Research Findings

Long-term Rice-Rice field demonstration of target-yield approach. Photo by R. Santhi.

Soil Nutrients and Crop Response-Curve Types in Farmers' Fields: Key to Balanced Fertilizer Use and Sustainable Soil Fertility Management

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Abstract

Significant efforts have been made during the last 50 years to make traditional Indian agriculture more productive but sustainable, using scientific approaches. In this mini-review, aspects of soil fertility are examined, with an emphasis on the relationships between changes in soil nutrient status and various types of crop response to those changes. In addition, the target-yield approach is re-examined with the aim of maintaining and enhancing long-term soil fertility. An important emerging conclusion is that in order to preserve and improve farmers' benefit from fertilizer inputs, and ensure soil health and fertility, a consistent multi-directional flow of information between farmers, extension officers, soil laboratories, and scientists is essential.

Keywords: Integrated plant nutrition; potassium; soil test.

Abbreviations: STCR - soil test crop response; IPNS - integrated plant nutrition system.

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Introduction

Significant efforts have been made during the last 50 years to make traditional Indian agriculture more productive but sustainable, using scientific approaches. In this mini-review, aspects of soil fertility are examined, with an emphasis on the relationships between changes in soil nutrient status and various types of crop response to those changes. In addition, the target-yield approach is re-examined with the aim of maintaining and enhancing soil fertility. An important emerging conclusion is that in order to preserve and improve farmers' benefit from fertilizer inputs, a consistent multi-directional flow of information between farmers, extension officers, soil laboratories, and scientists is essential.

Soil fertility

Soil nutrients naturally originate from three sources: local bed-rock weathering, sediments imported by water or wind, and biogenic minerals. The different forms of soil nutrients retain a dynamic equilibrium with their soluble forms (ions) in the soil solution; those that are available and taken up by the root system of the plant. This dynamic equilibrium is constantly changing due to interactions of soil composition and texture with temperature, soil water status, and plant demands for nutrients. Bray (1945) and Black (1973) elaborated this dynamic equilibrium through a nutrient mobility concept of soil-plant relationships.

Truog (1953) put the different forms of soil nutrients into three categories: a) readily available; b) moderately available; and c) slowly available nutrients. Readily available nutrients include soluble nutrients or ions in an exchangeable condition, as either anions or cations, associated with the extensive surface of soil colloids. Nutrients associated with recently formed, less stable chemical precipitates, or those that are fixed in between the lattices of clay minerals are moderately available. Nutrients associated with chemically stable precipitates or those forming the soil lattice or clay minerals are slowly available nutrients. The organic forms fall into the different categories depending on the ease with which they are mineralized in the soil. Usually, there are many members in each category.

Water is the major factor affecting soil nutrient dynamics. Chemical processes that slow down or pause when soil is dry are reactivated and intensified when water returns. Precipitation frequency, quantity, and intensity have significant chemical and physical influences on soil texture, structure, and nutrient readiness or loss. Thus, dry climates produce poor soils, while well distributed and adequate rainfall enhance soil fertility. However, extreme rain intensities usually cause soil erosion and nutrient loss.

In agricultural ecosystems, significant efforts are made to control the edaphic environment. Soil is tilled and prepared in order to maximize water absorbance. Where possible, water is supplied through irrigation. Nutrients are applied through chemical fertilizer or manure. However, soil nutrient dynamics in agricultural ecosystems are also under significant pressure; crops (monoculture in most cases), tend to accelerate soil nutrient depletion, compared to the natural ecosystem. Also, nutrient depletion might be selective, according to the preference of each crop species.

Ramamoorthy (1965) discussed the physical chemistry behind this complex interaction on the availability of plant nutrients in soil, in terms of the potential of nutrient ions such as phosphorus (P) and potassium (K) in the soil solution and in plant roots. He showed that there is need for P and K fertilizers as long as the equilibrium phosphate potential (EPP) and the equilibrium potassium activity ratio (EKAR) of the soil is less than that of the plant.

