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Precision nutrient management : A review

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ABSTRACT

Precision agriculture is a management strategy that employs detailed site specific information to precisely manage production inputs. Precision farming can contribute in many ways to long-term sustainability of agriculture. The idea is to know the soil and crop characteristics unique to each part of the field, and to optimize the production inputs within small portions of the field. Of all the production inputs, nutrients occupy the top position and nutrient management is crucial to the success of any farming system. The usual practice is to apply nutrients at one rate throughout the farming area. Such practice could lead to wastage of resources and maximum yields could not be achieved since, spatial variability is altogether ignored in the management option. Precision nutrient management system offers improved land stewardship, optimizes resource usage, since every part of a field receives precise amount of fertilizer required to maximize crop yields. Various strategies of precision nutrient management system are being developed among which management zone technique is gaining importance. The management zone strategy reduced the average N applied from 6.3 % to 46.1 % compared to uniform N management. The variable rate N application using management zones increased net returns from 11.75 to $ 39.17/ha over uniform N management.

Key words: Management, Nutrient improvement, Nutrient intake, Variable cost.

Food shortages and escalating food prices are serious global issues with social, political and economic implications. The factors that have created the food crisis are multiple and complex. One of the necessary components in the solution is the use of fertilizers. Fertilizers are currently responsible for between 40 and 60% of the world's food supply. As stated by the International Fertilizer Development Centre, "No country has been able to expand agricultural growth rates and eliminate hunger without increasing fertilizer use."

The Food and Agriculture Organization (FAO) of United Nations has estimated that the total world's demand for agricultural products will be 60 % higher in 2030 A.D. than it is today. But, the world's options for increasing food production are limited both by the supply of land and water. Increasing world population, among other factors, limits any significant expansion of global arable acres. For over half a century, the world has relied on increasing crop yields to supply an ever increasing demand for food. According to U.S. Department of Agriculture data, total world grain production rose from 0.905 billion tonnes in 1965 to 2.091 billion tonnes in 2007. To increase world food production in a sustainable manner, farmers will need to use the right fertilizer at the right rate, right time and right place.

In general, the fertilizer use efficiency is only about 40-60 % for N and 20-40 % for P. Hence, there is an urgent need to increase the nutrient use efficiency from the view point of costs and water quality concerns. The N use efficiency in different countries are given below (Table 1).

Table 1. Nitrogen use efficiency

Country	Year	NUE (kg/kg)	Change %	Rate of change (% per year)
USA	1980	42	-	-
	2000	57	+36	+1.6
UK	1981-85	36	-	-
	2001-02	44	+23	+1.1
Japan	1985	57	-	-
	2001	75	+32	+1.8
India	1970	60	-	-
	2004	20	-60	-1.7

Nitrogen is often the most limiting nutrient in agro-ecosystems and is therefore applied in the highest quantities According to FAO (2001), about 82 million Mg of nitrogenous fertilizers were applied globally in 2001. Of that, 60% was used for cereal production. Raun and Johnson (1999) estimated world-wide nitrogen use efficiency (NUE) for cereal production to be 33 % meaning that in 2001 alone, approximately 33 million Mg of N fertilizer was lost. Precision nutrient management practices allow timely and precise application of N fertilizer to meet plant

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needs as they vary across the landscape.

Precision nutrient management is a precise method of application of nutrients, based on the variability in soil and micro-climatic conditions that occur within the field. The scale of nutrient management recommendation domains change from large regions to farms, single fields or even single parcel within a large field. It may also be referred to as site-specific nutrient management (SSNM).

Although India has made considerable advance in agricultural research, but still the blanket recommendations for adoption over larger areas are in vogue. These blanket recommendations are no more useful to enhance productivity gains, which were witnessed between 1960s' and 1980s'. Now, to enhance growth rate in productivity, SSNM practices have to be developed. Advantages of SSNM in rice and maize are presented in Table 2. Precision nutrient management is important because: (i) nutrient variability within a field can be very high affecting optimum fertilizer rates, (ii) yield potential and grain protein can also vary greatly even within one field, affecting fertilizer requirement and (iii) increasing fertilizer use efficiency will become more important with increasing fertilizer costs and environmental concerns.

