A Review of Crop Productivity and Soil Fertility as Related to Nutrient Management in the Indo-Gangetic Plains of India

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The Indo-Gangetic Plain (IGP) is among the most extensive fluvial plains of the world and covers several states in northern, central, and eastern India. The IGP produces about 50% of the country's foodgrains ...enough to feed 40% of the population of India. The production of grains is, however, not uniform across the IGP regions because of various inadequacies in crop management of which rampant imbalanced fertiliser application is a key influence for stagnating or declining yields, nutrient use efficiencies, and soil health.

The IGP represents eight agro-ecological regions and 14 agro-ecological subregions in the northern, central, and eastern parts of India **(Figure 1)**. It covers about 43.7 million (M) ha, or approximately 13% of the total geographic area of India. Over the last 3 to 4 decades, states within the IGP have been successful in increasing their foodgrain production, chiefly rice and wheat. The strategies and measures that were adopted to achieve this success included the spread of high-yielding varieties, expansion of irrigated area, increased use of fertilisers and plant protection chemicals, strengthening of marketing infrastructure, and the introduction of subsidies. However, the production of grains is not uniform across the IGP region because of the spatial variation in the land resource and socio-economy. In reality, these management interventions intended for a 'money economy' combined with rampant, imbalanced fertiliser application have resulted in widespread cases of degradation and depletion of natural resources, loss of soil carbon, declining water levels, drainage congestion, loss in soil fertility, and nutrient imbalance, including multi-nutrient deficiencies (Abrol and Gupta, 1998; Bhandari et al., 2002). This paper reviews the (i) trends in crop productivity and soil fertility in relation to nutrient management in the IGP, and (ii) available information on the potential of some efficient and site-specific nutrient management (SSNM) strategies to increase crop productivity, boost farm income, and improve overall agricultural sustainability in the IGP.

Figure 1. Indo-Gangetic plains (IGP) of South Asia.
(Adapted from http://www.gecafs.org/research/indo_gangetic.html)

Average vs. Potential Rice-Wheat Yields

In most parts of the IGP where rice-wheat is currently produced, climatic factors allow a potential yield between 12.0 and 19.5 t/ha (Aggarwal et al., 2000). But the average yields of rice and wheat in the states of Punjab, Haryana, Uttar Pradesh, Bihar, and West Bengal are 7.5, 6.1, 4.5, 3.3, and 4.4 t/ha, respectively (Ladha et al., 2003). The large variation in average yields across these different states indicates that, at a regional level, considerable yield gaps still exist in most parts of the IGP. Shukla et al. (2004) observed that in the eastern states of Uttar Pradesh and Bihar, there is a large untapped potential for rice and wheat production. Similarly, Aggarwal et al. (2000) showed that several districts of Uttar Pradesh had potential yields similar to those in Punjab and Haryana. Yet, in most cases farmers of this region were not able to attain higher yields, mainly because of the sub-optimal input use and degrading soil quality.

Abbreviations: N = nitrogen; P = phosphorus; K = potassium; Zn = zinc; B = boron; INR = Indian rupee currency code; M t = million metric tons.

Table 1. Decadal trends in partial factor productivity.

Period	Increase in fertiliser nutrient consumption, M t	Increase in food grain production, M t	Response ratio, kg grain/kg applied nutrients ($N+P_2O_5+K_2O$)
1960-1970	1.47	26.40	17.9
1971-1980	2.44	31.09	12.7
1981-1990	5.28	46.80	8.9
1991-2000	3.18	19.53	6.3

Source: J.K. Ladha, personal communication.

Trends in Productivity

Partial Factor Productivity (PFP) is the average productivity, measured by grain output divided by a single input like fertiliser (Snyder and Bruulsema, 2007). Studies have shown sharply declining trends in the PFP of fertiliser over time in the rice-wheat cropping system of the IGP **(Table 1)**. Although this decline has been cited as a cause for concern about sustainability of the system, PFP can be highly misleading in this context. For example, survey data for a group of farmers in Central Luzon in the Philippines show that it took 10 to 15 years after the introduction of modern varieties for average N use in the wet season to increase from 10 to 60 kg/ha (Ladha et al., 2000). And the spread of higher levels of fertiliser use from one area to another has also taken time, requiring the transmission of knowledge and the construction of irrigation systems. As PFP is negatively correlated with fertiliser use by definition, an increase in fertiliser use will decrease PFP. However, this decline does not always imply a lack of sustainability in the system. Rather, as is clear from the above example, the

Table 2. Nutrient deficiencies observed at different research stations in the IGP under rice-wheat cropping system.

