Indian J. Fert., Vol. 9 (4), pp.80-94 (15 pages)

Fertiliser Best Management Practices for Maize Systems

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Maize is an important crop for food and nutritional security in India. Strong market demand and resilience of maize to abiotic and biotic stresses have increased the area and production of maize in the country over the past decade. Productivity of maize, however, has not increased proportionately and significant yield gaps are evident across maize growing areas in the country. Maize is an exhaustive crop and removes large amounts of plant nutrients from the soil to support high biomass production. The 4R Principles of applying right source of nutrients, at the right rate, at the right time and at the right place is expected to increase nutrient use efficiency, productivity and farm profit from maize production and provides opportunity for better environmental stewardship of nutrients. Adaptation of 4R Principle-based site-specific nutrient management decision support tools provides the opportunity for large-scale adoption of improved nutrient management across maize ecologies.

Maize, a crop of worldwide economic importance, provides approximately 30% of the food calories to more than 4.5 billion people in 94 developing countries. The demand for maize is expected to double worldwide by 2050. Maize is considered as the third most important food crop among the cereals in India and contributes to nearly 9% of the national food basket (7). Grown in an area of 8.55 mha with an average productivity of 2.5 t ha^{-1}, maize contributes to more than half of the coarse cereal production of the country. The annual maize production in India is about 21.7 mt with an annual growth rate of 3 to 4 % (1). Maize yields in India need to be increased significantly to sustain this growth rate to meet India's growing food, feed and industrial needs.

Area, production and productivity of maize grew impressively during XIth plan at a growth rate of 2.6, 8.2 and 4.9%, as a result of commendable response both from the producers and industries (12). Historically, the area, production and productivity growth of maize during pre-green revolution era (upto 1970) was in increasing order but it remained slow and static during for almost 2 decades of post-green revolution era. However, during past one decade (2003-2011), there has been quantum increase in area, production and productivity of maize in India (**Figures 1, 2 and 3**). Introduction of single cross hybrids in Indian maize programme since 2006 resulted in productivity enhancement of 134 kg ha^{-1} $annum^{-1}$ in the last five years although the extent of coverage was less than 25%. Growing market demand by the feed and starch industry and increase in minimum support price from Rs. 540 q^{-1} in 2006-07 to Rs. 1175 q^{-1} in 2012-13 led to make maize as a more competitive crop and

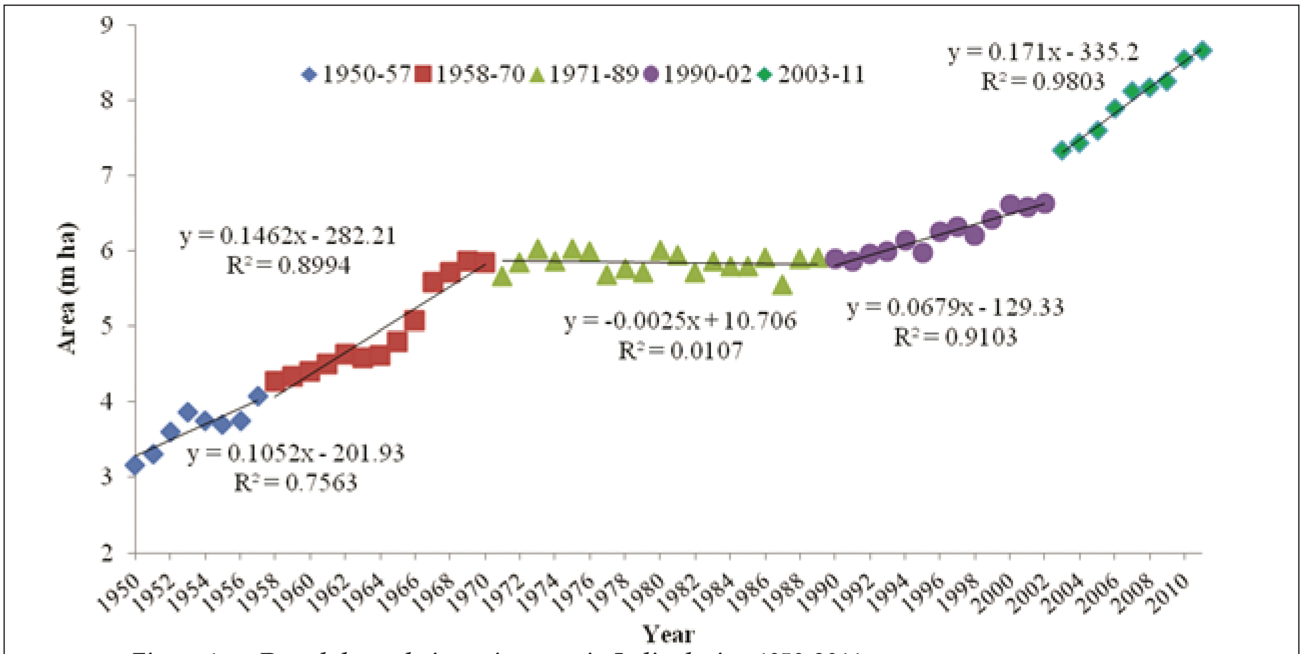

Figure 1 – Decadal trends in maize area in India during 1950-2011

encouraged farmers to grow maize to a large extent. Also, the export competitiveness of Indian maize especially for East Asian economies due to low freight charges made this crop more versatile with no carryover stocks and India exported a record 4.6 mt of maize during 2012-13 (12) and further opens the avenues for more demand of maize in India.

Consequently, maize is rapidly emerging as a favourable component crop in the major cereal based cropping systems of India. Development of high yielding maize hybrids with lesser water requirement, resilience to biotic and abiotic stresses, high resource use efficiency under various agro-climatic conditions, have led to development of new maize based cropping systems adapted to various farm typologies. With the current and projected challenges for natural resources such as water scarcity, temperature stresses etc, maize has emerged as a potential alternative for

