrogen additions into soils (16%).”).

13 Park S., Croteau P., Boering K. A., Etheridge D. M., Ferretti D., Fraser P. J., Kim K.-R., Krummel P. B., Langenfelds R. L., van Ommen T. D., Steele L. P., & Trudinger C. M. (2012) *Trends and seasonal cycles in the isotopic composition of nitrous oxide since 1940*, Nat. Geosci. 5(4): 261–265, 261 (“This result confirms that the increase in the atmospheric N_2O burden is largely due to nitrogen-based agricultural fertilizer use: when fertilizer is plentiful, the enzyme kinetics of the microbial N_2O production processes favour N (ref. 13), making the N_2O emitted isotopically lighter than in natural or unfertilized agricultural soils.”).

14 Chivenge P., Saito K., Bunquin M. A., Sharma S., & Dobermann A. (2021) *Co-benefits of nutrient management tailored to smallholder agriculture*, Glob. Food Secur. 30(100570): 1–8, 1 (“Relative to the farmer practice, across all crops SSNM increased grain yield by 12% and profitability by 15% with 10% less fertilizer nitrogen applied, thereby improving nitrogen use efficiency and reducing nitrogen pollution to the environment.”).

15 Reay D. S., Davidson E. A., Smith K. A., Smith P., Melillo J. M., Dentener F., & Crutzen P. J. (2012) *Global agriculture and nitrous oxide emissions*, Nat. Clim. Change 2(6): 410–416, 412 (“Overall, N_2O emissions associated with agriculture (including human sewage) are projected to rise from around 6.4 Tg N_2O-N yr^{-1} in 2010 to 7.6 Tg N_2O-N yr^{-1} by 2030[10] (Fig. 1), with much of this growth resulting from increased nitrogen-fertilizer use in non-OECD Asia, Latin America and Africa.”).

16 Grubb, M., *et. al.* (2022) *Chapter 1: Introduction and Framing*, in Climate Change 2022: Mitigation of Climate Change, Idris, I.E. & Lowe, J. (eds.), 1-23 (“FOOTNOTE 5: AFOLU accounted for about 13% of CO_2, 44% of CH_4 and 82% of N_2O global anthropogenic GHG emissions in 2007-2016 (SRCCL SPM A3).”).

17 Nabuurs, G. *et. al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)*, in Climate Change 2022: Mitigation of Climate Change, Angers, D. & Ravindranath, N.H. (eds.), 7-6 (“Agricultural CH_4 and N_2O emissions are estimated to average 157 ± 47.1 MtCH_4 yr^{-1} and 6.6 ± 4.0 MtN_2O yr^{-1} or 4.2 ± 1.3 and 1.8 ± 1.1 GtCO_2-eq yr^{-1} (using IPCC AR6 GWP100 values for CH4 and N_2O) respectively between 2010 and 2019.”).

18 Tian H., et al. (2020) *A comprehensive quantification of global nitrous oxide sources and sinks*, Nature 586(7828): 248–256, 252 (“High direct agricultural N2O emissions can be attributed to the large-scale application of synthetic nitrogen fertilizers in East Asia, Europe, South Asia and North

America, which together consume over 80% of the world's synthetic nitrogen fertilizers.").

19 Our World in Data (2014) Nitrogen use efficiency, (*See* Table 1: Results from Table 1 indicated that cereal NUE in 2014 was 71.61%, 32.02%, 34.34% for the United States, China, and India, respectively.)

20 Chand R. & Pandey L. M. (2009) *Fertiliser Use, Nutrient Imbalances and Subsidies: Trends and Implications*, MARGIN J. APPL. ECON. RES. 3(4): 409–432, 431 ("The study found that distortions in the pricing of N, P and K (caused largely by the increase in the subsidy to nitrogenous fertiliser) worked as a major setback to the reduction in these imbalances.").

21 Praveen K. V., Aditya K. S., Nithyashree M. L., & Sharma A. (2017) *Fertilizer subsidies in India: an insight to distribution and equity issues*, J. CROP AND WEED 13(3): 1–31, 30 ("Urea however still remains as a statutorily controlled fertilizer and the price is fixed by government. The subsidy in respect of non-urea fertilizers under NBS are fixed on annual basis based on their nutrient content.").

22 Chand R. & Pandey L. M. (2009) *Fertiliser Use, Nutrient Imbalances and Subsidies: Trends and Implications*, MARGIN J. APPL. ECON. RES. 3(4): 409–432, 422 ("Over the last 27 years, the nominal price of N has increased by about 4 per cent, against a 7 per cent increase in the nominal prices of P and K.").

