Site-Specific Nutrient Management: Implementation guidance for policymakers and investors

Overview of practice

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%.

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KEY MESSAGES

1. Site-Specific Nutrient Management (SSNM) optimizes the supply of soil nutrients over space and time to match crop requirements.
2. SSNM increases crop productivity and improves efficiency of fertilizer use.
3. SSNM mitigates greenhouse gases from agriculture in areas with high nitrogen fertilizer use.
4. Incentives for adoption of SSNM depend strongly on fertilizer prices.

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Overview of Site-Specific Nutrient Management (SSNM)

Fertilizer application recommendations are often based on crop response data averaged over large areas, though farmers' fields show large variability in terms of nutrient-supplying capacity and crop response to nutrients. Thus, blanket fertilizer application recommendations may lead farmers to over-fertilize in some areas and under-fertilize in others, or apply an improper balance of nutrients for their soil or crop. An alternative to blanket guidance, Site-Specific Nutrient Management (SSNM) aims to optimize the supply of soil nutrients over time and space to match the requirements of crops through four key principles (Table 1). 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). They are:

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.

Table 1 Examples of key scientific principles and associated practices of 4R nutrient stewardship

SSNM principle	Scientific basis	Associated practices
Product	Ensure balanced supply of nutrients Suit soil properties	Commercial fertilizer Livestock manure Compost Crop residue
Rate	Assess nutrient supply from all sources Assess plant demand	Test soil for nutrients Balance crop removal
Time	Assess dynamics of crop uptake and soil supply Determine timing of loss risk	Apply nutrients: Pre-planting At planting At flowering At fruiting
Place	Recognize crop rooting patterns Manage spatial variability	Broadcast Band/drill/inject Variable-rate application

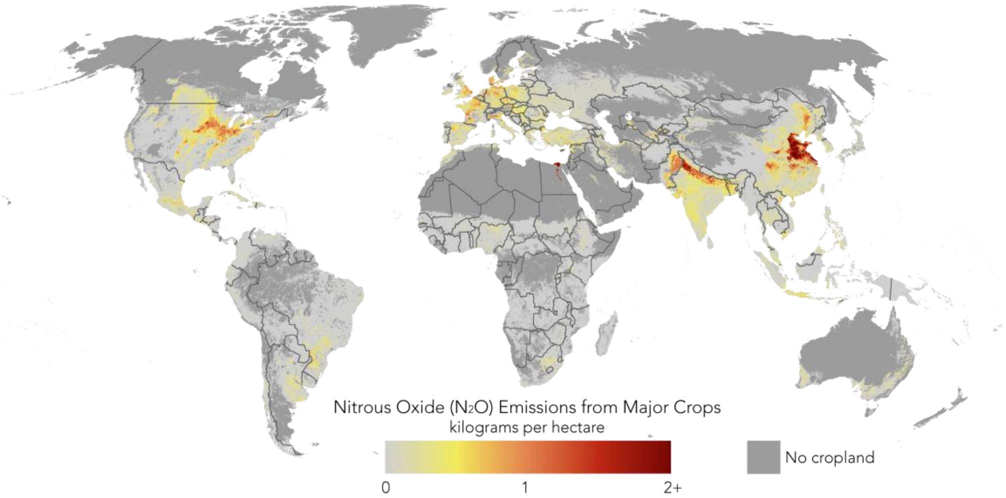

FIGURE 1 Nitrous Oxide Emissions from Major Crops (Peder Engstrom and Paul West, Institute on the Environment, University of Minnesota)