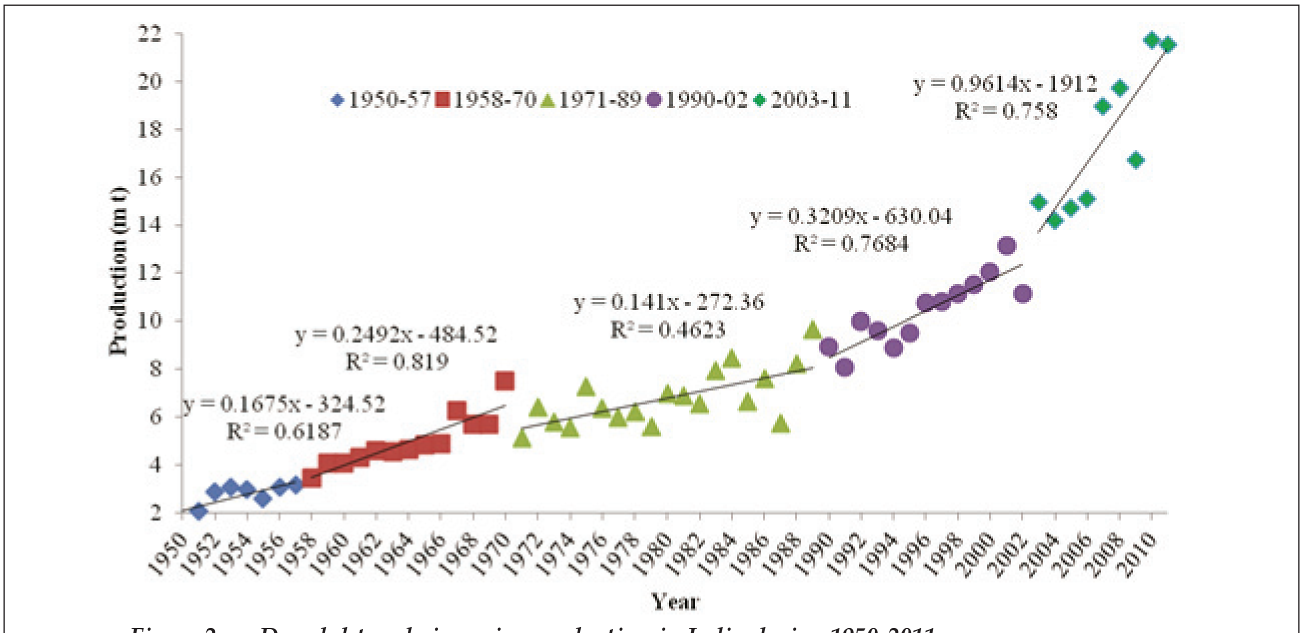

Figure 2 – Decadal trends in maize production in India during 1950-2011

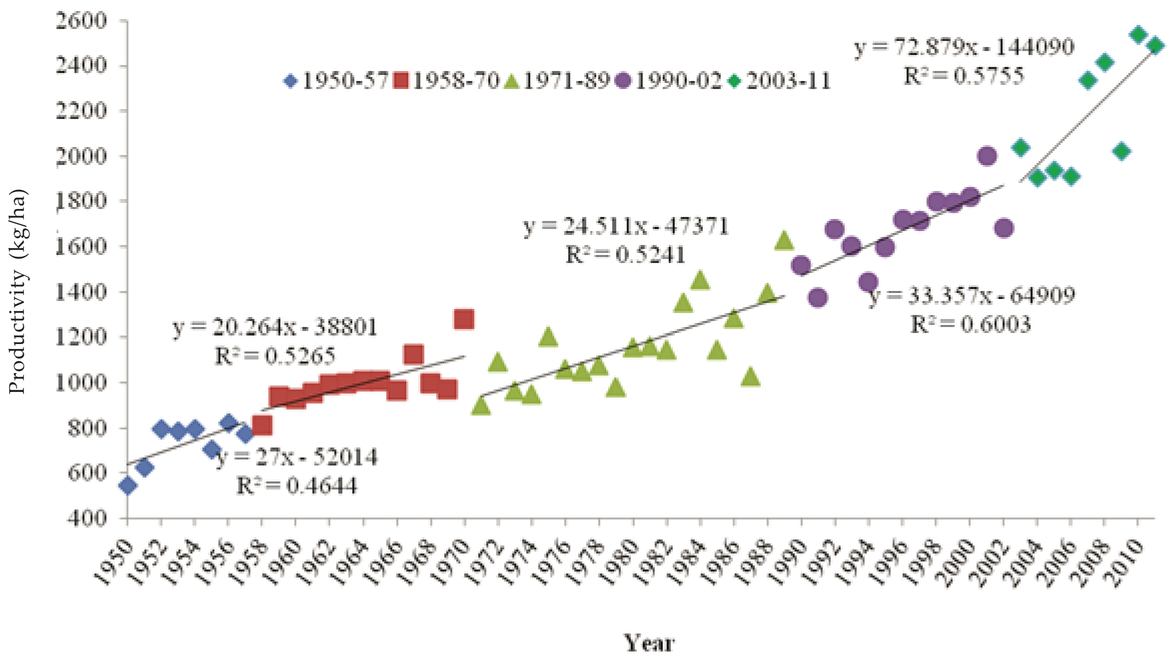

Figure 3 – Decadal trends in maize productivity in India during 1950-2011

diversification of rice-rice system with rice-maize and maize-rice systems; and rice-wheat system with rice-maize cropping systems in many ecologies of the country. Also, the market driven agriculture of specialty corn in peri-urban interface has opened another avenue for diversifying intensive cereal systems (13). High-yielding maize hybrids, with very high biomass production, extracts higher amounts of mineral nutrients from the soil than by other major cereals like rice or wheat. Biotechnology, breeding, and agronomic advancements have propelled maize yields to new highs with little guidance about fertilisation strategies for these modern maize hybrids to achieve their maximum yield potential. Being an emerging crop in many non-traditional ecologies and seasons, grown under different cropping systems and management practices, there exist large information gap on appropriate nutrient management strategies for maize in contrasting cropping systems and management practices. The fertiliser best management practices (FBMPs) for maize under such scenarios are still not well developed to help realize the sustainable benefit of these alternative maize based cropping systems. Application of existing fertilisation practices, developed decades ago, may not match uptake requirements of modern hybrids that are now grown at population densities higher than ever before. Nutrient requirement of maize varies from field to field due to high variability in soil fertility across farmer fields, and single homogenous nutrient recommendations may not be very useful in improving maize yields. Increasing fertiliser prices and escalating fuel prices in international market will make fertiliser input one of the costliest in agriculture. Fertiliser best management practices, with due importance to indigenous sources of nutrients such as organic manures, biofertilisers, crop residues, inclusion of legumes, use of nutrient efficient genotypes etc., will be required for sustainable management of emerging maize systems in the country. This paper provides a synthesis of current information on maize production systems, pros and cons of existing nutrient management strategies and the fertiliser best management practices for bridging yield gaps in current and emerging maize systems in the country.

Maize-based Cropping Systems in India

Maize is a versatile crop adapted to range of ecologies, seasons and regions in the country, and is grown in sequence or as companion crop with a range of crops under different production systems. However, the geographical spread of different maize-based rotations varies primarily with adaptability for a cropping window under prevailing ecology, land topography, soil type, moisture availability, and markets. Traditionally being a monsoon season crop, maize-wheat is still the predominant maize based system (1.8 mha) and is 3rd major crop-rotation in India and contributes ~3.0 % in national food

basket. The other major maize-based systems are maize-fallow, maize-mustard, maize-chickpea, maize-maize, maize-potato, etc. In recent past, the challenges of water shortages, temperature stresses in rice primarily in rice systems and to some extent in wheat systems, and opportunities of higher productivity of maize under these constrained environments as well as market opportunities for maize have led to evolution of several maize systems in non-traditional maize ecologies. For example rice-maize (~0.5 mha) has emerged as a potential maize system replacing winter rice in water scarce areas of double rice ecologies and wheat in terminal heat prone shorter wheat season ecologies. Introduction of high yielding maize hybrids for spring season and its adaptability to intensive rice systems have also led to evolution of rice-potato-maize system in larger areas of IGP. Emerging challenges of water scarcity and availability of very high yield potential hybrids for monsoon season coupled with improved agronomic management practices are leading to opportunities for re-evolution of maize-wheat-mungbean rotation in non-traditional intensive rice-wheat systems in western Indo-Gangetic Plains (IGP). Also, the emerging market opportunities for specialty corn and green cobs, high value intercropping systems involving maize are also emerging as potential maize systems in peri-urban regions of the country.

Yield Gaps in Maize

Fundamentally, yield gaps are caused by deficiencies in the biophysical crop growth environment that are not addressed by agricultural management practices. Yield potential (Yp) of any crop cultivar/ hybrid for a site and for a given planting date is the yield achieved when grown in environments to which it is adapted, with nutrients and water non-limiting and pests and diseases effectively controlled (10). Timsina *et al.* (37) using hybrid maize models, estimated yield potential of four maize hybrids in India that ranged from 7.1 to 19.7 t ha^{-1} and reported that planting during August to November gave exceptionally high yields due to low temperature during grain filling, long growth duration, and large receipts of solar radiation at some of the locations.

Attainable yield (Yat), generally set at 80–90% of Yp, is average grain yield in farmers' fields with best management practices and without major limitations of water and nutrients. Attainable yield can be limited by variety, planting density, water and nutrient management, soil-related constraints (acidity, alkalinity, salinity, etc.), and climate-related constraints (flooding, drought, etc.). Actual yield (Yac) is the yield farmers receive with their average management under all possible constraints. The difference between attainable yield (Yat) and actual yield (Yac) of crop species and varieties can be quite large. Attainable yield of maize in farmers' fields, achieved under optimal conditions, can vary significantly across the agro-ecologies mainly due to genotype x environment interactions but also due to confounding influence of biotic and abiotic stresses and agronomic management. Dass *et al.* (6) reported Yat and Yac of maize from experiments conducted in 13 representative locations in various agro-environments for 9 years (1995–2003) under the All India Coordinated Research Project (AICRPM) on maize. The selected locations were first divided into two categories: locations having lower productivity than the national average (Banswara, Udaipur, Godhra, Varanasi, Kanpur and Chhindwara) and locations (Mandya, Arbhavi, Ludhiana, Dhaulakuan, Bajaura, Dholi and Hyderabad) with greater productivity as compared to national average. Data indicated that the Yac is always less than Yat under all the agro-environments due to limited availability of agronomic inputs and their scheduling. Potential for improving Yat was more at the locations of the first group as compared to the locations of the second group. Except Banswara, other locations of the first group showed the potential for achieving Yat of 4–6 t ha^{-1}, while Yac at all the locations of this group was less than half (1-2 t ha^{-1}) of the Yat. It has also been reported that present average Yac at farmers' fields is only about 50% of the Yat, which could be increased through adoption of improved technology. On the other hand, Yat for most locations was about 4.0 t ha^{-1} except for Arbhavi (5.9 t ha^{-1}) in the high productivity group, whereas, Yac at most of the locations of this group was more (1.2–3.4 t ha^{-1}) as compared to the low productivity group (6). The data reveal that Yat of maize can be quite large, and so yield gap between Yp and Yat, between Yat and Yac, and that between Yp and Yac can be minimized.