23 National Academy of Agricultural Sciences (2009) *Crop Response and Nutrient Ratio, Policy Paper No.42,* 1–16, 1, 1–2 ("A NPK ratio of 4:2:1 (N:P2 O5 :K2 O) is generally considered ideal and accepted for macro-level monitoring of consumption of plant nutrients for the country as a whole. However, it is difficult to trace the genesis of this NPK ratio."); *and* ("This was Pre-Green Revolution era and only small amounts of fertilizer were used by farmers. Thus the doses were 22.4 to 44.8 kg N/P2 O5 /K2 O per hectare. The data obtained from these on-farm trials showed that increase in yield and response to N was much more than that to P or K, and that the response to combined application of NPK was not positive or even additive. A close examination of these data also showed that in irrigated wheat the All India average increase in yield due to N, P and K fertilization was 3.7, 2.3 and 1.4 q/ha respectively, while in rice it was 3.0, 2.2 and 1.4 q/ha, respectively. This made fertilizer N very popular with the farmers. Probably some of these data played a key role in deciding upon the NPK* ratio of 4:2:1.").

24 Chivenge P., Zingore S., Ezui K. S., Njoroge S., Bunquin M. A., Dobermann A., & Saito K. (2022) *Progress in research on site-specific nutrient management for smallholder farmers in sub-Saharan Africa*, FIELD CROPS RES. 281(108503): 1–11, 2 ("The main drawback of blanket fertilizer recommendations is their failure to account for the high spatial soil fertility variability that is common in smallholder farming systems. Such variability has been linked to inherent soil fertility differences or differences induced by management practices. Another problem is that some soils require that other constraints be addressed first, before any yield responses to nutrient additions are observed.").

25 Chand R., & Pavithra S. (2015) *Fertiliser Use and Imbalance in India*, ECON. POLIT. WKLY 50(44): 7, 98–104, 99 ("The paper makes an attempt to estimate the optimal ratio of N, P, and K for the prevalent cropping pattern in India based on crops and state-specific recommendations for fertilizer application prepared by various state agricultural universities (SAUs) and crop directorates of Indian Council of Agricultural Research (ICAR). Further, as the requirement of N, P and K varies from crop to crop and from one type of soil to another type, the norm for N, P and K ratio is bound to be different for different regions representing different cropping patterns, soil types, and their nutrient status at a given point of time.").

26 Masso C., Baijukya F., Ebanyat P., Bouaziz S., Wendt J., Bekunda M., & Vanlauwe B. (2017) *Dilemma of nitrogen management for future food security in sub-Saharan Africa – a review*, SOIL RES. 55(6): 425–434, 429 ("In addition to applying the right rate of N in the context of ISFM, timing of N

fertiliser including split applications, can both improve yields and protein content (Table4). Effective split application reduces N losses as the timing and rate for each application are adjusted to target the various demand peaks for N by the crop of interest during the growing season. Conversely, utilisation of high N rates to meet the crop N requirement in one single application generally results in increased N leaching and reduced crop REN (Fig.9).").

27 Dobermann A., et al. (2002) *Site-specific nutrient management for intensive rice cropping systems in Asia*, Field Crops Res. 74(1): 37–66, 39 ("We defined site-specific nutrient management (SSNM) as the dynamic, field-specific management of nutrients in a particular cropping season to optimize the supply and demand of nutrients according to their differences in cycling through soil-plant systems (Dobermann and White, 1999).").

28 Pasuquin J. M., Pampolino M. F., Witt C., Dobermann A., Oberthür T., Fisher M. J., & Inubushi K. (2014) *Closing yield gaps in maize production in Southeast Asia through site-specific nutrient management*, Field Crops Res. 156: 219–230, 228 ("This led to a more balanced NPK nutrition in the SSNM treatment resulting in more vigorous plant growth, and probably also greater resistance to diseases, and increased nutrient use efficiency.")

29 Chivenge P., Zingore S., Ezui K. S., Njoroge S., Bunquin M. A., Dobermann A., & Saito K. (2022) *Progress in research on site-specific nutrient management for smallholder farmers in sub-Saharan Africa*, Field Crops Res. 281(108503): 1–11, 2– 3 ("The SSNM approach is a dynamic, plant-based, field- and seasonspecific nutrient management approach that aims to synchronize nutrient supply and demand according to differences in crop requirements, indigenous nutrient supply (INS), and nutrient recovery from fertilizer and other sources (Dobermann and White, 1998; Dobermann et al., 2002, 2004). It was developed by researchers of the International Rice Research Institute (IRRI) and their national partners in Asia in the 1990's to address spatial variability in soil fertility and response to fertilizer application in smallholder rice farming systems (Fig. 1).").