Soil and fertilizer nutrients

The role of fertilizers as a prerequisite for food security, particularly in the production of food grains, cannot be overstated (Raju, 2008). The consumption of fertilizer nutrients increased significantly from 9.4 kg ha^{-1} in 1967-68 to 117 kg ha^{-1} in 2007-08, and further to 141 kg ha^{-1} in 2013-14, respectively. In the 1980's, out of a net cropped area of 143 million ha, soils in 95% of the districts were reported to be either low or medium in available P (Tandon, 1987). Fertilizer trials conducted in farmers' fields under irrigated conditions indicated a significant countrywide (in 49 districts of India) response to K application (Sekhon, 1985). Yield response to K was particularly significant in soils from the alluvial plains of India that had long been regarded as K sufficient. In fact, concerning K, nutrient availability, rather than soil nutrient content, is the critical determinant of soil fertility. Pratt (1951) defined three categories of soil K fractions (water soluble, exchangeable, and non-exchangeable) that largely differ in their availability coefficient for plants, with the ratio of 1:0.28:0.003, respectively. The potential K availability is largely dependent on pedogenesis - location-specific soil parent material and forming processes (Reddy *et al.*, 1987).

Crop nutrient requirements

Plant biomass production requires adequate supplies of mineral nutrients. With carbon (C) assimilated through photosynthesis, nitrogen (N) is needed for protein and nucleus assemblies that govern and enable all growth and developmental processes. Phosphorus is a crucial component of the energy coin, ATP, which enables energy flow and management in plant cells. Potassium is involved in the maintenance of plant water status, photosynthesis, and carbon allocation, storage, and remobilization (other macro- and microelements are important as well but are not discussed here). Plant nutrient demands over time are proportional to the biomass growth rate, nevertheless, nutrient deficiency might limit that rate. Furthermore, nutrient demands may vary among plant development phases. While N is required mostly during the earlier vegetative growth stage, K demands upsurge during the reproductive stage, when C storage or remobilization take place. Therefore, soil nutrient availability is often more about the timing than the demanded quantity.

Crop response to soil nutrient status

The relationships between plant nutrition, chemical composition of the plant and shape of yield curves have been extensively studied (Steenbjerg, 1951; 1954; Steenbjerg and Jakobsen, 1959; 1963). These authors found that the shape and the position of yield curves were influenced by several factors: the affinity between the specific nutrient and the soil particles; level and method of other nutrients applied; water availability; time; and the crop species. They showed that the yield curve on P deficient soils is sigmoidal and that P adsorption to the soil increased when the P rations applied were too small. Consequently, the nutrient proportion absorbed by the crop was depressed. Thus, only large nutrient rations, above the nutrient fixing capacity of the soils, would result in an increase in the crop nutrient uptake and the subsequent rise in yield. This type of plant response, termed as the 'Steenbjerg effect', was reviewed by Velayutham (1980) with a special focus on the problem of P fixation by minerals and soil colloids.

Monitoring soil nutrient status is essential, preferably prior to planting of each crop. The practical value and benefit of soil test based fertilizer use for achieving targeted crop yields - getting higher profitability from fertilizer use, and long-term soil fertility maintenance for sustainable agriculture - was established and disseminated through the All India Coordinated Soil Test Crop Response Project (AICRP-STCR), (Ramamoorthy *et al.*, 1967; Ramamoorthy and Velayutham, 1971; 1974; Velayutham, 1979).

Soil testing and crop response to fertilizers

Eight possible types of crop response to fertilizer application emerged from AICRP-STCR (Ramamoorthy, 1974). These types can be classified based on the significant sign of the regression coefficients for the linear, quadratic, and interaction terms of the fertilizer in the multiple regression equation connecting yield with soil test, fertilizer nutrient and their interaction (quadratic curve) for N, P and K nutrients (Fig. 1).

An example of the multiple regression equation as derived from a field experiment on finger millet (*Eleusine coracana*), in a red calcareous soil (Udic Haplustalf), Somayanur soil series, Coimbatore, Tamil Nadu, is given below:

$$Y = -3152.84+20.24 \cdot N_S+19.22 \cdot P_S+4.78 \cdot K_S+47.94 \cdot N_F-0.1057 \cdot N_F^2+29.03 \cdot P_F -0.20 \cdot P_F^2+78.535 \cdot K_F-0.5659 \cdot K_F^2-0.1856 \cdot N_S \cdot N_F-1.289 \cdot P_S \cdot P_F-0.211 \cdot K_S \cdot K_F$$