Systematic analysis of the role of general and location specific determinants of maize yields may help to narrow down the yield gap at various levels and improving actual yields. Potential, attainable and actual yields of maize were evaluated at seven representative locations in South Asia under various agro-environments to generate the productivity scenario of maize under these ecolologies. The analysis of the simulated, attainable and actual maize yields in major maize growing ecologies across South Asia (**Figure 4**) revealed wide 'management yield gaps' ranging from 36 to 77% (30). These gaps are ascribed mainly to three major factors, (i) low yielding genotypes, (ii) poor crop establishment due to random broadcasting and (iii) inadequate and inappropriate fertiliser

nutrient applications as 15-45% maize acreage remains un-fertilised and the rest of the acreage has imbalanced nutrient applications (6, 15).

Nutrient Use in Maize

Nutrient removal is far excess of their replenishment under intensively cropped cereal systems in India, which has led to widespread multi-nutrient deficiencies in soils, consistently increasing response of crops to nutrient application (21). As a result of improved agronomic, breeding, and biotechnological advancements in maize systems, yields have reached far higher levels than achieved ever before. However, greater yields of maize have always been accompanied by a significant removal of macro and micronutrient from the soil. The latest summary on soil test levels in North America by IPNI reported that an increasing percentage of U.S. and Canadian soils have dropped to levels near or below critical P, K, S, and Zn thresholds during the last 5 years (11). Soils with decreasing fertility levels, coupled with higher yielding hybrids, suggest that farmers have not sufficiently matched nutrient uptake and removal with accurate maintenance fertiliser applications. Timsina and Majumdar (36) indicated that maize grain yields in Bangladesh have been decreasing where maize was grown on the same land for the last 5 to 10 years. The authors attributed the yield decline to imbalanced and inadequate nutrient application by farmers.

Maize with the yield potential of less than one t/ha removes about 90-100 kg/ha of nutrients from the soil **(Table 1)**. With the introduction of improved cultivars, the productivity has increased up to 4.0 t/ha with nutrient removal of around 220 kg/ha. Introduction of single cross hybrids, the productivity further increased to 7.0 t/ha and total nutrient removal has also increased to 420 kg/ha.

In several states of the country particularly hill ecologies (North Eastern Himalayas, Uttarakhand, Himachal Pradesh) and rainfed and tribal states (Madhya Pradesh, Chhattisgarh, Rajasthan, Orissa, and West Bengal), large area under maize production still remained untreated with fertilisers. The extent of area was up to 90 % especially in areas where farmers are not sure to harvest their crop due to abiotic stresses, particularly during monsoon season. Besides, the current nutrient use in the high input maize systems indicates imbalance plant nutrition with very high use of N and less use of P and negligible use of K fertilisers and micro nutrients. This has led to nutrient imbalances in soils and lower nutrient use efficiency and economic profitability. This warrants adequate and balanced use of plant nutrients not only for specific farm and ecology but also in production systems using fertiliser best management practices adapted to local situations and farm typologies to achieve better efficiency and nutrient stewardship.

Nutrient Response of Maize

While managing plant nutrients in maize systems, nitrogen (N), phosphorus (P), and potassium (K) remain the major ones for increased and sustained productivity. However, cultivation

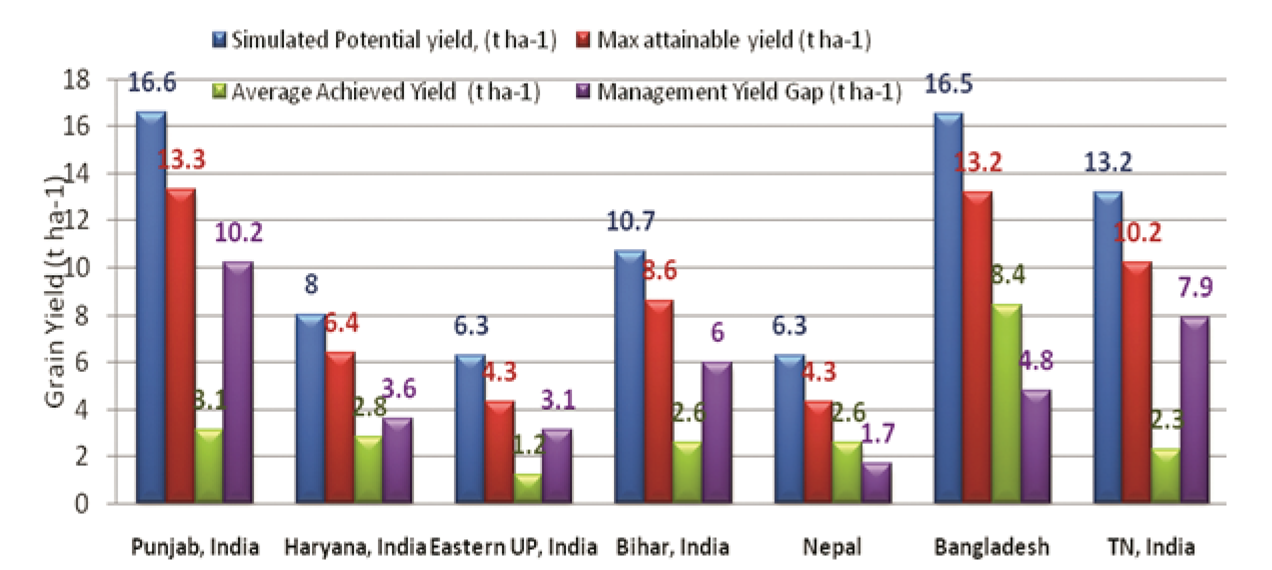

Figure 4 – Potential, attainable and actual yields and management yield gaps under different ecologies across South Asia

Table 1 – Major nutrient removal from the soil by the maize plant								
Plant part	Yield (t/ha)	Nutrient extraction (kg/ha)						Total
		N	P	K	Ca	Mg	Zn	
Traditional cultivars								
Grain yield	1.0	25	6	15	3.0	2.0	0.023	51.0
Stover	1.5	15	3	18	4.5	3.0	0.040	43.5
Total	2.5	40	9	33	7.5	5.0	0.063	**94.5**
Improved cultivars								
Grain yield	4.0	63	12	30	8.0	6.0	0.093	119.1
Stover	4.0	37	6	38	10.0	8.0	0.108	99.1
Total	8.0	100	18	68	18.0	14.0	0.201	**218.2**
Hybrid cultivars								
Grain yield	7.0	128	20	37	14.0	11.0	0.163	210.2
Stover	7.0	72	14	93	17.0	13.0	0.189	209.2
Total	14.0	200	34	130	31.0	24.0	0.352	**419.4**
Source: (41).								

of high yielding maize systems will likely exacerbate the problem of secondary and micronutrient deficiencies, not only because larger amounts are removed, but also because the application of large amounts of N, P, and K to achieve higher yield targets often stimulates the deficiency of secondary and micronutrients (17). However, for determining right rates of nutrients, information on crop yield response to fertiliser application, agronomic efficiency and return on investment (ROI) to fertiliser application is also essential. Soils of the major maize growing areas in India are inherently low in soil organic matter and nitrogen is the major limiting plant nutrient, with N availability being routinely supplemented through application of fertilisers. Though the yield increase in maize due to N fertilisation was substantial (92%), the average agronomic efficiency of N (kg grain kg^{-1} N) in maize was only 12.5 (28), indicating low N use efficiency. Satyanarayana *et al.* (32) reported variable maize yield response to N fertiliser application, ranging from 400-5160 kg ha^{-1} with an average response of 2154 kg ha^{-1}. Though N plays an important role in governing the yield of crops, lack of awareness on improved strategies of N management, coupled with relatively lower prices of N fertilisers (especially urea), encourages imbalanced use by farmers. Therefore, N management strategies that consider the yield response, agronomic efficiency of N (AEN), coupled with appropriate timing and splitting, may be used not only for minimizing the losses of N from agricultural fields but also for increasing the yield and profitability from N use. A recent study (3) reported that increasing N levels from 130 to 390 kg N ha^{-1} resulted in increasing maize yield from 4.3 to 9.02 t ha^{-1} in the maize-wheat cropping system (MWCS) of northern Karnataka. However, they also reported that in addition to crop response, AEN and ROI also need to be considered while deciding N application rate in the MWCS.