30 Richards M. B., Butterbach-Bahl K., Jat M. L., Lipinski B., Ortiz-Monasterio I., & Sapkota T. (2015) *Site-Specific Nutrient Management: Implementation guidance for policymakers and investors*, Practice Brief, Global Alliance for Climate-Smart Agriculture, 1–10, 2 ("Right product: Match the fertilizer product or nutrient source to crop needs and soil type to ensure balanced supply of nutrients. Right rate: Match the quantity of fertilizer applied to crop needs, taking into account the current supply of nutrients in the soil. Too much fertilizer leads to environmental losses, including runoff, leaching and gaseous emissions, as well as wasting money. Too little fertilizer exhausts soils, leading to soil degradation. Right time: Ensure nutrients are available when crops need them by assessing crop nutrient dynamics. This may mean using split applications of mineral fertilizers or combining organic and mineral nutrient sources to provide slow-releasing sources of nutrients. Right place: Placing and keeping nutrients at the optimal distance from the crop and soil depth so that crops can use them is key to minimizing nutrient losses. Generally, incorporating nutrients into the soil is recommended over applying them to the surface. The ideal method depends on characteristics of the soil, crop, tillage regime and type of fertilizer.").

31 Richards M. B., Butterbach-Bahl K., Jat M. L., Lipinski B., Ortiz-Monasterio I., & Sapkota T. (2015) *Site-Specific Nutrient Management: Implementation guidance for policymakers and investors*, Practice Brief, Global Alliance for Climate-Smart Agriculture, 1–10, 1 ("Site-Specific Nutrient Management (SSNM) provides guidance relevant to the context of farmers' fields. SSNM maintains or enhances crop yields, while providing savings for farmers through more efficient fertilizer use. By minimizing fertilizer overuse, greenhouse gas emissions can be reduced, in some cases up to 50%.").

32 Pasuquin J. M., Pampolino M. F., Witt C., Dobermann A., Oberthür T., Fisher M. J., & Inubushi K. (2014) *Closing yield gaps in maize production in Southeast Asia through site-specific nutrient management*, Field Crops Res. 156: 219–230, 226 ("Large reductions in total fertilizer N use with SSNM

contributed to the overall higher AEN compared to FFP. A more balanced NPK nutrition in the SSNM might have also led to increases in AEN through more vigorous plant growth and greater resistance to diseases.").

33 Chivenge P., Saito K., Bunquin M. A., Sharma S., & Dobermann A. (2021) *Co-benefits of nutrient management tailored to smallholder agriculture*, GLOB. FOOD SECUR. 30(100570): 1–8, 3 ("Some studies have shown that increased yield and PFP N with SSNM were associated with a reduction in insect and disease damage and improved lodging resistance of rice crop (Sta Cruz et al., 2007; Peng et al., 2010). Surplus N causes excessive vegetative growth, which makes crops prone to lodging, and pest and disease attack.").

34 Dunn B. and Dunn T. (2017) *Lodging in rice*, NSW DEPARTMENT OF PRIMARY INDUSTRIES PRIME-FACT 1561: 1–4, 1 ("Lodging occurs when plant stems weaken to the point they can no longer support the weight of the grain causing it to fall over. As growers push for maximum grain yield, lodging is becoming a significant factor in rice production, increasing the time and cost of harvest and often resulting in significant yield loss.").

35 Shah L. et al. (2019) *Improving Lodging Resistance: Using Wheat and Rice as Classical Examples* INT. J. MOL. SCI. 20(17): 4211, 1–39, 1 ("One of the most chronic constraints to crop production is the grain yield reduction near the crop harvest stage by lodging worldwide. This is more prevalent in cereal crops, particularly in wheat and rice.").

36 Wang G., Zhang Q. C., Witt C., & Buresh R. J. (2007) *Opportunities for yield increases and environmental benefits through site-specific nutrient management in rice systems of Zhejiang province, China*, AGRIC. SYST. 94(3): 801–806, 805 ("The agronomic N use efficiency was 80% higher with SSNM than with FFP. About 30–50% of fertilizer N used in current rice production could be reduced through adoption of SSNM, which, in return, reduces the risk of pollution from rice fields (Wang et al., 2001b, 2004). Because of the substantial reduction of fertilizer N application at early growth stages with SSNM, less vegetative growth occurs early in the season improving micro-climate and canopy formation in SSNM plots. As a consequence, fewer pesticides are needed because the rice crop is more healthy with SSNM, for instance, reducing the risk of sheath blight disease (Sta. Cruz et al., 2001).").