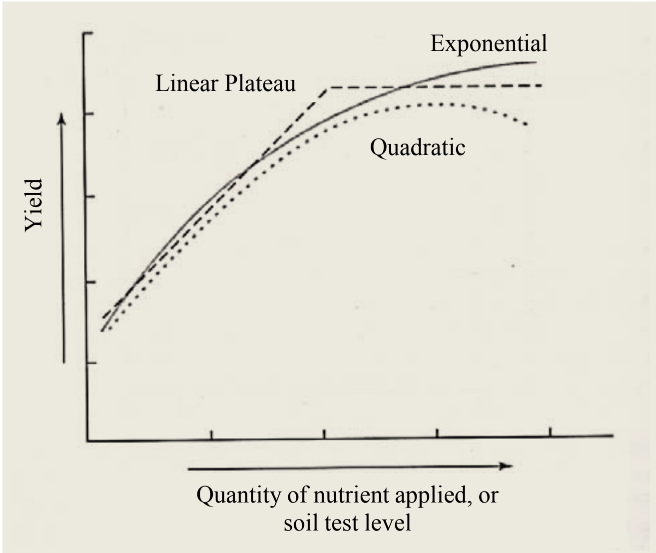

Fig. 1. Soil test - crop response calibrations curves - conventional linear, exponential, and quadratic models. Adopted from Havlin *et al.*, 2013.

Where Y = predicted yield; N_S, P_S and K_S are soil test values of available N, P and K respectively; N_F, P_F and K_F are fertilizer N, P_2O_5 and K_2O, respectively; N_F, P_F and K_F are linear terms, while N_F^2, P_F^2 and K_F^2 are quadratic terms. All units are in kg ha^{-1}.

The eight response types are as detailed below (Fig. 2 and Table 1):

Type I (- - +): soil test values are lower than the critical level required for a specific nutrient (N, P, or K) to be available for the crop. At nutrient application doses that fail to meet that level, crop depression is often noticed. However, when the critical is reached, optimal fertilizer doses above soil test values are expected to improve crop performance and increase profitability of fertilizer use. This situation is quite rare for N, but more frequent for P and K (Table 1).

Type II (- - -): for any level of soil test values within the range studied, the applied nutrient has a depressing effect on crop performance. In such cases, the nutrient is immediately fixed to the soil particles, leaving no residues for uptake by plants. This is a theoretical situation which has very rarely been observed in farmers' fields (Table 1).

Type III (+ + +): at any level of soil test values, crop response rises with the increasing fertilizer dose. In these soils, the equilibrium between the soluble and adsorbed phases of the