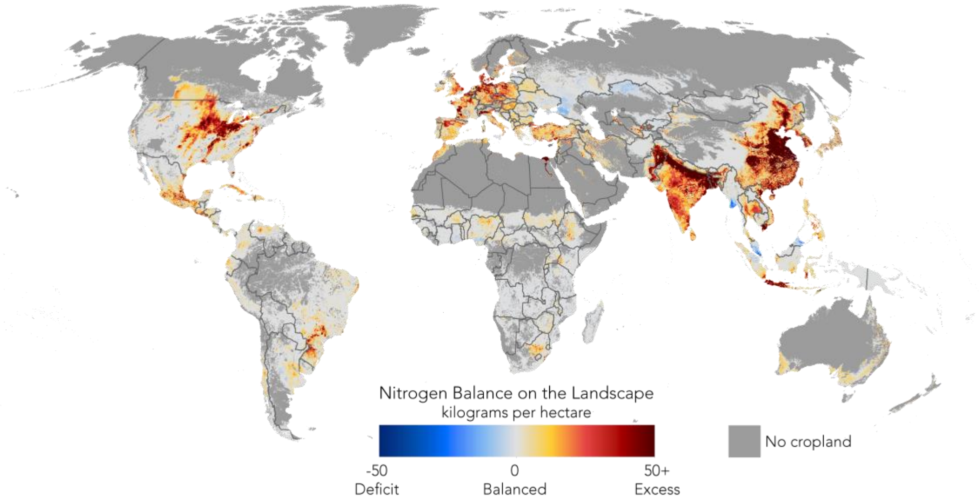

FIGURE 2 Nitrogen balance on the Landscape (Peder Engstrom and Paul West, Institute on the Environment, University of Minnesota)

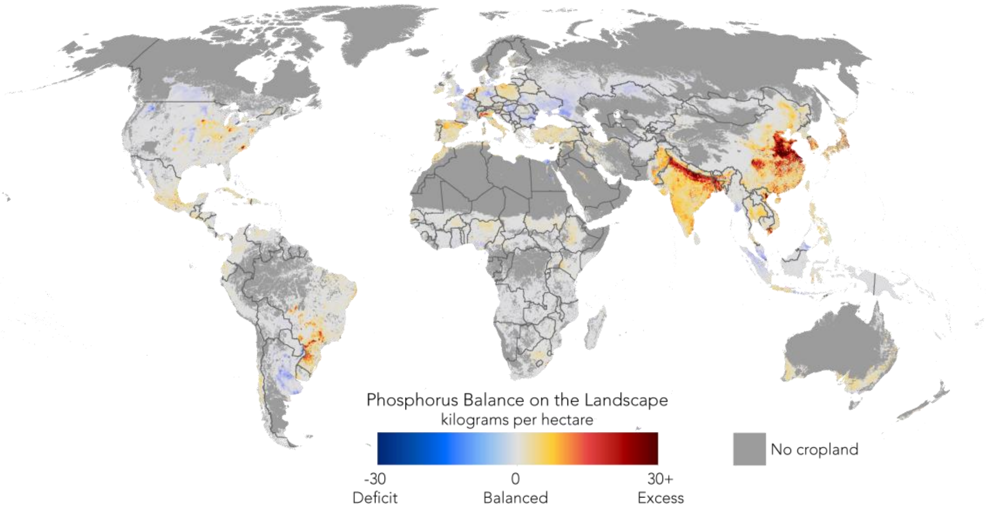

FIGURE 3 Phosphorus Balance on the Landscape (Peder Engstrom and Paul West, Institute on the Environment, University of Minnesota)

Benefits of the practice

Higher profits. SSNM can increase and maintain yields by optimizing the balance between supply and demand of nutrients and providing more balanced plant nutrition (Wang et al. 2007). In general, it improves nutrient-use efficiency and provides greater returns on investments in fertilizer (Ortiz-Monasterio and Raun 2007).

Reduced nitrous oxide emissions. Agriculture contributes 70-90% of nitrous oxide (N_2O) emissions, mostly from N fertilizer. SSNM reduces N_2O emissions by reducing total N application and/or timing applications to crop needs, thus avoiding N losses to volatilization, leaching and runoff.

Improved disease resistance. The more balanced NPK nutrition that comes with SSNM may lead to improved resistance to plant diseases (Pasuquin et al. 2014).

Challenges to adoption of SSNM

Technology and knowledge requirements. SSNM requires knowledge of underlying soil properties and the ability to monitor crops' nutrient status and adjust fertilizer inputs accordingly. While the need to conduct on-farm nutrient trials and soil tests has historically been a barrier to implementation of SSNM, the development of decision support systems and farmer-friendly tools and techniques that use proxy information to calculate nutrient requirements make SSNM more accessible to farmers and farm advisors (see "Tools for implementing SSNM", below).

Availability of fertilizers. Cost and access to fertilizers—whether synthetic or organic—is not universal. Development of input markets or identification of on-farm nutrient sources may be a necessary precursor to adoption of SSNM, though SSNM can help farmers make best use of limited nutrient resources.

Variable economic benefit. For SSNM to increase farmers' profits, SSNM must deliver either a) savings from reduced fertilizer use without a reduction in yields, or b) yield increases that are valued higher than the costs of acquiring and using SSNM technology. Farmers are more likely to see positive net returns with high-value crops, where yield increases can substantially increase profits, or when fertilizer prices are high.