Centers	Nutrients deficient P	K	S	Zn	Fe	Mn	Cu	B
PDCSR, Modipuram	-	√	√	√	-	√	√	√
GBPUA&T, Pantnagar	√	√	-	√	-	√	-	√
CSAUA&T, Kanpur	√	√	√	√	-	-	-	-
NDUA&T, Faisabad	√	√	√	√	-	√	-	√
BHU, Varanasi	√	√	√	√	-	√	√	√
RAU, Sabour	√	√	√	-	-	-	-	-
BAU, Ranchi	√	√	√	√	-	-	-	√
HPKV, Palampur	√	√	√	√	-	-	-	√
PAU, Ludhiana	√	√	√	√	√	√	√	√
R S Pura	√	√	√	√	-	√	√	-

decline was the result of the adjustments farmers had to make to switch to modern varieties.

As an alternative to PFP, it is preferable to calculate sustainability trends through production functions or through Total Factor Productivity (TFP), measured by grain output divided by all inputs (Ali and Byerlee, 2000). Data used to measure TFP at the farm level are difficult to collect because they require a large amount of detail, including the prices and quantities of all inputs and outputs. Nevertheless, Murgai (2000) estimated the trend in TFP in the rice-wheat system of Punjab, and suggested that "fears about unchecked reductions in productivity growth in this system are exaggerated." However, it is important to remember that TFP does not directly measure environmental degradation. In fact, Ali and Byerlee (2000) found substantial deterioration of soil and water quality in all cropping systems in Pakistan's Punjab, including those with positive TFP growth. It was most severe in the wheat-rice system, where it reduced TFP growth by 0.44% per annum during the period 1971-94. If TFP growth is positive in the presence of environmental degradation, this indicates that technological progress and improved infrastructure have more than compensated for any environmental degradation. But even if this effect has happened in the past there is no guarantee that it will continue in the future.

Trends in Soil Fertility

Research conducted in the IGP over the last 20 years indicates gradual but continuous nutrient mining from soils **(Table 2)**. First, there has been a widening N:P:K use ratio for fertiliser in the IGP. In fact, in a long-term study funded by IPNI (personal communication, unpublished data), N:P:K ratios within the same district varied between 1.6:1.0:1.0 and 3.5:1.7:1.0 within a span of just 8 years (1997-98 to 2004-05). Secondly, the decreased use of organic manures, reduced recycling of crop residues, and bumper harvests over the past three decades have induced large secondary and micronutrient deficiencies. A survey of Indian soils has revealed that about 49% of soils distributed over 20 states are deficient in available Zn (Nayyar et al., 2001). In the same study, the incidence of B deficiency was found to be the highest in the acid soils of West Bengal followed by the calcareous soils of Bihar.

Impact of Site-Specific Nutrient Management Approaches

In the soil-test based approach to calculate site-specific fertiliser recommendations, fertiliser rates are established based on the concept of crop removal, with an adjustment for soil residual nutrients. While this approach actually fits most production systems in India quite well, given that most of the crop biomass is removed from harvested fields, the role that residual soil nutrients play in meeting crop nutrient requirements becomes a challenge. For example, if a soil tests medium or low in most plant nutrients, then application of these nutrients based on crop removal from a target yield is going to address these nutrient demands. However, on soils where the soil nutrient analysis indicates a high level of nutrient supply, the issue of whether to apply the nutrient at removal rates becomes a challenge to the researcher. The best option, therefore, is to apply all macronutrients and secondary nutrients that are required to meet crop yield removal and those micronutrients that soil testing show to be marginal or deficient. This then provides the environment for full yield expression in the absence of any nutrient deficiency. And once this yield potential of a site has been determined, the next step is to refine nutrient application rates with further field trials. The positive impact of this approach to fertilisation was clearly shown in a series of research experiments conducted by IPNI on soil test-based SSNM in rice-rice and rice-wheat cropping systems in seven different locations in the IGP. When the yield-limiting nutrients were identified and applied at each location as a SSNM treatment, it was able to generate large improvements in yield and profitability over farm practice across all sites. A smaller gap existed between SSNM and the State recommendation, although most sites still suggested an economic advantage for the SSNM approach **(Table 3)**.

Plant-based SSNM is a dynamic, farm-specific management of nutrients in a particular crop or cropping system using crop-based estimates of indigenous nutrient supply. This approach tries to optimise the supply and demand of nutrients according to their differences in cycling through soil-plant systems. The approach was evaluated comprehensively for agronomic, economic, and environmental performance in 56 farmer fields with irrigated wheat and transplanted rice in Pun-

Table 3. Effect of site-specific nutrient management (SSNM) on wheat productivity (t/ha) and economic return (INR/ha) in parentheses at seven locations in India.