P response is highly variable and is influenced by soil characteristics and growing environment of the crop. P application rate, therefore, must be based on expected response of a particular location. An average maize P response of 853 kg ha^{-1} across 36 locations in Bihar and West Bengal was reported (14), which also indicated that the average P responses were higher in winter maize (1070 kg/ha) than in spring maize (513 kg/ha). However, P application based on yield response alone does not take into account the nutrient removal by crops where response is low or negligible. In such scenarios, nutrient removal by the crop would not be replenished adequately by external application, which may lead to nutrient mining and decline in soil fertility. One way to counter that would be to apply a maintenance dose that replenishes part of the nutrient exported out of the field with harvested crop part (grain and straw). This will ensure that soil fertility levels that can support intensive production systems are maintained. Finally, management of P fertiliser for maize systems must take account of residue and organic amendments applied to the soil.

Indian soils, despite often having relatively large total K content, resulted in variable yield and economic loss to the farmers with skipping application of K. Long-term use of N and P in the absence of K illustrates the seriousness of nutrient imbalance of a region. Li

et al. (19) demonstrated the effect of K fertilisation on maize production within a region that has typically relied on N and P alone. They reported that balanced use of N, P, and K fertiliser generated an average yield increase of 1.2 t/ha and improved farm income by USD 300/ha when compared to common farmer practice. Grain yield response to fertiliser K is highly variable and is influenced by soil, crop and management factors. Majumdar *et al.* (21) reported that the average yield loss of maize in Indo-Gangetic Plains due to omission of K application was 700 kg ha^{-1}. These observations were in contrary to the general perception that omitting potash for a season will not adversely affect maize production in the country. The results also demonstrate clearly the low K supply levels of most maize growing soils in India. Therefore, improved K management will have great potential for improving the overall productivity of maize systems in India.

A systematic approach of nutrient management (22) indicated that N, P, K, and Zn were the most limiting nutrients for maize growth in Tamil Nadu and relative yields were 57, 63, 71, and 75% of the optimum when N, P, K, and Zn were omitted. Also, maize yields and responses to applied nutrients varies considerably across farmer fields, mainly because of small and marginal landholdings that result in high variability in soil nutrient availability over small distances (33). The generally high variability in maize nutrient responses across fields and establishment practices suggests that spatial and temporal differences of nutrient availability needs to be accounted for while formulating nutrient management strategies in maize. Besides, large variability in crop response to all nutrients indicates the need to develop fertiliser recommendation tools that consider more than just a soil test (19). In other words, best-bet approaches for nutrient management like site-specific nutrient management and decision support tools like Nutrient Expert for Hybrid Maize, based on realistic estimates of indigenous nutrient supply and nutrient requirements for a targeted crop yield for individual farmers' fields, will be required to improve yield and nutrient use efficiencies in maize production systems.

Fertiliser Best Management Practices for Maize

Nutrient management in multiple cropping systems is a complex process. Maize and maize-based systems involving cereals, extract large amounts of mineral nutrients from the soil due to large grain and stover yields. Proper nutrient management of exhaustive maize-based systems should aim to supply fertilisers adequate for the demand of the component crops and apply in ways that minimize loss and maximize the efficiency of use. The amount of fertiliser required depends on many factors including the indigenous supply of each nutrient which can be of appreciable quantities (5). Phosphorus inputs from irrigation and rain waters are negligible but 1,000 mm irrigation through surface water may provide up to 30 kg K ha^{-1} yr^{-1} (8, 9) and up to 1,100 kg S ha^{-1} yr^{-1} (27). In Rice-Maize (RM) systems, K inputs may be much larger than 30 kg ha^{-1} where groundwater is used. Thus, emphasis must be upon the nutrient requirements for target yields and nutrient supply by integrated use of indigenous sources, soil organic matter (SOM), farm yard manure (FYM), composts, crop residues, and increasingly, fertilisers to achieve and sustain high yields and nutrient use efficiencies of intensive maize-based systems. Fertiliser is the dominant source of nutrients and is required to increase yield of crops but should be applied in such a quantity that it becomes profitable and will have least adverse effect on environment.

Improving our understanding of uptake timing and rates, partitioning, and remobilization of nutrients by maize plants provides opportunities to optimize fertiliser rates, sources, and application timings. Optimizing nutrient management in maize systems includes using the right source at the right rate, at the right time, and at the right place - the 4R approach (4). While developing fertiliser recommendations for maize, two major aspects of plant nutrition are important to understand for managing high yielding maize production systems. This includes: 1) the amount of a given mineral nutrient that needs to be acquired by the plant during the growing season, referred to as "total nutrient uptake," or nutrients required for production, and 2) the amount of the nutrient transported out of the field with grain and straw/stover, referred to as "removed with harvested product". Providing the nutrients as and when required by the crop and replenishing the exported nutrient out the field with harvested products ensures sustainability of production systems. Further improvement of fertility practices require matching in-season nutrient uptake with availability, a component of the right source, which is interconnected with the other components of 4R Principle. The maximum rate of nutrient uptake coincides with the greatest period of dry matter accumulation during vegetative growth for most nutrients. Unlike the other nutrients, P, S, and Zn accumulation are greater during grain-filling than vegetative growth; therefore, season-long supply is critical for balanced crop nutrition. Similarly, micronutrients demonstrate more narrow periods of nutrient uptake than macronutrients, especially Zn and B. Therefore, fertiliser sources that supply nutrients at the rate and time that match maize nutritional needs are critical for optimizing nutrient use

efficiencies.

Effectively minimizing nutrient stress requires matching nutrient supply with plant needs, especially in high-yielding conditions. Sulphur and N, for example, are susceptible to similar environmental challenges in the overall goal of improving nutrient availability and uptake. However, the timing of N uptake in comparison to S is surprisingly different (2), suggesting practices that are effective for one but may not improve uptake of the other. In case of Nitrogen, two-thirds of the total plant uptake is acquired by VT/R1 crop physiological stage of maize, whereas S accumulation is greater during grain-filling stages with more than one-half of S uptake occurring after VT/R1. Similarly, potassium, like N, accumulates two-thirds of total uptake by VT/R1 and greater than one-half of total P uptake occurs after VT/R1 (2), suggesting that season-long supply of P and S is critical for maize nutrition while the majority of K and N uptake occurs during vegetative growth. Unlike N, P, K, and S, which have a relatively constant rate of uptake, micronutrients exhibit more intricate uptake patterns. Uptake of Zn and B, for example, begins in the early vegetative stages and reaches a plateau at VT/R1 stage of the crop. Thereafter, Zn exhibits a constant uptake rate similar to that of P and S, while B uptake follows a major sigmoidal uptake phase concluding around R5 stage of maize. Zinc and B follows shorter periods of more intense uptake in comparison to macronutrients. Late vegetative and reproductive growth, constituting only one-third of the growing season, accounts for as much as 71% of Zn uptake by maize. A similar trend is also noticed for B where, as much as 65% of B uptake occurred over only one-fifth of the growing season (2). This also indicates that matching micronutrient needs of maize in high- yielding conditions clearly requires supplying nutrient sources and rates that can meet crop needs during key growth stages. Therefore, the 4R approach (right source, right time, right amount and right place) holds merit not only attaining higher yields but efficiency, profitability and environmental stewardship.

Integrated Nutrient Management Including Crop Residues

Intensified and multiple cropping systems require judicious application of fertiliser, organic and bio-fertilisers for yield sustainability and improved soil health. Integrated plant nutrient supply (IPNS) system encompasses a combined use of different sources of plant nutrients for maintaining and improving the soil fertility for sustainable crop production without degrading the soil resource on long-term basis. It relies on a combined use of organic manures including green manures, recycling of crop residues, bio-fertilisers, vermicompost and a judicious and need based use of fertilisers. A summary of multi-location trials on integrated nutrient management in maize (16) under partially irrigated conditions (**Table 2**), comprising of different combinations and levels of organic and fertiliser sources of nutrients {without organic manure (O_0) and application of FYM @ 6 t/ha (O_1) with four levels of fertiliser nutrients *i.e.*, 100:40:30 (N_1), 150:60:40 (N_2), 187:75:50 (N_3) and 225:90:60 N: P_2O_5: K_2O kg/ha (N_4)}, showed that application of FYM @ 6 t/ha at N_4 level resulted in highest grain yield during both the years which was at par with sole fertiliser application at N_3 level in the second year. The application of O_1N_4 resulted in 21.5 & 25.2; 14.4 &13.6; 9.2 & 11.6; 20.0 & 16.8 and 11.1 & 9.0 per cent increase over O_0N_1, O_0N_2, O_0N_3, O_1N_1, and O_1N_2 in the pooled grain yield of all the locations during 2007 and 2008, respectively. Pooled analysis of nutrient productivity across locations during both the years showed that it was highest with the application of O_0N_1 treatment as the application level produced maximum yield response often observed at the lower part of yield response curves.