Where can SSNM be implemented?

In principle, SSNM can be used anywhere fertilizers are applied. The terms "Site-Specific Nutrient Management" and "precision farming" are sometimes used to describe the use of geo-referenced technology to manage within-field variability. However, applying the principles of SSNM does not require such technology, and can be done by farmers lacking machinery.

Contribution to CSA pillars:

How does SSNM increase productivity, farm livelihoods and food security?

SSNM generally maintains or increases crop yields. In a 2014 study of 13 sites in Southeast Asia, SSNM led to grain yield increases of 13% over a three-year period, although yields declined slightly in the first year (Pasuquin et al. 2014). A study of 179 rice farms in 6 Asian countries found that SSNM led to yield increases of 7% and total profitability increases of 12% (Dobermann et al. 2002). In recent studies across large numbers of locations in wheat systems in South Asia, SSNM led to 18-27% increases in grain yield of wheat, when compared to farmers' standard fertilizer practices (Jat and Satyanarayana 2013). An average of 107 on-farm experiments in Chinese rice fields found 5% higher grain yields under SSNM than under farmers' practice, attributed to a reduction in insect and disease damage caused by optimal N inputs (Peng et al. 2010).

SSNM can improve overall profitability of farming enterprises by saving farmers money on fertilizer, though this depends strongly on baseline yields, baseline fertilizer use and the price of fertilizer. In SSNM tests using optical sensors on 14,000 ha of farmers' wheat and barley fields in Mexico (see "Tools for implementing SSNM on the farm", below), SSNM saved 40-70 kg N/ha without affecting grain yield (Ortiz-Monasterio and Raun 2007). In experiments with wheat production in India, SSNM increased net returns from USD 390 to 1071/ha over farmers' practice, despite increasing labor costs by USD 123/ha (Singh et al. 2015).

How does SSNM help adapt to and increase resilience to climate change impacts?

Most of the research on SSNM has been focused on increasing productivity and incomes, and mitigation. However, good nutrient management in general should increase yields and resilience of crops (Thornton and Herrero 2014). In addition, if optimization of fertilizer inputs is based on attainable yield in the current year (as is done with optical sensors, see "Tools for implementing SSNM on the farm" below) it could save farmers money on fertilizer in bad weather years.

How does SSNM mitigate greenhouse gas emissions?

As a greenhouse gas mitigation strategy, SSNM is most applicable to farming systems in which N fertilizers are currently used, and especially overused (Figure 1, Figure 2, Figure 3). SSNM reduces the quantity of N applied, thus reducing total reactive N (Nr: NH_3, NH_4+, NO_3-, NO_2-, NO, N_2O) losses to the environment (through leaching or volatilization, for example) and N2O emissions. In one study, implementation of SSNM practices resulted in a 30% reduction of fertilizer use in rice paddies (Wang et al. 2007). In another study in wheat, N2O emissions were reduced by 50% (Matson et al. 1998) and leaching losses by 90% (Riley et al. 2001).

Use of slow- or controlled-release fertilizers also generally results in lower N_2O emissions, since plant nutrient demand and nutrient release from fertilizer application are better harmonized. Fertilizer deep placement is also a promising strategy, reducing reactive N losses by up to 35% (Gaihre et al. 2015). Using slow- or controlled-release products and techniques as part of SSNM can further decrease N2O emissions and reactive N losses from leaching and volatilization to the environment.

SSNM may prescribe increased N application, where soils are nutrient-depleted (Dobermann et al. 2002), but this does not necessarily increase emissions. A growing body of evidence suggests that the emission response to increasing N input is exponential rather than linear, with very low emissions until plant needs are met (Shcherbak et al. 2014). For low-input systems, modest increases in N fertilizer rates are thus likely to have little impact on N_2O emissions, and runoff is less likely since fields do not reach N oversaturation. Even if N_2O emissions increase slightly, SSNM can still reduce emissions intensity: the quantity of greenhouse gas emissions per kg of food produced. A recent study in Kenya's highlands indicates that current GHG emission intensities for upland crops grown at low input are at least a magnitude higher than in OECD states due to low yields (Bellarby et al. 2014).

Tools for implementing SSNM on the farm

Optical sensors

Farmers and extension agents can use optical sensors (Figure 4) to develop SSNM recommendations, particularly for N. 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).