Components of precision nutrient management (PNM)

Following components of precision nutrient management were implemented in the past five years (Roperia *et al.*, 2006) are : 1. *Mapping Work Station*: Established a mapping workstation installed with SoilTec Prescription Mapping System. 2. *Precision Agriculture System*: Set up a Precision Agriculture System at an alfalfa customer's field, including soil-testing system, soil information collection by GPS, prescription mapping, variable-rate application by Terragator. 3. *Hand-held Crop Information Collector*: This is an electronic device used to collect crop related information by big potato growers during the season. 4. *Petiole Testing*: This is an innovative service provided to determine the nutrient status of potato crop by measuring the petiole of the leaves. 5. *Soil Testing*: Soil samples were taken from small farms from typical regions and the information was captured using GPS. This geo-referenced information has been useful in tracking the history of small farms and to measure the yield improvements over a period of time. 6. *Remote Sensing Imagery*: Remote sensing images were used to differentiate the problems of weed and nutrient deficiency from each other.

PNM technology development phases

Technology development of precision nutrient management can be divided into three phases.

Phase I: Includes grid sampling and fertility maps; and variable rate application.

Phase II: It comprises of (a) utilizing a variety of data layers (maps of soil properties, terrain attributes, sensors of EC, remote sensing and yield maps, (b) dividing a field into few larger sub-units commonly called as "Management Zones", (c) soil sampling and developing location specific response functions in management zones and (d) varying soil or crop treatments by management zones

Phase III: Simulation modeling to evaluate Management options. This involves: (i) Empirical calibration of models to local conditions and (ii) Simulating effects of spatial and temporal variation on crop growth at sub-field level.

Crop simulation models or even more complex soil-landscape-crop simulation models are increasingly used in precision farming research, but their complexity has often hampered the use of modeling in making practical decisions on input use. Many recent modeling efforts have focused on understanding spatial variability at the sub-field level and simulating scenarios for site-specific crop management (Booltink *et al.*, 2001). The challenge is to

Table 2. Site-specific nutrient management in different countries

Crop (Country)	N treatment	N applied (kg/ha)	N Saved (kg/ha)	Yield (t/ha)	NUE (kg/kg)
Maize	Conventional	142	-	10.3	73
(USA)	SSNM 1	141	+1	10.4	74
	SSNM 2	113	+29	10.2	90
Rice	Conventional	130	-	7.6	58
(Philippines)	SSNM	87	+43	7.5	86
Rice	Conventional	171	-	6.0	37
(China)	SSNM	126	+45	6.4	52
Rice	Conventional	142	-	5.0	35
(India)	SSNM 1	110	+32	5.0	45
	SSNM 2	108	+34	4.9	45

make these models robust enough for practical decision-making, limit the amount of input variables needed, minimize the need for local "model calibration", and use models for exploring management options a priori as well as in real-time during the growing season.

Steps in PNM

Practical steps of PNM usually include a cyclic process of: (i) *Characterization:* Measure extent, scales, and dynamics of variation, (ii) *Interpretation:* Assess significance, identify major causes of uncertainty, and formulate management targets, (iii) *Management:* Apply inputs at the appropriate scale and in a timely manner, and (iv) *Monitoring:* Monitoring the outcome in a continuous learning process of change. This may be accomplished in discrete steps ("mapping approaches"), or as dynamic processes executed in real-time ("sensing approaches", "modeling approaches"), or as combinations of both (Dobermann *et al*., 2004).

Methods of PNM

(i) Management Zone Concept : The use of site-specific management zones (SSMZ) for variable rate application (VRA) has been shown to be a simple and effective way to increase nitrogen use efficiency (Khosla *et al.,* 2002, Hornung *et al.,* 2003). Site-specific management zones are defined as homogeneous sub regions of a field that have similar yield limiting factors (Khosla and Shaver, 2001, Inman *et al.,* 2005). Numerous methods and combinations of methods have been used to delineate management zones including remote sensed imagery, yield data, farmer's experience combined with bare soil imagery and topography (Fleming *et al.,* 1999), soil electrical conductivity, grid soil sampling, and soil survey information (Franzen *et al.,* 2000). Conceptually, by using management zone delineation technique, production fields could be classified into management zones that reflect the zone's productivity potential (Inman *et al.,* 2005). For example, a field may be classified into three zones *viz.* high, medium, and low productivity potential management zones. Using the management zones approach, agricultural inputs are envisaged to be applied variably across the field in accordance with the productivity potential of the management zone. However, within a management zone, agricultural inputs are applied uniformly at a constant rate.