While managing maize residues in IPNS, it is important to understand nutrient distribution within the maize crop. Of the total nutrient

Table 2 – Effect of integrated nutrient management on yield and nutrient productivity (kg/ha) of quality protein maize in different agro-ecologies (pooled data of 7 locations across different ecologies in India)

Treatment	Yield (kg/ha)		Nutrient productivity (kg grain/kg nutrient applied)	
	2007	2008	2007	2008
O_0N_1	4226^{f}	4395^{f}	28.1^{a}	26.1^{a}
O_0N_2	4735^{e}	4930de	20.8^{b}	20.5^{b}
O_0N_3	5136^{cd}	5173^{cd}	17.7^{bcd}	16.8^{c}
O_0N_4	5482^{b}	5512^{bc}	15.4^{cd}	14.7^{cd}
O_1N_1	4482^{ef}	4766^{ef}	19.9^{bc}	20.1^{b}
O_1N_2	5069^{d}	5333^{c}	16.6^{bcd}	16.6^{c}
O_1N_3	5433^{bc}	5745^{ab}	14.9^{d}	14.6^{cd}
O_1N_4	5839^{a}	6099^{a}	13.5^{d}	13.2^{d}
p value	<.0001	<.0001	<.0001	<.0001

Means with at least one letter common are not statistically significant using Fisher's Least Significant Difference

uptake in maize, nearly 80% of P is removed in maize grain compared to K and B, which are retained to a greater percentage in stover. For each nutrient, the fraction that is not removed with the grain remains in leaf, stalk, and reproductive tissues and constitutes the stover contribution that is returned to the field if the residues are returned back into the field. Returning the stover recycles back about 25% of N and P, 50 % of S and 75 % K uptake by cereal crops and replenishes large part of nutrient off-take from the field. Effective stover management through conservation agriculture based management practices can ensure almost 50% nutrient and most of the potassium and micronutrients back to the soil which will ensure sustainability of maize production in future. However, the availability of such nutrients, immediately after recycling of the straw, is influenced by microbial immobilization and mineralization processes and may not meet the nutrient demands of high yielding maize at the time of rapid growth stages.

Site-specific Nutrient Management (SSNM)

Precision Agriculture is an emerging concept wherein the input variables such as fertilisers are applied in right amount, at the right place and at the right time (variable rate application) as per demand of the crop-plants, rather than prophylactic application. It helps to improve input use efficiency, economy, and ensures sustainable use of natural resources, as it minimizes wastage. Site-specific nutrient management (SSNM) is one such approach that utilizes FBMPs for optimizing nutrient management in crops, including maize.

Site-specific nutrient management is a widely used term in all parts of the world, generally with reference to addressing nutrient differences, which exist within and between fields, and making adjustments in nutrient application to match these location or soil differences (17). In brief, the use of any diagnostic tool to evaluate soil fertility status, and subsequent prediction of external nutrient supply based on a specific crop yield goal, became the practice associated with the use of the term SSNM. It describes nutrient management recommendations that take into account the soil, crop to be grown and growing conditions of a specific location. SSNM recommendation may varies significantly, from a field specific soil test to output of decision support models based on predictive equations supported by SSNM principles. Ultimately, the success of a SSNM recommendation can be judged based on its performance relative to either a state recommendation, or the existing farmers' practice. Whether we have increased productivity and profitability to the farmer as compared to existing practices, and addressed the efficiencies necessary to support the sustainable use of fertiliser nutrients, defines the success of an SSNM approach. The SSNM approach was successfully implemented by the International Plant Nutrition Institute (IPNI) that improved field specific recommendation to a farmer, in a cost effective and timely fashion (18).

An experiment was conducted in rice-maize system at AICRP on maize centre Hyderabad, comparing SSNM with that of state recommendation and recommendation based on AICRP results, showed that highest yield of both rice and maize and also the highest system productivity were obtained with SSNM (35). This study further indicated that application of SSNM principles, aided by nutrient balance studies, can help improve nutrient management in rice-maize systems towards improving yield and profitability (**Figure 5**). Another field experiment on SSNM, conducted under AICRP on Maize in two major maize-based cropping systems, *i.e.* maize-wheat at 8 locations (Delhi, Bajaura, Udhampur, Dholi, Ludhiana, Pantnagar, Banswara and Ranchi) and rice-maize at 3 locations (Jorhat, Banswara, Hyderabad) during *Kharif* 2008 (**Figure 6**), indicated a significantly higher yield of maize under SSNM compared to state recommendations at most of the locations.

Nutrient Expert Decision Support System for SSNM in Maize Systems

SSNM is, however, a knowledge-intensive technology in which optimum fertiliser management for a crop field is tailored to specific local condition, growth duration of the variety, crop residue management, past fertiliser use, and input of nutrients from external sources. Such knowledge requirements have slowed the wide-scale promotion and adoption of SSNM by the farmers. Development of tools that consolidate the complex and knowledge-intensive SSNM information into simple delivery systems is the key for enabling farmers and their advisors to rapidly implement this technology on a large scale. IPNI in collaboration with CIMMYT has recently developed Nutrient Expert (NE), a new nutrient decision support system (DSS) for maize, based on SSNM principles. Nutrient Expert, while providing fertiliser recommendations, considers yield response and targeted agronomic efficiency in addition to the contribution of nutrients from indigenous sources. It also considers other important parameters of the growing environment affecting nutrient management recommendations in a particular location and enables crop advisors to provide farmers with fertiliser guidelines that are suited to individual farming

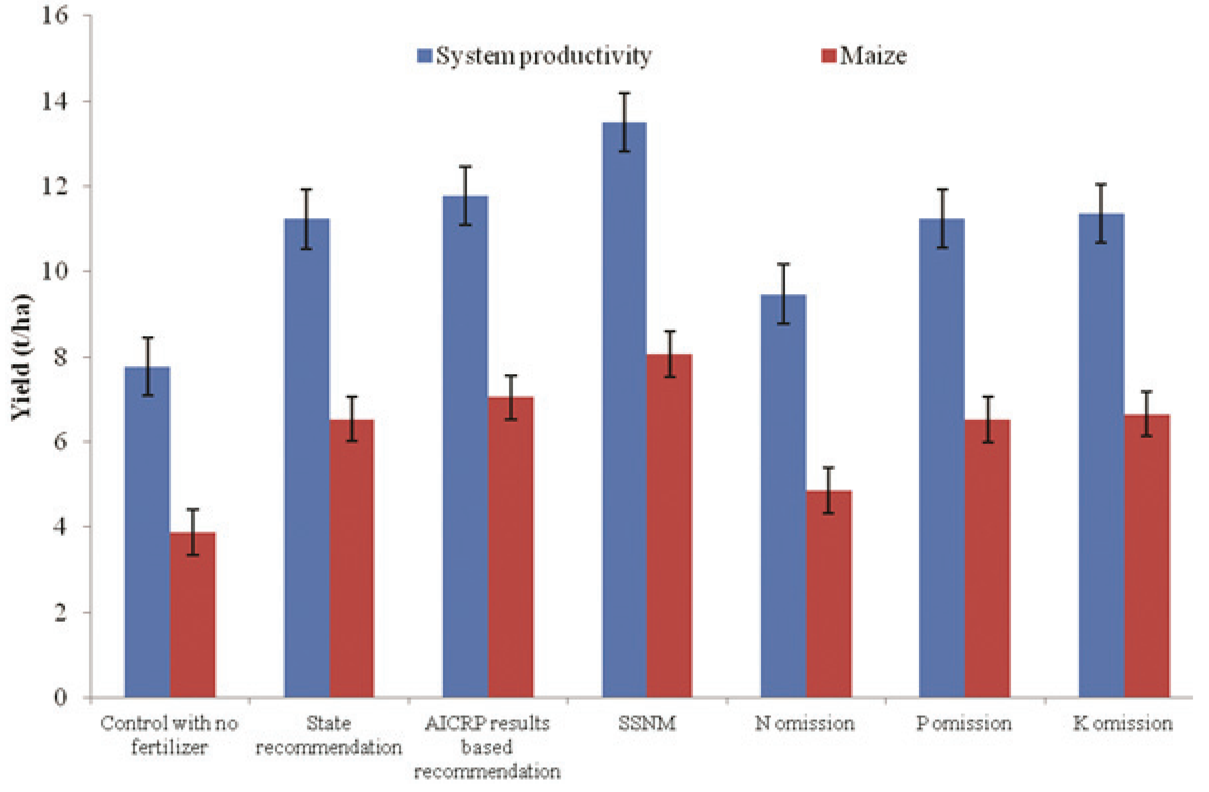

Figure 5 – Grain yield of maize and system productivity of an SSNM experiment in rice-maize system