FIGURE 4 Using a handheld sensor to measure NDVI (Photo: Tek Sapkota)

The application of optical sensor-based nutrient management requires a local calibration of the sensor for a given nutrient, crop and region. This calibration relates the grain yield of the crop to the NDVI readings. Once calibration is complete, optical sensors require: (1) establishment of a reference strip in the farmer's field that will receive a non-limiting amount of N, (2) collection of an NDVI reading in the reference strip and in the field area where the farmer needs to know how much N should to be applied, and (3) the NDVI readings collected from these two areas in the field together with the date of planting and date of sensing are entered in a mathematical model developed for each region. Such models have already been developed for common crops in certain countries such as China, India, Mexico, and Zimbabwe; an online calculator is available at www.nue.okstate.edu/Algorithm/Algorithm_Outline.htm.

Software for SSNM: Nutrient Expert® and Crop Manager

Computer or mobile phone-based tools are increasingly used to facilitate improved nutrient management practices in farmers' fields, especially in geographies where blanket fertilizer recommendations prevail. These tools provide small-scale maize, rice and wheat farmers with crop and nutrient management advice customized to their farming conditions and needs. Nutrient Expert® and Crop Manager are examples of decision-support systems developed for SSNM in cereal production systems.

BOX 1: The science of N_2O emissions

According to recent reports by the Intergovernmental Panel on Climate Change (IPCC) and FAO, synthetic fertilizers contribute 12-14% of global total GHG emissions from agriculture (680-725 Mt CO2eq per year in 2010/2011). About 70% of these emissions come from non-Annex I countries, primarily from countries with emerging economies such as Brazil, China, India and Indonesia (Tubiello et al. 2014).

IPCC 2006 Guidelines estimate that for every 100 kg of N applied to mineral soils as fertilizer or manure, 1 kg of N_2O is emitted and in cattle, poultry and pig manure and urine deposited by grazing animals on pasture, range and paddock, 2% of added N is lost as N_2O. IPCC 2006 are global estimates, based mainly on assessments in OECD states and may strongly deviate for countries in the pantropics. Since emissions depend strongly on soil and climatic factors and management, the uncertainty range is high (0.3-3.0 kg N_2O per 100 kg N applied).

N2O emissions from soils are due to microbial N turnover processes in soils, with microbes competing with plants for N in the rhizosphere. Plant-microbe competition for N is low or not existing at the beginning of the growing season, when most fertilizer is applied. Timely meeting of the N demand of crops, as with SSNM, favors plant N uptake over microbial N processing and thus results in lowered N_2O emissions.

The main microbial N_2O production pathway is de-nitrification, which describes the microbial process of reduction of nitrate, via N_2O to molecular di-nitrogen under anaerobic or micro-aerobic conditions (Butterbach-Bahl et al. 2013). Thus, keeping synthetic fertilizer in the reduced state as ammonium, for example by using urease or nitrification inhibitors, reduces the production of nitrate by microbial nitrification – which also can produce N_2O - and decreases losses of nitrate by leaching or volatilization in form of N_2 and N_2O due to de-nitrification. However, there is little data from the subtropics, and some available data shows that both nitrification and de-nitrification contribute equally to N2O emissions (Panek et al. 2000).

Nutrient Expert®

Nutrient Expert® is an interactive, computer-based decision-support tool that enables smallholder farmers to rapidly implement SSNM in their individual fields with or without soil test data. The software estimates the attainable yield for a farmer's field based on the growing conditions, determines the nutrient balance in the cropping system based on yield and fertilizer/manure applied in the previous crop and combines such information with expected N, phosphorus (P) and potassium (K) response in target fields to generate location-specific nutrient recommendations. The software also does a simple profit analysis comparing costs and benefits between farmers' current practice and recommended alternative practices. The algorithm for calculating fertilizer requirements was developed from on-farm research data and validated over 5 years of testing. The software is currently available without charge for wheat & maize systems in South Asia (http://software.ipni.net/article/nutrient-expert).

Crop Manager

Crop Manager is a computer-and mobile phone-based application that provides small-scale rice, rice-wheat, and maize farmers with site- and season-specific recommendations for fertilizer application. The tool allows farmers to adjust nutrient application to crop needs based on soil characteristics, water management, and crop variety on their farm. Recommendations are based on user-input information about farm location and management, which can be collected by extension workers, crop advisors, and service providers. The software is freely downloadable at http://cropmanager.irri.org/home.