In Eastern Washington, Mulla and Bhatti (1997) showed that N application could be reduced by as much as 42 kg/ha using VRA. Khosla and Alley (1999) found that using VRA on a 14.4 ha field in Virginia reduced total N applied by 22 kg/ha without reduction in grain yield when compared with uniform N treatment. Moreover, the results of Khosla and Alley (1999), Khosla *et al.* (2002), and Hornung *et al.* (2003) demonstrated that N input optimization via high N application rates in more productive areas and low N rates in less productive areas has potential to increase nitrogen use efficiency.

(ii) The Real-Time Nutrient Management Methods (Variable Rate Applications at Critical Growth Stages by using Remote Sensing or On-The-Go Crop Sensors).

Remote sensing provides a great deal of fundamental information relating spectral reflectance and thermal remittance properties of soils and crops to their agronomic and biophysical characteristics at scales that may range from small patches within a field to large regions (Pinter *et al.,* 2003). This makes it an attractive tool for site-specific decisions in many environments, particularly with regard to soil characterization, non-destructive monitoring of plant growth and detection of environmental stresses which may limit crop productivity (Dobermann *et al.,* 2004).

Sensors developed for on-the-go measurement of soil properties have the potential to provide benefits from the increased density of measurements at a relatively low cost. When a GPS receiver and a data logger are used to record the position of each soil sample or measurement, a map can be generated and processed along with other layers of spatially variable information. This method is frequently called a "map-based" approach. On the other hand, some soil sensors may be used to vary application rates in response to sensor output in real time without a GPS receiver. Therefore, on-the-go soil sensors can be a part of either "map-based" or "real-time" systems (Adamchuk *et al.*, 2004).

Techniques for delineating management zones and nitrogen management

(i) Soil Crop Management Zone: This technique involves three data layers such as bare soil imagery, topography, farmer's experience based on soil colour. Variation in soil nutrient supply within a large field, or among many small fields within a landscape may be most significant. Both spatial and temporal variation must be characterized. Site-specific crop management (SSCM) should aim at improving the input - output characteristics of the soil and crop system as they vary in space and time. This may involve the use of advanced technologies at the sub-field scale, or simply by improving field-level inputs (Dobermann *et al.*, 2004).

(ii)Yield Based Management Zone: This technique involves six data layers such as bare soil imagery, topography, previous year's yield map, soil OM, soil texture and soil CEC.

Accumulation of yield data from a number of seasons and crops in the same field can provide an excellent means of gaining a precise understanding of the field and yield variations (Plant, 2001). Since yield monitors are becoming a standard feature of a combine harvester and the crop yields are routinely recorded at the time of harvest, yield maps of several crops and seasons could be combined within a geographic information systems (GIS) framework to identify consistently high/low-yielding areas within a paddock. These areas could then be labelled as 'management zones' requiring different management practices. The number and size of management zones within a field could vary since it is a function of the natural variability within the field, the size of the field and the ability of the farmer to differentially manage regions within a field (Zhang *et al.,* 2002).

(iii) Electrical Conductivity Management Zone : This technique involves only one data layer that is based on Soil EC.

(iv) Site-specific Management Zone: This technique involves alternative soil sampling procedure to create management zones and mainly based on aerial imagery, smart sampling and spatial modeling which involves the following steps.

Step 1. Acquire bare soil imagery

Step 2. Differentiate spectral variations/ strata using spatial statistical techniques

Step 3. Take soil samples based on cluster sampling (2-4 cluster/strata) and

Step 4(a) Use spatial modeling to predict measured soil properties, and (b) based on predicted soil properties for the entire field, management zones are delineated.

Precision nitrogen management strategies

The N management strategies commonly used during previous years included (i) Uniform N rate, (ii) Grid-based, (iii) SSMZ-based constant yield goal (SSMZ-CYG) and (iv) SSMZ-based variable yield goal (SSMZ-VYG). The uniform N strategy is based upon a conventional uniform N application using a constant yield goal. The grid-based strategy uses a variable-rate N application based upon intensive grid soil sampling (1 acre grids) and a constant yield goal. The last two strategies are variable-rate N applications based upon SSMZ using constant and variable yield goal approaches. Among the management strategies, SSMZ-VYG was found to be the best (Koch *et al.,* 2003) which fetched higher net returns (Table 3).