37 Chivenge P., Saito K., Bunquin M. A., Sharma S., & Dobermann A. (2021) *Co-benefits of nutrient management tailored to smallholder agriculture*, GLOB. FOOD SECUR. 30(100570): 1–8, 6 ("However, a few available impact assessment studies of SSNM with thousands of smallholder farmers have also shown grain yield improvements of 2–17% and profitability increases of 4–48% (SI Table 4), which is comparable to the results of our meta-analysis.").

38 Peter C., Fiore A., Hagemann U., Nendel C., & Xiloyannis C. (2016) Improving the accounting of field emissions in the carbon footprint of agricultural products: a comparison of default IPCC methods with readily available medium-effort modeling approaches, INT. J. LIFE CYCLE ASSESS. 21(6): 791–805, 792. ("For the accounting of field emissions at country level, the IPCC guidelines for National GHG Inventories (IPCC 2006a) provide, in the fourth volume dedicated to Agriculture, Forestry and Other Land Use sector (AFOLU), three calculation pathways (Tiers) characterized by different degrees of complexity: Tier 1 includes low-accuracy methodologies, which can be applied by using the default emission factors provided by the IPCC; Tier 2 methodologies require the use of national emission factors reflecting local pedo-climatic characteristics; finally, Tier 3 methodologies are based on model simulations or in situ measurements.")

39 Peter C., Fiore A., Hagemann U., Nendel C., & Xiloyannis C. (2016) Improving the accounting of field emissions in the carbon footprint of agricultural products: a comparison of default IPCC methods with readily available medium-effort modeling approaches, INT. J. LIFE CYCLE ASSESS. 21(6): 791–805, 792. ("However, Tier 1 methodologies are intended for use at large spatial scales, and they can generate

substantial errors in predictions at finer spatial scales. In fact, at regional and sub-regional levels, Tier 1 methods are not always sufficiently accurate to account for the spatial variability of GHG emissions due to different soil, climate, and management practices.”)

40 Zhao Z., Cao L., Deng J., Sha Z., Chu C., Zhou D., Wu S., & Lv W. (2020) *Modeling CH4 and N2O emission patterns and mitigation potential from paddy fields in Shanghai, China with the DNDC model*, AGRIC. SYST. 178(102743): 2. (“The DNDC model has incorporated a relatively complete suite of biophysical and biogeochemical processes, which enables the DNDC model to simulate crop growth, soil C and N dynamics, and GHG emissions in agroecosystems.”)

41 Richards M. B., Butterbach-Bahl K., Jat M. L., Lipinski B., Ortiz-Monasterio I., & Sapkota T. (2015) *Site-Specific Nutrient Management: Implementation guidance for policymakers and investors,* Practice Brief, GLOBAL ALLIANCE FOR CLIMATE-SMART AGRICULTURE, 1–10, 2 (“The principles, called the ‘4 Rs’, date back to at least 1988 and are attributed to the International Plant Nutrition Institute (Bruulselma et al. 2012).”).

42 Janssen B. H., Guiking F. C. T., van der Eijk D., Smaling E. M. A., Wolf J., & van Reuler H. (1990) *A system for quantitative evaluation of the fertility of tropical soils (QUEFTS)*, GEODERMA , 46(4): 299–318, 300 (“QUEFTS: Quantitative Evaluation of the Fertility of Tropical Soils. In the system, chemical soil fertility is conceived as the capacity of a soil to provide plants with nutrients. In many unfertilized soils, crop growth is limited by a low supply of one or more of the major nutrients N, P and K, while there is a relatively ample supply of secondary and trace elements. Therefore the QUEFTS system is as yet restricted to an appraisal of the status of N, P and K. Yields are calculated as a function of the availability of these nutrients.”). *See also* Chivenge P., Saito K., Bunquin M. A., Sharma S., & Dobermann A. (2021) *Co-benefits of nutrient management tailored to smallholder agriculture*, GLOB. FOOD SECUR. 30(100570): 1–8, 1 (“The science behind SSNM was initially based on a stepwise model that allows calculating the required nitrogen (N), phosphorus (P), and potassium (K) amounts to attain a targeted yield, with additional rules for the timing and in-season adjustment of fertilizer applications.”).

43 Richards M. B., Butterbach-Bahl K., Jat M. L., Lipinski B., Ortiz-Monasterio I., & Sapkota T. (2015) *Site-Specific Nutrient Management: Implementation guidance for policymakers and investors*, Practice Brief, GLOBAL ALLIANCE FOR CLIMATE-SMART AGRICULTURE, 1–10, 5 (“Optical sensors measure reflectance from the leaves to generate a vegetative index called NDVI (Normalized Difference Vegetation Index), which measures the nutrient status of the plants based on their size and color (green versus yellow). The original technology was developed for large farms; however, a small handheld version that costs a fraction of the original technology (approximately USD 500) is now commercially available (Crain et al. 2012).”).