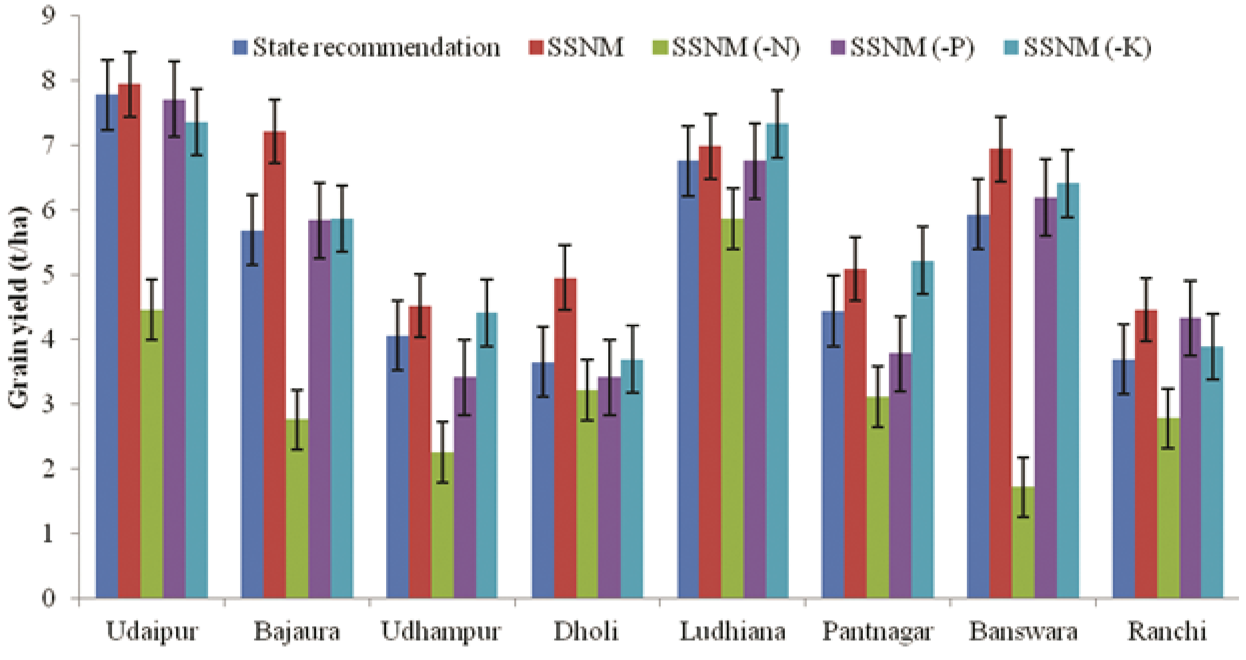

Figure 6 – Effect of nutrient management practices on grain yield of maize at different locations in India

Table 3 – Comparison of nutrient use in maize between NE and FP in southern India during Kharif 2011

Parameter	Unit	FP Southern India (n = 32)	NE	NE-FP	
Fertiliser N	kg/ha	80-550 (193)	110-230 (161)	-32	Ns
Fertiliser P_2O_5	kg/ha	38-230 (89)	17-81 (39)	-50	***
Fertiliser K_2O	kg/ha	23-352 (114)	18-104 (48)	-66	***

***Significant at $p < 0.001$; Ns = non-significant.FP, and NE = Farmer Practice, and Nutrient Expert. Values in parenthesis represent mean values

conditions. The tool uses a systematic approach of capturing site information that is important for developing a location-specific recommendation (24). The tool has been successfully used to provide farmer specific fertiliser recommendations in the major maize growing ecologies across the country and improved yield and farmer profit as compared to existing fertiliser management practices. A recent study using the NE tool for maize in South India (31) revealed that the N, P_2O_5, and K_2O use by farmers varied from 80 to 550, 38 to 230, and 23 to 352 kg/ha, with an average of 193, 89, and 114 kg/ha, respectively. The corresponding NPK use based on NE recommendations varied from 110 to 230, 17 to 81, and 18 to 104 kg/ha, with an average of 161, 39, and 48 kg/ha, respectively. The NE-based fertiliser recommendations reduced N, P_2O_5, and K_2O use by 32, 50, 66 kg/ha indicating 17, 56, and 58% reductions in fertiliser use over farmers' practice (FP). Data in **Table 3** for nutrient use in Kharif maize further revealed that the lowest N use in FP has increased from 80 to 110 kg/ha in NE, whereas, the maximum N use in FP has decreased from 550 to 230 kg/ha in the NE based recommendations. Data pertaining to relative performance of NE over sate recommended fertiliser dose (SR) and FP for grain yield of maize, fertiliser cost, and GRF in the same study are given in **Table 4**. Across all sites (n=32) during the Kharif season, NE-Maize increased yield and economic benefit (i.e. gross return above fertiliser costs or GRF) over FP and SR (**Table 4**). Compared to FP, it increased yield by 1.06 t/ha and GRF by 12,902 INR/ha with a significant reduction in fertiliser cost of 3,239 INR/ha. Recommendations from NE-Maize also increased yield (by 0.9 t/ha) and GRF (by 8,033 INR/ha) over SR with a moderate reduction in fertiliser cost (-1,041 INR/ha). This indicates that NE, in addition to suggesting the right rate of nutrients sufficient to meet the attainable yield targets, also helps in optimising nutrient use through appropriate reductions in fertiliser application. In contrast to SR, which gives one recommendation per state (e.g. 150 kg N, 75 kg P_2O_5, and 75 kg K_2O per ha in Andhra Pradesh), NE recommended a range of N, P_2O_5, and K_2O application rates depending on attainable yield and expected responses to fertiliser at individual farmers' fields. Further, the estimated maize yield response by NE to application of N, P_2O_5 and K_2O fertilisers across the growing seasons varied from 2 to 8, 0 to 1.8, and 0 to 2 t/ha with a mean response of 5.02, 0.69, and 0.77 t/ha (data not shown), and captured the temporal variability of nutrient requirement between seasons along with the spatial variability between farmers' fields. The varied yield response to N, P, and K application suggests that single homogenous state recommendations may become inadequate for improving maize yields in the region. Thus, fertiliser N, P_2O_5, and K_2O requirements determined by NE, varied among fields or locations, proved to be critical in improving the yield and economics of maize farmers in the region. In effect, use of the NE actually increased yields and profit, while reducing economic risk to the farmer, simply by

Table 4 – Performance of NE based recommendations for yield and economics of maize in southern India

Parameter	Unit	FP	SR Kharif 2011 (Monsoon season) Southern India (n = 32)	NE	NE-FP	
Grain Yield	kg/ha	6874	7033	7936	1062	***
Fertiliser Cost	INR/ha	7214	5016	3975	-3239	***
GRF	INR/ha	61484	66353	74386	12902	***

*** Significant at $p<0.001$, GRF = gross return above fertiliser cost;
SR-State Recommendation Prices (in INR/kg): Maize = 10.00; N = 11.40; P_2O_5 = 32.2; K_2O = 18.8

providing some direction in the most appropriate fertiliser rate.

Yield improvement with NE-based fertiliser recommendation could primarily be attributed to a balanced application of nutrients based on SSNM principles. The NE program recommended application of secondary and micronutrients especially S, Zn, Mn, Fe, and B at 24 out of 32 locations in the study area (data not shown). This clearly explains how NE helped in promoting balanced use of all the essential nutrients thereby improving yields and optimising nutrient use in the maize growing areas of Southern India.