Research on Precision Nitrogen Management

There are three basic approaches: (i) site - specific N recommendation based on Grid soil sampling, Residual Soil-nitrate N values, N availability Maps and N fertilizer recommendation maps, (ii) second approach is to develop Site-specific optional N rate recommendations based on condition - specific N-response curves and (iii) Third approach focuses mainly (a) to develop Site-specific intervention N management based on crop N status monitoring (Canopy reflectance of light and Chlorophyll content), (b) estimate N requirement using established relationships between reflectance and N content and fertilize the crop to achieve optimal N content, (c) in some cases portion of a crop is fertilized to optimum levels and used as the standard for adjusting the N recommendations for the remainder of a field and (d) plant N is estimated using a previously developed index which is calculated from measured canopy reflectance.

Participatory site-specific nutrient management : simplifying nutrient management technologies to fit farmers' needs. These simplified technologies are discussed here.

Simplifying the field identification of soil series by farmers: Simplifying soil identification to a graphical, visual decision-aid helps the farmers learn the names and major characteristics of their soils. They use the soil series names to share their experiences, successes, and even failures, with other farmers with similar soils. The soil series identification tool is based on a decision-tree concept whereby five factors have been found to be sufficient to identify 38 of the maize producing soils.

(i) Soil color (black/dark brown, brown/yellowish brown, red/reddish brown, light gray/pinkish white); (ii) soil texture (loam/sandy loam, gravelly loam, clay, gravelly clay, sand); (iii) coarse fragments (none, rock fragments, limestone nodules, lateritic nodules); (iv) soil pH (4.5-5.5, 5.5-6.5, 6.5-8.0) and (v) soil depth (shallow, moderate, deep).

The soil series is used to identify or index soil parameters, potential yields, climatic data, and other information needed by the decision-aid to logically reason to a prediction and recommendation.

Simplifying the testing of soils

The soil test kit permits obtaining a measure of soil pH, nitrate and ammonium, phosphorus, and potassium within about 30 to 45 minutes and can short-circuit the lengthy delays typical of soil testing (Attanandana *et al.*, 1999b).

Simplifying fertilizer recommendations (Decision Support System)

The third simplification that is introduced is by using decision-aids to make fertilizer recommendations from the results of the soil series identification and the soil test kit results. Simplifying model predictions from those of sophisticated simulations to simple decision-aids also helps farmers and growers to use the information. The current N P K fertilizer recommendations for most crops are obtained from field experiments and the recommendations could not be transferred to the other places where the climate, soil type and plant variety are different. The purpose of the decision-aid is to take this information and develop a prediction of fertilizer requirements necessary to resolve the deficiency identified during the diagnosis by the soil test kit.

The components of the decision-aid are: (i) diagnosis of existing deficiencies / excesses, (ii) prediction of the fertilizer requirement, suggestion of an alternate crop, (iii) economic analysis of the response and the costs of the fertilizer requirement, and (iv) presentation of the results in farmer-friendly form and manner. There are three nutrient calculation algorithms embedded in the software, one each for nitrogen, phosphorus, and potassium. The N algorithm is based on the DSSAT 3.5 simulation model which has been adapted to accept soil test kit nitrate as the current N status of the field (Attanandana *et al.,* 1999a). The PDSS program based on a simple P algorithm was used for phosphate fertilizer prediction. Potassium fertilizer requirements are based on a Mitscherlich-Bray equation (Attanandana and Yost, 2003).

For extension officers, these algorithms were implemented in both desktop and hand held computers in both Thai and English versions. This software is called Sim Corn. This program (a decision-aid) was developed that implemented, in a user-friendly way, the two components of site-specific nutrient management already mentioned (soil series identification in the field and the soil test kit analysis of farmers' fields), together with algorithms to estimate fertilizer N, P and K requirements. Survey of 400 farmers revealed economic benefits of up to 200 US$/acre.

Economic feasibility of precision nutrient management

The profitability potential for variable-rate management is significantly enhanced, if the initial means of forming application maps are inexpensive (Koch and Khosla, 2002). Recent research in precision farming has focused on site-specific management zones (SSMZ) as a means to generate application maps and improve nutrient management in cropping systems (Khosla *et al.,* 2002; Fleming *et al.,* 2001; Khosla and Shaver, 2001; Fleming *et al.,* 2000; Luchiari *et al.,* 2000; Nolan *et al.,* 2000).