Site	Farm practice	State recommendation	SSNM	Increase over SR, % (INR/ha)	Increase over FP, % (INR/ha)
Ranchi	2.56 (1,575)	4.15 (25,276)	4.06 (26,854)	-2.2 (1,578)	58.5 (25,309)
Modipuram	4.77 (29,292)	4.90 (31,859)	6.43 (58,083)	31.0 (26,224)	46.5 (28,791)
Kanpur	4.72 (7,258)	5.45 (17,644)	6.00 (31,338)	10.1 (13,694)	27.1 (24,080)
Ludhiana	5.45 (27,772)	6.28 (39,105)	6.55 (46,219)	4.3 (7,114)	20.1 (18,447)
Sabour	3.92 (18,306)	4.97 (28,614)	5.82 (45,116)	17.1 (16,502)	48.7 (26,810)
Pantnagar	3.87 (7,828)	5.10 (14,276)	6.39 (19,426)	25.3 (5,150)	66.0 (11,598)
Palampur	2.64 (55,122)	3.76 (54,583)	3.87 (60,905)	3.0 (6,322)	46.5 (5,783)

Table 4. Grain yield of rice and wheat, agronomic (AEN), recovery (REN), and physiological (PEN) N efficiencies, total fertiliser cost (TFC), and gross returns above fertiliser cost (GRF) in 56 farmer fields under rice-wheat cropping system in Punjab.

	----- Rice -----		----- Wheat -----	
	FFP	SSNM	FFP	SSNM
Grain yield, kg/ha	5.1	6	4.2	4.7
AEN,kg grain/kg N	8.8	16.1	8.3	13.6
REN, kg N/100 kg N	20	30	17	27
PEN, kg grain/kg N	34.7	44.2	29.4	37.1
TFC (INR/10 ha)	23,055	34,930	31,059	34,800
GRF (INR/ha)	24,578	28,014	22,316	25,274

jab (Khurana et al., 2007; Khurana et al., 2008). The results of the study clearly brought out the positive impact of SSNM on grain yields, and agronomic, recovery, and physiological efficiencies of N under rice-wheat cropping system in Punjab vis-à-vis farmer practice **(Table 4)**. Also, the highly negative P and K balances observed in farmer fields were reduced using the SSNM approach, indicating that SSNM promotes more balanced fertilisation than is followed by farmers.

A geographical information system (GIS) approach has recently been successfully applied to rice fields (Sen et al., 2008), where developed maps showing the spatial variability in soil nutrient status (Sen et al., 2007) are used as a site-specific fertiliser recommendation tool. This mapping is based on two factors: 1) nutrient content of agricultural soils varies spatially due to variation in genesis, topography, cropping history, fertilisation history, and resource availability; and 2) a lack of adequate infrastructure for soil testing within the patchwork of small holdings. The interpolation technique used in the GIS platform creates a smooth surface map of the study area utilising point information (geographic location and corresponding soil parameters), where each point on the map has a soil parameter value associated with it **(Figure 2)**. Besides the logistical and economic advantages of implementing such a system, once established the technique can create an effective extension tool where field agents work more directly with farmers. Thus, farmers become more aware of how their fields rank within the landscape in terms of basic soil fertility, which in turn enables a system of more rational use of fertiliser application.

Though SSNM approaches are far from perfect, they do help to overcome many of the challenges associated with statewide blanket recommendations that currently are used extensively in the IGP. A systems approach with well-developed analytical framework, databases, and powerful simulation models can improve these approaches further to help sustain food security of India for a long time.

Conclusions

Crop productivity, factor productivity, and soil fertility are not uniform across the IGP regions because of the spatial variation in land-resource characteristics and socio-economy in the region. Also, the imbalanced fertiliser application in the IGP has resulted in stagnating or declining effects on yields, nutrient use efficiencies, and soil health. Nutrient management using new and more efficient, knowledge-intensive, and site-specific approaches have shown promise to help sustain food security of India for a long time. A systems approach with well-developed analytical frameworks, databases, and powerful simulation models can help improve these approaches further. BC-SA

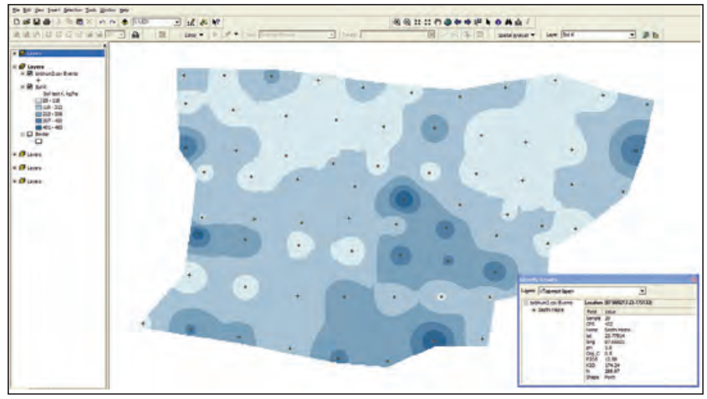

Figure 2. Example of nutrient variability map as a fertiliser decision support tool in farmer fields.

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