44 Manalo J. A., Pasiona S. P., & Bautista A. M. F. (2022) *Understanding the complexities in the adoption of the Rice Crop Manager tool in the Philippines*, INT. J. AGRIC. SUSTAIN. 20(4): 381–392, 381 (“Overall, we argue that there is a need to tackle social system and socio-technical issues relating to RCM adoption. Examples of social system issues include the lack of resources of farmers and poor internet connectivity; of sociotechnical issues are conflict with existing initiatives and overwhelming administrative issues in the local agriculture offices. Among the recommendations to improve RCM uptake in the Philippines are addressing the work overload issue of AEWs, improving rural internet access, and integrating a multi-sectoral agriculture extension system.”).

45 Chivenge P., Zingore S., Ezui K. S., Njoroge S., Bunquin M. A., Dobermann A., & Saito K. (2022) *Progress in research on site-specific nutrient management for smallholder farmers in sub-Saharan Africa*, FIELD CROPS RES. 281(108503): 1–11, 8 (“It is clear that SSNM research and dissemination efforts in the public sector need to be strengthened in SSA. Furthermore, business models that enhance the dissemination of SSNM and the associated digital tools together with private sector engagement are needed to

promote farmer adoption. Strengthening the financial services to smallholder farmers and input supply systems, and reducing farmers' uncertainty about variability of market prices could help scaling of SSNM."). *See also* Manalo J. A., Pasiona S. P., & Bautista A. M. F. (2022) *Understanding the complexities in the adoption of the Rice Crop Manager tool in the Philippines*, Int. J. Agric. Sustain. 20(4): 381–392, 387 ("A number of administrative issues were shared by the key informants during the interviews. These issues resulted in delays in implementation and added stress in their operations. The informants noted delays in the release of funds prior to the project take-off and in the delivery of gadgets. They also raised the issue that when some of these gadgets came, they were expensive to maintain. For example, a key informant said that it was so costly to print a colored recommendation, which is an important point as some local governments are very poor.").

46 Amgain L., Timsina J., Dutta S., & Majumdar K. (2021) *Nutrient expert ® rice - an alternative fertilizer recommendation strategy to improve productivity, profitability and nutrient use efficiency of rice in Nepal*, J. Plant Nutr. 44(15): 1–16, 1 ("Due to large variations in slope, altitude, soil, and management, performance of NEVR varied across locations. Its performance was better in Terai due to flat lands and less variations in soil types, compared to sloping lands and varied soils of mid-hills. NE tool provided adequate guidance to apply the required rate of fertilizer that matched the crop requirement and soil nutrient supply of each farmer fields.").

47 Manalo J. A., Pasiona S. P., & Bautista A. M. F. (2022) *Understanding the complexities in the adoption of the Rice Crop Manager tool in the Philippines*, Int. J. Agric. Sustain. 20(4): 381–392, 385–386, 390 ("In general, farmers expressed a highly positive reception to RCM. They appreciate that the text messages or even just the printout they receive are easy-to-follow and serve as a useful guide for them.") *and* ("That RCM recommendations are not followed because farmers have their own long-standing traditional practices is completely understandable if one considers the behavioural communication literature. Changing an established behaviour takes time.").

48 Intaravanne Y., & Sumriddetchkajorn S. (2015) *Android-based rice leaf color analyzer for estimating the needed amount of nitrogen fertilizer*, Comput. Electron. Agric. 116: 228–233, 228 ("Nowadays, visual inspection of the color of the rice leaf is the cheapest way in correlating to the amount of N fertilizer needed. It can be accomplished via a standard leaf color chart (LCC). Since it was first developed by Furuya (1987), it has been modified and improved from its beginning form to an 8-panel LCC, a 6-panel LCC, and a compact 4-panel LCC (Witt et al., 2005). Several countries have also promoted the use of the LCC with some local adjustments to fit desired specific rice breeds (Yang et al., 2003; Islam et al., 2007; Krannuch, 2005). Although its cost is around USD 1 and it is easy to use, incorrect visual reading of colors from an LCC via naked eyes and the fading of the color charts (Sánchez-Marañón et al., 2015)…").