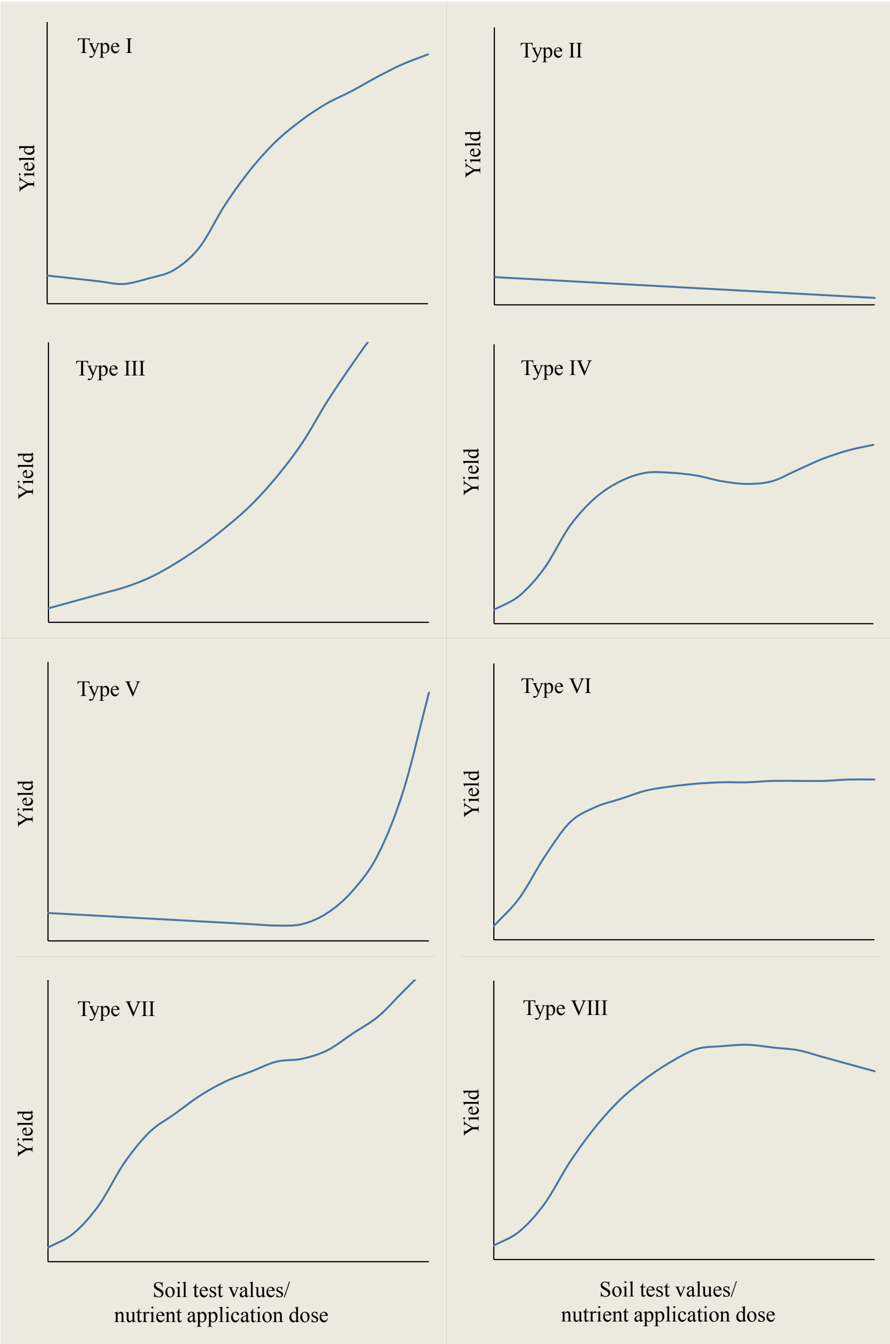

Fig. 2. Eight types of crop response to soil nutrient (N, P, or K) status, identified in 31 field experiments (Ramamoorthy *et al.,* 1974).

nutrient is extremely dynamic, allowing increasing nutrient availability with no losses to the environment. This situation was also very rare (Table 1).

Type IV (+ + -): up to a certain soil test value, crop response and profitability both increase with the rising fertilizer dose. Nevertheless, above this critical point crop performance tends to decline to a minimum point at a particular level of the fertilizer dose, above which the yield increases again. Such soils have limited nutrient adsorption capacity. Fertilizer applied beyond this limit might be concentrated in the soil solution and reach toxic levels. Alternatively, depending on precipitation regime and soil characteristics, the excess nutrient might be lost to the environment. Generally, aiming at high yields beyond that minimum point is subject to economic considerations that depend on cost-benefit calculations.

Type V (- + +): at lower range of soil test values, crop response to fertilizer application is slightly negative, until a minimum point at a critical soil test value beyond which crop response becomes exponential, as in Type III. As in Type II, the applied nutrient is immediately fixed to the soil particles up to a saturation point, beyond which additional fertilizer is available to the crop. As in Type IV, employing fertilizer doses above the critical point are subject to cost-benefit considerations. This situation is more frequent with K than with N or P (Table 1).

Type VI (- + -): crop response is shaped as a saturation curve, as the quantity of fertilizer required for a minimum response increases with the rising soil test values. Soil capacity to maintain an adequate level of exchangeable nutrient is limited and the fertilizer loss proportion increases. Thus, at the higher range of soil nutrient status, an increased fertilizer dose might appear impractical.

Type VII (+ - +): the crop is highly responsive to fertilizer at any soil nutrient status. However, at the higher range of soil nutrient status, crop response and profitability further increase with the rise of fertilizer dose.

Type VIII (+--): the positive crop response to fertilizer application decreases with the increasing soil test values up to a limit at which a negative response occurs to any further nutrient application. Being the most common type (Table 1), optimizing the multiple regression equation of this response provides the calibration of the fertilizer dose required to maximize fertilizer use efficiency and consequently, the economic yield (Ramamoorthy *et al.*, 1974).