The Grid-based strategy increased average N applied by 1.3 and 30.7 %, over the uniform strategy for sites 1 and 2, respectively (Table 3). The SSMZ-CYG strategy increased average N applied over the uniform strategy by 1.3 % for site 1, while providing a 37.4 % savings in N applied at site 2. The SSMZ-VYG strategy provided a 6.3 % and 46.1 % savings in average N applied over the uniform strategy for sites 1 and 2, respectively. The average amount of N applied at each site was always less under the SSMZ-VYG strategy compared to uniform N application. With less N applied, N expense was reduced at both sites under the SSMZ-VYG strategy. These savings will impact net returns for the SSMZ-VYG strategy as N fertilizer expense is significantly reduced (Koch *et al.,* 2003). Variable-rate N applications using site-specific management zones increased net returns at both sites compared to uniform N applications (Koch *et al.,* 2003).

Table 3. Comparison of nitrogen management strategies

N Management strategy	Mean N rate ($/acre)		Net returns (kg/acre)	
	Site 1	Site 2	Site1	Site 2
Uniform (CYG)	158	91	8.16	3.50
Grid based (CYG)	160	119	-0.61	-10.37
SSMZ (-CYG)	160	57	-5.56	16.53
SSMZ (VYG)	148	49	12.87	14.98

Constraints for adoption of precision nutrient management

Some of the major constraints for adoption of precision nutrient management as given in Table 4 are: system weakness, stereotypic experimental research in agronomy, perception of field as an object of scientific study rather than as a business unit, research neither considers end user needs nor seeks stake holder participation and lack of man power trained in ICTs and Geospatial technology in NARS.

Some of the obstacles for adoption of precision farming in developing countries in general and India in particular are: culture and perceptions of the users, small farm size, lack of success stories, heterogeneity of cropping

Table 4. Issues related to precision nutrient management in developed & developing countries

Farming situation	Developed countries	Developing countries
Farm size	Big	Small
Soil fertility	High	Low
Fertilizer usage	High	Low
Yield levels	High	Low
Profitability	High	Low
Risks	Low	High
Farm machinery	High end	Low end
Precision farming	Complicated	Simple
techniques	RS,GIS,GPS	LCC, SSNM
Relevant PNM tech	Real-time and sensor based	Discrete and Image based

systems and market imperfections, land ownership, infrastructure and institutional constraints, lack of local technical expertise, knowledge and technical gaps and data availability, quality and costs.

Major challenges

The challenges that are to be faced before realizing the real benefits from precision nutrient management are: (i) making the interpretation process more automatic, generic and mechanistic as against empirical, (ii) location-specific RS solutions for integrated crop management program, (iii) developing simple and robust technologies and methodologies and (iv) evaluation at multiple sites with standardized methodologies providing proof of economic and environmental benefits

Opportunities

Business opportunities for precision farming technologies including GIS, GPS, RS and yield monitoring systems are immense. Recently, the governments of certain Asian countries initiated special efforts to promote precision farming. In Japan, the Ministry of Agriculture has allocated special funds for research on remote sensing applications of precision farming. A quasi-governmental institute "Bio-oriented Technology Research Advancement Institute (BRAIN)" is also funding research on precision farming. In Malaysia, the Malaysian Agricultural Research and Development Institute (MARDI) is promoting research on precision farming of upland rice. In India, Precision Farming Development Centres (PFDC) - have been established in more than 17 SAU's.

Availability of cheaper high resolution (5m) In India, Precision Farming Developmnet Centres (PFDC) have been established in more than 17 SAU's. Multi-spectral images (Remote Sensing) has helped in making site-specific decisions in many environments, soil characterization, non-destructive and real-time monitoring of crop growth and detection of abiotic stresses. The scope for precision nutrient management is unlimited.

It is concluded that although precision farming is discussed in developed countries, but it is still at a nascent stage in developing countries, including India. Precision farming in developing countries cannot be convincing, if only environmental benefits are emphasized. On the other hand, its adoption would be improved, if it can be shown to reduce the risk. Variable-rate N applications utilizing site-specific management zones based upon a variable yield goal were found to be more economically feasible than conventional uniform application. Although various on-the-go soil sensors are under development, but only electrical and electromagnetic sensors have been widely used in precision agriculture and The Sim Corn software was developed in Thailand to be used on hand held computer and desktop for extension officers and interested people for fertilizer recommendation of each soil series.

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