Policy for SSNM

National policy is critical in facilitating SSNM and other soil fertility practices because fertilizer and crop prices largely determine their economic viability.

Some countries use fertilizer subsidies in order to make fertilizers more accessible to farmers, which can help resource-poor farmers break out of cycles of low-productivity crop cultivation and poverty. For example, Malawi garnered much international interest when it began providing vouchers to vulnerable households for fertilizer and maize seed in 2005, dramatically increasing national production and food security (Dorward and Chirwa 2011). However, fertilizer subsidies can have adverse effects, such as in China, where decades of artificially low fertilizer prices have led not only to higher food production but also to fertilizer overuse (about 550 kg per ha compared to 100 kg per ha in the rest of the world) and consequent nutrient pollution (Li et al. 2013).

Reducing subsidies creates motivation for farmers to efficiently use fertilizers, and thus demand for SSNM. In China a proposed cap on fertilizer use has helped spur research and innovation. While fertilizer overuse is unlikely to be a problem in Malawi, recommendations to improve Malawi's program include encouraging the proper timing, placement, and formulation of fertilizers and combining inorganic fertilizers with organic inputs by including legume seed in the subsidy package to provide green manure (see practice brief on Integrated Soil Fertility Management). Linking adoption of best practices to access to subsidized inputs could also be explored (Dorward and Chirwa 2011).

Fertilizer producers and suppliers are also important partners in effectively using fertilizers and developing appropriate products, such as slow-release fertilizers, better-balanced NPK fertilizers, and large granules for fertilizer deep placement. Some fertilizer manufacturers are eager to promote efficient fertilizer use in response to public pressure and environmental concerns. Input suppliers provide a key point of contact with farmers, and in many countries have replaced agricultural extension as farmers' primary source of information.

Metrics for CSA performance of SSNM

SSNM's contribution to CSA is related to productivity, net farm profitability, and reduced N_2O emissions. Estimates of productivity and profitability may be based on farmer-reported data collected by extension agents or service providers. While use of remote sensing to estimate biological crop yield is being explored in many countries and likely will become the basis of productivity monitoring in the future, current resolution of satellite imagery used in remote sensing is not sufficiently detailed to capture variation between smallholders' fields.

N fertilizer use may be monitored as a proxy for N_2O emissions, though default IPCC methods (assuming 1% of fertilizer is lost as N_2O) give only a rough idea of emissions. The lack of measurements of N_2O losses following fertilizer applications to cropping systems in developing countries currently hampers the ability to assess the consequences of increased fertilizer use for boosting crop production on the global environment. Several empirical models have been developed, including the Stehfest and Bouwman (2006) and Zhou et al. (2015) models to estimate these variables. However, datasets used for the development of these models are strongly biased for representing environmental and management conditions in OECD countries or China (Zhou et al. 2015). Other approaches, such as the Cool Farm Tool or biogeochemical models, are either based on IPCC methodology, which is unlikely to represent the local situation due to the importance of soil characteristics and management for emissions, or have yet not been tested sufficiently due to lack of representative datasets on emissions, management, yields and environmental conditions.

Interaction with other CSA practices

Integrated soil fertility management (ISFM)

ISFM is a set of soil fertility management practices that include the use of fertilizer, organic inputs, and improved germplasm and how to adapt these practices to local conditions to maximize the agronomic efficiency of the applied nutrients and improving crop productivity (see ISFM practice brief). ISFM and SSNM are complementary practices, though SSNM has historically been targeted to farming systems where farmers are already using (or over-using) fertilizers, and ISFM seeks to improve productivity in very low-input systems. ISFM may be more appropriate for systems where farmers rely primarily on organic fertility sources.

Conservation agriculture (CA)

CA is a method of crop production and soil management based on minimal tillage, leaving crop residues on the soil surface, and crop rotation (see CA practice brief). CA, through these three key principles, influences the soil physical, chemical and biochemical processes and, in turn, modifies the nutrient dynamics in the soil. Therefore, SSNM's 4R nutrient stewardship must be formulated taking these nutrient dynamics into consideration when used in CA. Preliminary results show that SSNM improves productivity when used in conjunction with CA practices: targeted use of fertilizers can improve crop yields and residue inputs to soil, critical to successful implementation of CA (Sapkota et al. 2014).

Further reading

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Date published November 2015

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