Upgrading fertilizer use strategy

Depending on the nature and duration of the crop, the initial level of soil nutrient, and the quantity of fertilizer applied, crop response can fall into any of the eight types. Fertilizer application by this approach, based on soil tests and the shape of yield (response) curves, however, does not take into account the removal of soil nutrients for the level of production obtained. Continuous fertilizer application by this approach might decrease soil fertility level over time.

The approach of fertilizer application based on soil tests for targeted yield of crops underlying the 'Law of Optimum' - as elaborated by Ramamoorthy *et al.* (1967), Velayutham (1979), Ramamoorthy and Velayutham (2011), Velayutham and Santhi (2013) and Velayutham *et al.* (2016) - ensures balanced and profitable fertilizer use for realizing targeted yield goal and maintenance of soil fertility in the long run. In Table 2, the effects of the long-term STCR Rice-Rice targeted yield and soil fertility management are demonstrated: the mean grain yield obtained per season (over 18 years, with two seasonal rice crops a year) matched the targeted yield. Furthermore, fertilizer use efficiency was increased significantly. When the two approaches, STCR and IPNS (Chen, 2006) were combined, yield and fertilizer use efficiency increased further. Additionally, the long-term soil fertility was maintained (Table 3); soil organic C increased, soil N content responded mainly to the organic fertilizer, P content was preserved and even rose, whereas K content decreased, pointing to the need to improve the application practices of this nutrient, the most soluble one. Alternating the two approaches based on 1) yield response curves and 2) targeted yield, to interpret soil tests as fertilizer determinant, will be a prudent long-term strategy for both getting profitability from fertilizer use and maintaining/upgrading soil fertility for sustainable agriculture.

Climate and fluctuations of soil fertility

Van Der Paauw (1950, 1952, 1956, 1960 and 1962) has analyzed fluctuations of soil fertility, and crop and yield responses to

Table 1. The frequency (number of cases) of the eight crop response types to N, P, and K, as occurred in 31 field experiments (Ramamoorthy *et al.*, 1974).

Crop response type	Sign*	Nutrient		
		N	P_2O_5	K_2O
Type I	- - +	3	3	7
Type II	- - -	-	-	-
Type III	+ + +	2	1	-
Type IV	+ + -	3	4	4
Type V	- + +	2	3	6
Type VI	- + -	2	4	1
Type VII	+ - +	7	2	-
Type VIII	+ - -	12	14	13
Total		31	31	31

Note: *The three signs represent the signs of the partial regression coefficient of the linear, quadratic, and interaction terms, respectively, of the three fertilizer nutrients in the multiple regression equation describing crop response to soil nutrient status and added fertilizer.

Table 2. Yield targeting in rice and efficiency of fertilizer use (mean of 18 crops per season) on an Alfisol.

Treatments	Kharif (1998-2015)		Rabi (1998-2015)	
	Grain yield	Fertilizer use efficiency	Grain yield	Fertilizer use efficiency
	---*Mg ha^{-1}*---	----*kg kg^{-1}*----	---*Mg ha^{-1}*---	----*kg kg^{-1}*----
General agronomic recommendation	5.41	12.07	4.92	11.15
STCR-NPK alone - 6/5 Mg ha^{-1}	5.73	13.85	5.06	15.31
STCR-NPK alone - 7/6 Mg ha^{-1}	6.56	14.66	5.90	15.98
STCR-IPNS - 7/6 Mg ha^{-1}	6.79	16.38	6.06	17.88
Absolute control	2.77	-	2.73	-

Fertilizer prescription equations (STCR-IPNS)

Kharif (summer - rainy season)	Rabi (winter - dry season)
$N_F = 4.39\ T - 0.58\ N_S - 0.8\ N_O$	$N_F = 4.63\ T - 0.56\ N_S - 0.90\ N_O$
$P_F = 2.22\ T - 3.63\ P_S - 0.98\ P_O$	$P_F = 1.98\ T - 3.18\ P_S - 0.99\ P_O$
$K_F = 2.44\ T - 0.39\ K_S - 0.72\ K_O$	$K_F = 2.57\ T - 0.42\ K_S - 0.67\ K_O$

Where: N_F, P_F, and K_F represent fertilizer dose in kg ha^{-1} of N, P_2O_5, and K_2O, respectively; T represents rice yield target in q ha^{-1}; N_S, P_S, and K_S represent soil test NPK results (alkaline $KMnO_4$-N, Olsen-P and NH_4OAc-K in kg ha^{-1}, respectively); N_O, P_O, and K_O are the NPK quantities (kg ha^{-1}) supplied through farmyard manure. Yield targets (T) - Kharif: 6 and 7 Mg ha^{-1}; Rabi: 5 and 6 Mg ha^{-1}. Adopted from Maragatham, 2016.