49 Singh J., Singh V., & Kaur S. (2020) *Precision nitrogen management improves grain yield, nitrogen use efficiency and reduces nitrous oxide emission from soil in spring maize*, J. Plant Nutr. 43(15): 2311–2321, 2311 ("A close linear relationship (R2 ¼ 0.75) between chlorophyll meter (SPAD) readings and LCC score showed that like SPAD meter, LCC score can reliably consider leaf greenness as an indicator of leaf N concentration."). *See also* Singh A. *Evaluation of leaf colour chart based fertilizer nitrogen management technology using PAU-LCC in transplanted rice (Oryza sativa L.)*, Int. J. Chem. Stud. 7: 344–349, 344 ("Close linear relationship (R2=0.732, n= 504) between PAULCC score and SPAD meter readings suggests that PAU-LCC can be used as economical substitute to SPAD for making need based fertilizer N topdressings in transplanted rice.").

50 Peng S., Buresh R. J., Huang J., Zhong X., Zou Y., Yang J., Wang G., Liu Y., Hu R., Tang Q., Cui K., Zhang F., & Dobermann A. (2010) *Improving nitrogen fertilization in rice by sitespecific N management. A review*, Agron. Sustain. Dev. 30(3): 649–656, 655 ("Thirdly, some farmers are reluctant to invest time

in monitoring leaf N status using the leaf color chart. Many farmers have difficulty in determining leaf color chart readings accurately.”). *See also* Intaravanne Y. & Sumriddetchkajorn S. (2015) *Android-based rice leaf color analyzer for estimating the needed amount of nitrogen fertilizer*, Comput. Electron. Agric. 116: 228–233, 228 (“Although its cost is around USD1 and it is easy to use, incorrect visual reading of colors from an LCC via naked eyes and the fading of the color charts (Sánchez-M arañón et al., 2015) could often occurs, leading to the improper application of N fertilizers.”).

51 Taneja G., Pal B. D., Joshi P. K., Aggarwal P. K., & Tyagi N. K. (2014) Farmers’ preferences for climate agriculture: an assessment in the Indo-Gangetic plain, International Food Policy Research Institute, 20 (*see* Table 6.2).

52 Islam Z., Bagchi B., & Hossain M. (2007) *Adoption of leaf color chart for nitrogen use efficiency in rice: Impact assessment of a farmer-participatory experiment in West Bengal, India*, Field Crops Res. 103(1): 70–75, 73 (“Year of schooling had significant positive influence on the adoption in all three rice seasons (P 0.01). Results clearly demonstrated that young and educated farmers were more in favor of LCC adoption than older and less educated ones.”).

53 Intaravanne Y. & Sumriddetchkajorn S. (2015) *Android-based rice leaf color analyzer for estimating the needed amount of nitrogen fertilizer*, Comput. Electron. Agric. 116: 228–233, 228 (“As the color level of the rice leaf corresponds to the nitrogen status of rice in the field, farmers compare the rice leaf color to a leaf color chart (LCC) in order to estimate the amount of N fertilizer needed for the rice field. However, the ability of the farmers and degeneration of the LCC color affect the accuracy in reading the rice leaf color level. In this paper, we propose a mobile device-based rice leaf color analyzer called “BaiKhao” (means rice leaf in Thai). Our key idea is to simultaneously capture and process the two-dimensional (2-D) data of the color image from the rice leaf and its surrounding reference, thus eliminating expensive external components and alleviating the environmental fluctuation but yet achieving a high color-reading accuracy.”).

54 Biwang A., (10 September 2020) *New, free fertilizer app for rice available on Play Store*, Phillipine Rice Research Institute (“Derived from a four-stripped handy “ruler” called Leaf Color Chart (LCC), the PhilRice Leaf Color Computing Application (PhilRice LCC App), which can assess nitrogen status of the rice plant, is now available on Google Play Store”).

55 Tao M., Ma X., Huang X., Liu C., Deng R., Liang K., & Qi L. (2020) *Smartphone-based detection of leaf color levels in rice plants*, Comput. Electron. Agric. 173(105431): 1– 10, 1 (“Leaf color is correlated with nitrogen content, and detection of nitrogen content in rice leaves is important for guiding farmers in applying fertilizer. However, the performance of existing detection methods highly depends on the field environmental condition. Also, these methods require special imaging and computing equipment. To fill these gaps, a smartphone app was developed based on a standard leaf color chart (LCC) to detect color levels of rice leaves. Using the app developed, regions of rice leaf and LCC in an image were successfully identified by the color threshold segmentation. . .The smartphone app allowed for an accurate, time-efficient, and lowcost detection of rice leaf color levels, which will help farmers in making decisions related to nitrogen fertilizer management for rice production.”).