Other Precision Tools and Techniques for Real-time Nutrient Application

Blanket recommendations based on fixed-time application of fertiliser N doses at specified growth stages do not consider the dynamic soil nutrient supply and crop nutrient requirements, and lead to untimely application of fertiliser nutrients. Therefore, need based fertiliser management in maize can help to improve recovery efficiency and to reduce nutrient losses. In-season N application adjustments of maize can be accomplished using leaf colour charts (LCC), SPAD and Green-Seeker sensors. Improved N management using the LCC has consistently shown to increase yield and profit as compared to FFP (29). Applying right rate of N (240 and 150 kg/ha in maize and wheat), coupled with the right timing for N fertiliser (3-split applications) using LCC-based real time N management proved to be beneficial in increasing the yield and profitability of maize-wheat farmers of Northern Karnataka (3). Singh *et al.* (34) evaluated different need based fertiliser N management strategies in maize and confirmed the usefulness of LCC 5 as threshold during vegetative growth stages for improving fertiliser N recovery efficiency and for obtaining high yields. They also observed that there was no response to fertiliser N application at R1 stage following different LCC threshold values. The authors further recorded that using LCC 5 as threshold of N application led to equivalent grain yield achieved with fixed time application of 150 kg N ha^{-1} but with the application of only 90 kg N ha^{-1}. The recovery efficiency was increased by 19.8–22.8 along with grain yield production improvement by 7.1–8.5 kg grain per kg applied fertiliser N.

Other Issues

There are other important crop management strategies that have positive influence on FBMPs.

Cropping System Optimization Including Legumes in Maize Systems

Optimizing cropping systems is one of the best-bet management strategies not only for improving productivity but also profitability and resource use efficiency and nutrient economy. In India, several best-bet maize based leguminous systems have been identified (for example, maize- wheat-greengram, maize-maize-cowpea/ greengram), which provides both the economic produce as well as stover for incorporation, as a viable means for N economy. Direct and residual effects of different legumes and sesbania green manuring on productivity, profitability, N-use efficiency and residual soil fertility in four maize based cropping systems (maize–wheat-moongbean, maize-mustard-moongbean, maize-maize-sesbania and maize-chickpea-sesbania) under conservation agriculture practices is under investigation at the Directorate of Maize Research (DMR), New Delhi, since Kharif 2008. The legumes were grown during summer (April/May to June), followed by maize in rainy season (July to October) and wheat/ maize/mustard/chickpea in winter season following recommended package of practices. Besides producing grains, green gram added significant amount of N (30-40 kg/ha) into the soil. Maximum amount of biomass on dry weight basis and highest N input in the soil was from *Sesbania* (126-135 kg N ha^{-1}). Remarkable improvement in the growth and yield of maize, following summer legumes, was also observed in addition to saving of N to the extent of 50–60 kg ha^{-1} with *Sesbania*, and 35–40 kg ha^{-1} with green gram. The succeeding crops grown in winter season also benefited by residual effect of summer legumes and showed N economy of 15–25 kg ha^{-1} after green gram, and 25- 29 kg ha^{-1} after *Sesbania*. There was a significant improvement in soil organic C and nutrient status after six cropping cycles with summer legumes. Results revealed that dual-purpose summer legumes were better options for improving productivity, profitability, N economy and soil fertility of maize based cropping system.

Tillage/Crop Establishment x Nutrient Interactions

Globally, research evidence suggests that adoption of conservation agriculture based management practices under different maize based production systems and ecologies can address the emerging challenges of natural resource degradation, energy, water and labour crises, low nutrient use efficiency and climate change effects. The variable soil environment under contrasting tillage and residue management practices have important bearing on dynamics of nutrients in the soil and influence the nutrient economy and use efficacy. Therefore, understanding nutrient dynamics under contrasting soil management practices is important for managing nutrients in an efficient way. Conservation tillage (CA) practices are increasingly becoming popular in maize systems in India. A nutrient omission study in winter maize (20) under zero- and conventional tillage showed that (**Figure 7**) N, P and K omission plot yields are higher under zero-till situations suggesting higher nutrient availability. Several researchers (23, 39) comparing CT and no-till production systems, suggested that more efficient utilization of fertiliser with no-till production produced higher yields. Pampolino *et al.* (25) also reported similar observations while evaluating NE-Wheat in different tillage options under varied growing environments. This suggests that tillage has a strong influence on nutrient dynamics and their availability to crops, and tillage X nutrient interactions must be addressed while developing nutrient management strategies for maize grown under variable tillage environments.

Nutrient Management Research Gaps

Traditionally, the nutrient management research was primarily focused on developing generalized prescriptions for larger domains and for conventional crop management practices. However, during recent past, conservation agriculture based crop management practices have emerged as one of the potential alternate to conventional tillage based maize production systems. But, still most research advances in nutrient management including SSNM caters to conventional tillage based crop management systems. The contrasting tillage management practices (conventional and conservation agriculture) will have implications on soil moisture regime and nutrient dynamics that in turn will influence nutrient response and economic profitability of nutrient application. Therefore, there is a need to develop prescriptions and application strategies in line with the 4R principles (right source, right rate, right time and right place) for conservation agriculture based maize systems. Therefore, to implement best management practices for plant nutrients at different scales our future nutrient management research in maize systems should focus on the following:

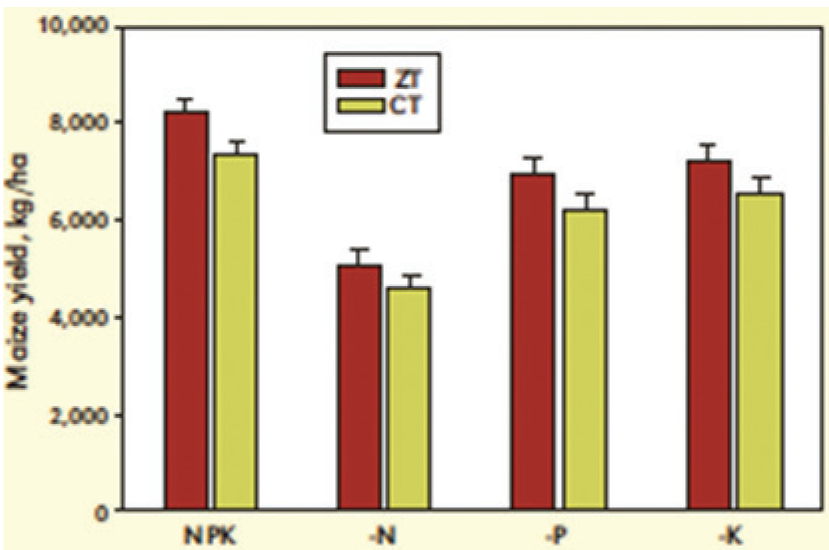

Figure 7 – Average yields of winter maize in omission plot trials under zero-till (ZT) and conventional till (CT) systems

- Crop physiological processes and efficiency under contrasting management practices will be variable that will lead to variable nutrient responses. Basic understanding of such processes will allow designing appropriate nutrient management decision tools/prescriptions.
- Nutrient availability under enhanced moisture availability under conservation agriculture scenarios needs to be understood properly to determine appropriate rate and time of nutrient application.
- Scientific basis of attainable yield targets need to be established under contrasting management practices for tillage and residues in various cropping systems under diverse ecologies (rainfed, irrigated).
- Calibrating sensors for nutrients not only for N but also P, K, Zn, etc.
- Establish relationships for on-the-go remote sensing sensors and satellite remote sensing for SSNM.
- Use of remote sensing and GIS for mapping fertility variability and making nutrient prescriptions at different scales.
- Geo-referencing/mapping of large domains for developing homologous regions for nutrient prescriptions.
- Develop, validate, and bring to scale decision support tools (Nutrient Expert) and farmer friendly simple practices for system based SSNM for small holder precision.
- Develop and deploy regional recommendations that can be distributed through ICT solutions
- Development of appropriate machinery for nutrient application (surface application, drilling, band placement, fertigation) under different management scenarios (no-till with and without surface

residues, conventional till with and without residue incorporations) is urgently required.

CONCLUSION

In India, maize has traditionally been grown as subsistence crop in unfavourable ecologies and hence there exist large management yield gaps in maize systems under different ecologies. Large proportion of these management yield gaps are contributed by imbalance and inappropriate plant nutrition and multiple nutrient deficiency. However, under the emerging resource constrained and variable climatic conditions, there has been a growing realization for maize to feed the future. Therefore, the technological advancements in maize systems needs twin shifts from subsistence to commercial maize farming and from production oriented to profit oriented sustainable farming. Therefore, defining precise recommendation domains for fertiliser best management practices for plant nutrients in maize systems and their implementation using modern tools, techniques and approaches have to play major role not only for bridging yield gaps but also for improving nutrient use efficiency, economic profitability and reducing losses and to address climate change issues.

REFERENCES

1. ASG. *Directorate of Economics and Statistics*, Govt. of India, New Delhi (2011).

2. Bender, R. R., Haegele, J. W., Ruffo, M. L. and Below, F. E. *Better Crops with Plant Food*, 97(1): 7-10 (2013).

3. Biradar, D. P., Aladakatti, Y. R., Shivamurthy, D., Satyanarayana, T. and Majumdar K. *Better Crops-South Asia*, 6(1): 19-21(2012).