Table 3. Yield targeting and maintenance of soil fertility status after 36 rice crops on Alfisol.

Treatments	Soil organic carbon	Available nutrients		
		N	P	K
	-----*g kg^{-1}*-----	---------------------*kg ha^{-1}*---------------------		
Initial status (1998 Kharif)	4.6	280	20.2	670
Absolute control	5.4	177	16.7	412
General agronomic recommendation	6.3	230	19.6	476
STCR-NPK alone - 6 Mg ha^{-1}	7.5	237	21.7	493
STCR-NPK alone - 7 Mg ha^{-1}	7.8	250	25.0	504
STCR-IPNS - 7 Mg ha^{-1}	8.6	266	29.3	567

Adopted from Maragatham, 2016.

fertilization, as affected by alternating periods of low or high rainfall. He reported that in the Netherlands, soil P and K contents gradually rose during relatively dry periods and declined during wet ones. Cropping under the Asian monsoonal climate, characterized by two distinct seasons - Kharif (very wet summer) and Rabi (dry winter) - results in significant changes, particularly concerning nutrient availability. Crop P and K requirements must be adequately met for rain-fed crops, in both seasons. Fluctuations of the content of water soluble P corresponds with the alternating periods of rainfall (data not shown). Therefore, as shown in Table 2, fertilizer application practices should be adjusted to the cropping season in order to optimize nutrient use efficiency, maximize profitability, and maintain soil fertility.

An information flow among stakeholders is essential

The ultimate goal of the STCR-IPNS approach is to enhance the agricultural production at farm, state, and national levels. The way to achieve this goal is by securing sustainable agriculture and soil quality through the maintenance of soil health and productivity. These, in turn, require one-to-one contact between the farmer, extension, and soil laboratory technicians and scientists, acting together to disseminate consistent soil test programs and best management practices, including realization of the 'target yield' of crops and profitability from fertilizer use.

To achieve this vision, a solid network of multi-direction information flow should be developed and include all stakeholders involved. Soil testing laboratories must be established throughout the country, acquiring and qualifying highly committed staff in order to ensure high quality soil analyses (Bhumbla, 2010). Each farmer will be connected to the local soil testing lab, which will test and certify the farm and provide fertilizer recommendations and consultancy. A linkage will be established between soil testing labs working under various agencies (state government, NGO's, research institutes, fertilizer industry, etc.) to periodically monitor soil fertility trends and to promote balanced fertilizer application on farms and at a regional level. This network will be governed academically and administratively by a national headquarters. Information will be evaluated and processed, and then used to support decisions at the regional and national level. The recently launched nationwide flagship program, 'Land Resource and Soil Health Card', linked to the 'Digital India' paradigm shift augers well for meeting the STCR-IPNS strategy at the national level.

Epilogue

As observed by Sir Albert Howard (1947), "The real arsenal of democracy is a fertile soil, the fresh produce of which is the birthright of the nations". Mother Earth sustains the existence and prosperity of mankind. Inter-generational equity demands that we adopt good crop and land husbandry practices and hand over the fertility and quality of the land and soil undiminished to posterity.

Acknowledgements

This paper is based on the 5th Dr. B. Ramamoorthy Memorial lecture delivered at Tamil Nadu Agricultural University (TNAU) on 5th December 2016, World Soils Day. Thanks are given to Prof. R. Santhi of TNAU for the photograph and Mr. S. Udayakumar, PhD Scholar in the Dept. of Soil Science and Agricultural Chemistry, TNAU, Coimbatore for library and computer assistance in the preparation of the paper.

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The paper "Soil Nutrients and Crop Response-Curve Types in Farmers' Fields: Key to Balanced Fertilizer Use and Sustainable Soil Fertility Management" also appears on the IPI website at:

Regional activities/India