56 Food and Agriculture Organization of the United Nations (2018) e-Agriculture Promising Practice: Rice Crop Manager and Rice Advice: Decision tools for rice crop management, 1 (“The web based tool (Rice Crop Manager) and the android application (RiceAdvice) both aim at providing smallholder rice-farmers with timely field specific guidelines for crop and nutrient management practices. . .Rice Crop Manager is a free decision-making tool accessible through the web browser for Windows, Android and Linux. It can be used on a smartphone, tablet or computer. RiceAdvice is a free application for Android and an Android-based smartphone or tablet is needed for its use.”).

57 International Rice Research Institute (2019) *Crop Manager* (*last visited* 28 November 2022)

(“Use of RCM recommendations provided an average yield increase of 0.4 tons (400 kg) per crop per hectare equivalent to about USD100/ha/cropping season added net benefit in the Philippines and an average of 0.5 tons (500kg) per crop per hectare equivalent to about USD150/ha/cropping season in India.”).

58 Manalo J. A., Pasiona S. P., & Bautista A. M. F. (2022) *Understanding the complexities in the adoption of the Rice Crop Manager tool in the Philippines*, Int. J. Agric. Sustain. 20(4): 381–392, 388 (“Conflict with existing projects. A key informant raised the issue that RCM conflicts with an existing project by the Bureau of Soils and Water Management. From their end, they felt that it would be confusing to farmers if they talked about the two initiatives at the same time.”).

59 Manalo J. A., Pasiona S. P., & Bautista A. M. F. (2022) *Understanding the complexities in the adoption of the Rice Crop Manager tool in the Philippines*, Int. J. Agric. Sustain. 20(4): 381–392, 381 (“Overall, we argue that there is a need to tackle social system and socio-technical issues relating to RCM adoption. Examples of social system issues include the lack of resources of farmers and poor internet connectivity; of sociotechnical issues are conflict with existing initiatives and overwhelming administrative issues in the local agriculture offices. Among the recommendations to improve RCM uptake in the Philippines are addressing the work overload issue of AEWs, improving rural internet access, and integrating a multi-sectoral agriculture extension system.”)

60 Chivenge P., Saito K., Bunquin M. A., Sharma S., & Dobermann A. (2021) *Co-benefits of nutrient management tailored to smallholder agriculture*, Glob. Food Secur. 30(100570): 1–8, 2 (“In China, the Nutrient Expert platform currently provides SSNM-based advice for 23 different crops, including fruits and vegetables.”).

61 Pampolino M., Majumdar K., Jat M. L., Satyanarayana T., Kumar A., Shahi V. B., Gupta N., & Singh V. (2012) *Development and Evaluation of Nutrient Expert for Wheat in South Asia*, Better Crops 96(3): 29-31, 29 (“Nutrient Expert (NE) for Wheat, a new nutrient decision support tool, is based on the principles of site-specific nutrient management (SSNM) and recommends balanced application of nutrients based on crop requirement. The tool was a joint development of wheat stakeholders in India including representatives from national research and extension system, private industries, International Maize and Wheat Improvement Center (CIMMYT), and International Plant Nutrition Institute (IPNI). It enables crop advisers to rapidly develop field-specific fertilizer recommendations for wheat using existing site information. Field evaluation showed that the location-specific nutrient recommendations from the tool increased yield and economic benefits of wheat farmers as compared to the existing practices.”); *See also* Pampolino M. F., Witt C., Pasuquin J. M., Johnston A., & Fisher M. J. (2012) *Development approach and evaluation of the software for nutrient management in cereal crops*, Comput. Electron. Agric. 88: 103–110, 103 (“Nutrient Expert for Hybrid Maize (NEHM) increased yield and profit of farmers in Indonesia and the Philippines. In Indonesia, NEHM increased yield by 0.9 t ha1 , which increased profit by US$ 270 ha1 over farmer’s fertilizer practice (FFP). Compared with FFP, NEHM recommendations reduced fertilizer P (4 kg ha1), increased fertilizer K (+11 kg ha1), and did not significantly change fertilizer N. In the Philippines, NEHM increased yield by 1.6 t ha1 and profit by US$ 379 ha1 compared with FFP. Compared with FFP, NEHM gave higher rates of all three nutrients (+25 kg N ha1 , +4 kg P ha1 , and +11 kg K ha1), which substantially increased fertilizer costs (US$ 64 ha1) but still increased profit by about six times the additional investment in fertilizer.*”); and* Amgain L., Timsina J., Dutta S., & Majumdar K. (2021) *Nutrient expert ® rice - an alternative fertilizer recommendation strategy to improve productivity, profitability and nutrient use efficiency of rice in Nepal*, J. Plant Nutr. 44(15): 1–16, 1 (“Present study used NEVR Rice as nutrient management protocol in farmers’ fields across Terai and mid-hills regions of Nepal during 2014–2018. The study revealed that NE-based fertilizer recommendations resulted in increase in yield over 2.0 t.ha1 (p 0.05) and double the profits compared to existing blanket fertilizer recommendation, and farmers’ fertilizer practice.”).