4. Bruulsema, T.W., Fixen, P. E. and Sulewski, G.D. *4R Plant Nutrition Manual: A Manual for Improving the Management of Plant Nutrition*, North American Version. International Plant Nutrition Institute, Norcross, GA, USA (2012).

5. Cassman, K. G., Peng, S., Olk, D. C., Ladha, J. K., Reichardt, W., Dobermann, A. and Singh, U. *Field Crops Res*., 56:7–38 (1998).

6. Dass, S., Jat, M. L., Singh, K. P. and Rai, H. K. *Indian J. Fert.*, 4 (4): 53-62 (2008).

7. Dass, S., Jat, S. L., Chikkappa, G. K., Kumar, B., Kaul, Jyothi, Parihar, C. M. Kumar, A., Kumar, R., Kamboj, M. C., Singh, V., Yatish, K. R., Jat, M. L. and Singh, A. K. *Maize J.*, 1(1): 7-12 (2012).

8. Dobermann, A., Cassman, K. G., Cruz, P. C. S., Adviento, M. A. A. and Pampolino, M. F. *Nutr. Cyc. Agroecosy.*, 46:11–21 (1996).

9. Dobermann, A., Cassman, K. G., Mamaril, C. P. and Sheehy, J. E. *Field Crops Res.*, 56:113–138 (1998).

10. Evan, L. T., and Fischer, R. A. *Crop Sci.*, 39:1544–1551 (1999).

11. Fixen, P. E., Bruulsema, T. W., Jensen, T.L., Mikkelsen, R. L., Murrell, T. S., Phillips, S. B., Rund, Q. and Stewart, W. M. *Better Crops*, 94(4): 6-8 (2010).

12. Indexmundi, http://www.indexmundi.com/agriculture/?country=in&commodity-corn&graph=exports, March (2013).

13. Jat, M. L., Gupta, R. K., Erienstin, Olaf, Ortiz, and Rodomiro. *Chronica Hort.*, 46 (3): 27-31 (2006).

14. Jat, M. L., Kumar, D., Majumdar, K., Kumar, A., Shahi, V., Satyanarayana, T., Pampolino, M., Gupta, N., Singh, V., Dwivedi, B. S., Singh, V. K., Singh, V., Kamboj, B. R., Sidhu, H. S. and Johnston, A. *Indian J. Fert.*, 8(6): 62-72 (2012).

15. Jat, M. L., Saharawat, Y. S., Majumdar, K. and Gupta, R. *In: Addressing Climate Change effects and Meeting Maize Demand for Asia, Book of extended summaries for the eleventh Asian Maize Conference* (Eds Zaidi et al), Nanning, China, November 7-11, p 370-372 (2011).

16. Jat, S. L., Parihar, C. M., Singh, A. K., Jat, M. L., Sinha, A. K., Mishra, B. N., Meena, H., Paradkar, V. K., Singh, C. S., Singh, D. and Singh, R. N. *Indian J. Agric. Sci.*, **83**(4): (2013). (*Accepted for publication*).

17. Johnston, A. M., Khurana, H. S., Majumdar, K. and Satyanarayana, T. *J. Indian Soc. Soil Sci.*, 57 (1): 1-10 (2009).

18. Johnston, A. M., Majumdar, K. and Satyanarayana, T. *Indian J. Fert.*, SII-4:1-8 (2011).

19. Li, S., Jin, J., Duan, Y., Guo, T., Zhang, Y. and Li, Y. *Better Crops Plant Food*, 96(4): 18-20 (2012).

20. Majumdar, K., Jat, M. L. and Shahi, V. B. *Better Crops-South Asia*, 6(1): 8-10 (2012).

21. Majumdar, K., Jat, M. L., Pampolino, M., Kumar, A., Shahi, V., Gupta, N., Singh, V., Satyanarayana, T., Dwivedi, B.S., Singh, V.K., Kumar, D., Kamboj, B.R., Sidhu, H.S., Meena, M.C. and Johnston, A. *Indian J. Fert*., 8(5): 44-53 (2012).

22. Malarvizhi, P., Thiyageshwari, S., Paramasivan, M., Geetha, R., Kasthuri Thilagam, V., Nagendra Rao, T. and Satyanarayana, T. *Better Crops-India*, 3(1): 22-24 (2009).

23. Moschler, W. W. and Martens, D.C. *Agron. J.*, 65: 781-778 (1975).

24. Pampolino, M., Majumdar, K., Jat, M. L., Ocampo, A., Zaini, Z., Satyanarayana, T., Bana, A., Gupta, N., Pasuquin, J. M. and Kartaatmadja, S. *Paper presented at the 12th Congress of the European Society for Agronomy*, Helsinki, Finland, 20-24 August https://helda.helsinki.fi/handle/10138/36048 (2012a).

25. Pampolino, M., Majumdar, K., Jat, M. L., Satyanarayana, T., Kumar, A., Shahi, V. B., Gupta, N. and Singh, V. *Better Crops with Plant Food*,

96(3):29-31 (2012b).

26. Parihar, C. M., Jat S. L., Singh, A.K., Jat, M. L., Jat, R. K., Singh, D. K. and Sai Kumar, R. *DMR Technical Bulletin 2011/3*, Pusa Campus, New Delhi, pp 36 (2011).

27. Pasricha, N. S. *In: Proceedings of the 16th World Congress Soil Sciences*. ISSS/CIRAD, Montpellier, France (1998).

28. Prasad, R. *Indian J. Fert.*, 7(12): 66-76 (2011).

29. Rajendran, R, Stalin, P., Ramanathan, S. and Buresh, R.J. *Better Crops-South Asia*, 4(1):7-9 (2010).

30. Saharawat, Y. S., Singh, B., Malik, R. K., Ladha, J. K., Gathala, M. K., Jat, M. L. and Kumar, V. *Field Crop Res.*, 116: 260-267 (2010).

31. Satyanarayana, T., Majumdar, K., Pampolino, M., Johnston, A. M., Jat, M. L. Kuchanur, P., Sreelatha, D., Sekhar, J. C., Kumar, Y. Maheswaran, R., Karthikeyan, R., Velayutahm, A., Dheebakaran, Ga., Sakthivel, N., Vallalkannan, S. Bharathi, C., Sherene, T., Suganya, S., Janaki, P., Baskar, R., Ranjith, T. H., Shivamurthy, D. Aladakatti, Y. R., Chiplonkar, D., Gupta, R., Biradar, D. P., Jeyaraman, S. and Patil, S. G. *Better Crops-South Asia*, 6(1): 4-7 (2012).

32. Satyanarayana, T., Majumdar, K., Shahi, V., Kumar, A., Pampolino, M., Jat, M. L., Singh, V. K., Gupta, N. Singh, V., Dwivedi, B. S., Kumar, D., Malik, R. K., Singh, V., Sidhu, H. S. and Johnston, A. *Indian J. Fert.*, 8(8): 62-71 (2012).

33. Sen, P., Majumdar, K. and Sulewski, G. *Indian J. Fert.*, 4 (11): 43-50 (2007).

34. Singh, V., Singh, Y., Singh, B., Thind, H. S., Kumar, A. and Vashistha, M. *Field Crops Res.*, 120: 276–282 (2011).

35. Sreelatha, D., Sivalakshmi, Y., Anuradha, M., and Rangareddy, R. *Maize J.*, 1(1): 58-60 (2012).

36. Timsina, J. and Majumdar, K. *Better Crops-South Asia*, 6(1): 25-26 (2012).

37. Timsina, J., Buresh, R. J., Dobermann, A., Dixon, J., Tabali, J. IRRICIMMYT Alliance Project "Intensified Production Systems in Asia (IPSA)", IRRI-CIMMYT Joint Report, IRRI, Philippines (2010).

38. Timsina, J., Jat, M.L. and Majumdar, K. *Plant and Soil*, **335**:65–82 (2010).

39. Wells, K. L. *In Nitrogen in Crop Production, Hauck et al., (eds.), ASACSSA-SSSA*, Madison, Wisconsin, USA (1984).

40. Yadav, R. L., Subba Rao, A. V. M. *PDCSR Bulletin No 2001-2*, Modipuram, Meerut, pp. 96 (2001).

41. Zaidi, P.H. and Singh, N.N. *Directorate of Maize Research*, New Delhi, pp. i-vi + 1-145 (2005). ■