62 Sapkota T.B., Jat M.L., Rana D.S., Khatri-Chhetri A., Jat H.S., Bijarniya D., Sutaliya J.M., Kumar M., Singh L.K., Jat R.K., Kalvaniya K., Prasad G., Sidhu H.S., Rai M, Satyanarayana T., & Majumdar K. (2021) *Crop nutrient management using Nutrient Expert improves yield, increases farmers' income and reduces greenhouse gas emissions*, Sci. Rep. 11(1564): 1–11, 1 ("Reduction of excess nutrient application and balanced fertilizer use are the key mitigation options in agriculture. We evaluated Nutrient Expert (NE) tool-based site-specific nutrient management (SSNM) in rice and wheat crops by establishing 1594 side-by-side comparison trials with farmers' fertilization practices (FFP) across the Indo-Gangetic Plains (IGP) of India. We found that NE-based fertilizer management can lower global warming potential (GWP) by about 2.5% in rice, and between 12 and 20% in wheat over FFP. More than 80% of the participating farmers increased their crop yield and farm income by applying the NE-based fertilizer recommendation. We also observed that increased crop yield and reduced fertilizer consumption and associated greenhouse gas (GHG) emissions by using NE was significantly influenced by the crop type, agro-ecology, soil properties and farmers' current level of fertilization. Adoption of NE-based fertilizer recommendation practice in all rice and wheat acreage in India would translate into 13.92 million tonnes (Mt) more rice and wheat production with 1.44 Mt less N fertilizer use, and a reduction in GHG of 5.34 Mt CO2e per year over farmers' current practice. Our study establishes the utility of NE to help implement SSNM in smallholder production systems for increasing crop yields and farmers' income while reducing GHG emissions.").

63 Pampolino M. F., Witt C., Pasuquin J. M., Johnston A., & Fisher M. J. (2012) *Development approach and evaluation of the software for nutrient management in cereal crops*, Comput. Electron. Agric. 88: 103–110, 103 ("NE enables crop advisors to develop SSNM recommendations using existing site information. Nutrient Expert for Hybrid Maize (NEHM) increased yield and profit of farmers in Indonesia and the Philippines. In Indonesia, NEHM increased yield by 0.9 t ha1, which increased profit by US$ 270 ha1 over farmer's fertilizer practice (FFP). Compared with FFP, NEHM recommendations reduced fertilizer P (4 kg ha1), increased fertilizer K (+11 kg ha1), and did not significantly change fertilizer N. In the Philippines, NEHM increased yield by 1.6 t ha1 and profit by US$ 379 ha1 compared with FFP. Compared with FFP, NEHM gave higher rates of all three nutrients (+25 kg N ha1 , +4 kg P ha1 , and +11 kg K ha1), which substantially increased fertilizer costs (US$ 64 ha1) but still increased profit by about six times the additional investment in fertilizer.") *see also* Sapkota T. B. et al. (2021) *Crop nutrient management using Nutrient Expert improves yield, increases farmers' income and reduces greenhouse gas emissions*, Sci. Rep. 11: 1564, 1–11, 1 ("More than 80% of the participating farmers increased their crop yield and farm income by applying the NE-based fertilizer recommendation. We also observed that increased crop yield and reduced fertilizer consumption and associated greenhouse gas (GHG) emissions by using NE was significantly influenced by the crop type, agro-ecology, soil properties and farmers' current level of fertilization. Adoption of NE-based fertilizer recommendation practice in all rice and wheat acreage in India would translate into 13.92 million tonnes (Mt) more rice and wheat production with 1.44 Mt less N fertilizer use, and a reduction in GHG of 5.34 Mt CO2e per year over farmers' current practice.").

64 Rice Advice, *Home* (*last visited* 28 November 2022). ("RiceAdvice is an Android based decision support tool for providing farmers with pre-season field-specific management guidelines for rice production systems in Africa. The guidelines include target yield, nutrient management, crop calendar and good agricultural practices. Up to early 2017, more than 20,000 RiceAdvice guidelines have been generated. 15.000 + in Nigeria, followed by Mali and Senegal. Farmers using RiceAdvice report yield gains between 0.6 - 1.8 tons per hectare, and income gains between $100 - $200 per ha. Over 95% of the farmers want to continue using RiceAdvice.").

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