Research Findings

Potash campaigning in West Bengal. Photo by Potash for Life, India.

The 'Law of Optimum' and its Application for Realizing Targeted Yields in India - A Mini-Review

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Abstract

The 'Law of Optimum' is put forward as the unifying concept in plant nutrition for realizing 'targeted yield of crops' through soil test-based nutrient management. This concept has been calibrated using a novel factorial field experiment technique, designed and used under the All India Coordinated Soil Test Crop Response (STCR) project. This initiative was conducted in India on a range of soils and crops over four decades and was validated through hundreds of demonstration trials in farmers' fields.

Early results established that the relationship between wheat grain yield and the total nutrient uptake by the plant followed a linear relationship implying that, for obtaining a given yield, a definite quantity of nutrients must be absorbed by the plant. Based on crop nutrient uptake required to obtain a desired yield level (targeted yield), the 'Law of Optimum' calculates nitrogen

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(N), phosphorus (P), and potassium (K) application doses, taking into account nutrient contribution from three measurable sources: 1. soil fertility (available nutrients, based on chemical soil tests); 2. added fertilizers; and, 3. added organic manure. Over 2,000 demonstration trials in farmers' fields conducted so far have validated the concept, realizing the yield targets within a 10% deviation. Operationally, the 'Law of Optimum' harmonizes the much debated approaches of 'fertilizing the soil' versus 'fertilizing the crop', ensuring a real balance is achieved among available nutrients. The principles underlying the 'Law of Minimum', 'Law of Diminishing Returns' and the 'Law of the Maximum' governing plant nutrition are strongly embedded in the 'Law of Optimum'. Furthermore, this law also provides a basis for maintaining consistent soil fertility with high productivity and efficient nutrient management in 'Precision Farming', to achieve sustainable agriculture.

Introduction

Nutrient application in agricultural systems is expected to increase in the coming years to produce more food, feed, and fiber from the diminishing arable lands. Efficient application of nutrients is key to sustainability in agricultural systems. Efficient fertilization means optimizing crop yields, while minimizing nutrient losses to the environment, which is important economically and environmentally. Efficient nutrient application necessitates balanced fertilizer use and sound management decisions and practices.

Soil's nutrient supplying capacity, namely soil fertility, can be easily determined in laboratories. However, soil fertility assessment of specific locations at a countrywide scale requires systematic soil sampling, delivery, and feedback reporting. Crop responses to added nutrients can be tested in field experiments; nevertheless, results are site-specific and often not applicable to other locations with different soils or climate. Recognizing the lack of correlation between soil tests and crop responses to fertilizer in multi-location fertilizer-rate trials in the past, and the frequent need for site-specific refinements of fertilizer prescriptions, a novel and unique field experimentation methodology was designed for soil test crop response (STCR) correlation studies (Ramamoorthy, 1968). This novel approach has been developed to become a leading concept and a useful strategy to increase fertilizer use efficiency and boost food production in India. This paper highlights the 'Law of Optimum', articulated by Ramamoorthy and Velayutham (2011), and its application and validation over the past four decades.

Historical perspectives

Quantitative relationship studies on plant growth factors and their effect on plant growth and yields dates back to Sprengel (1832) and von Liebig (1843). The well-known Liebig's 'Law of Minimum' says that the yield achieved is in direct relation to the quantity of the limiting nutrient. This is the factor governing yield, which remains constant irresponsive to any increases in other nutrients. When this most limiting factor is corrected, yields are then regulated by the next limiting nutrient. In agricultural production, the soil nutrient status is adjusted with step-wise yield increases until there are no remaining growth limiting factors. Paris (1992) demonstrated the applicability of this law in two crop response experiments. Mitscherlich (1909), in his 'Law of Diminishing Returns' stated that crop yields are influenced by all limiting factors simultaneously and the influence of each such factor is proportional to the severity of its limitation. His equation provided a basis for optimizing fertilizer doses from fertilizer rate trials. Mitscherlich's concept and equation was challenged and modified by Balmukand (1928), Bray (1945), Willcox (1955), and Boyd (1956).

Based on his nutrient mobility concept, Bray (1945) modified Mitscherlich equation as follows:

$$log\ (A-Y) = log\ A - C1b - CX$$

Where:

A = maximum yield when all nutrients are present in adequate quantities;
Y = yield obtained with nutrient 'b' in soil, when it is less than adequate;
C1 = efficiency factor of the nutrient supplied by the soil;
X = quantity of fertilizer added; and,
C = efficiency factor for the method of applying fertilizer.

The exponential function of the 'Mitscherlich-Bray yield curve' is the curve that never reaches a maximum; regardless of the nutrient level present in the soil, the indicated yield never reaches 100%. The computational basis for calculating maximum yield, a vital parameter to the percent yield sufficiency concept, has thus been questioned. The exponential curve will never indicate yield depression from an excess or toxic nutrient level. This method also does not take into account nutrient interactions, their effect on yield and hence on the fertilizer requirement for 'balanced fertilization'.

Colwell (1978) proposed an orthogonal polynomial model for calculating fertilizer requirement from multi-location fertilizer rate trials. However, similar experiments and data generated under the STCR project failed to optimize fertilizer requirements due to underestimation of soil test values in the orthogonal polynomial model.

Wallace (1993) proposed the 'Law of the Maximum', having two major characteristics. First, the effect of a given input is progressively magnified as other limiting factors are corrected. The final result is greater than the sum of the effects of the individual inputs because of the way in which they interact; the interaction multiplies the effects of each. Second, yields can be highest or maximum only if there are no remaining limiting factors; the fewer limiting factors that remain, the higher the yield will be. How closely this can be approached and attained, of course, depends on relative economics. When dealing with Mitscherlich-type limiting factors, those most economical to use can be chosen first. Using examples of multi-nutrient rate trials, Wallace's model demonstrates the negative synergy of imperfection. While shortage of a single factor limits yield, for instance, to 90% of its agronomic potential, a similar limit by two factors is manifested by 81% of the potential yield. Five such limiting factors would yield 59%, and for ten, it would be 35%. A farmer may do everything to 90% of perfection and yet only achieve 35% of the maximum possible yield. This underlines the need for best management practices and precision nutrient management.

Soil test crop response (STCR) correlation studies

The usefulness of a soil testing service as a vital part of the expanding fertilizer use program was widely recognized and 24 soil testing laboratories were first established in 1955-56 with assistance from United States Agency for International Development (USAID). With the initial research work carried out at the Indian Agricultural Research Institute (IARI) with the then tall varieties of rice and wheat, the fertilizer doses arrived at for different crops on the basis of agronomic experiments in the US were taken as applicable to the 'medium' soil fertility status. Those doses were either reduced or increased by 30 to 50% empirically for soils tested as 'high' or 'low' respectively (Muhr *et al.*, 1965). Ramamoorthy and Velayutham (1971) reported an average increase in yield of only 11% when the fertilizers were applied based on such recommendation without soil testing. With the introduction of high yielding varieties and hybrids of crops during the mid-1960's Green Revolution era, fertilizer input demands increased significantly. Fertilization became very costly and hence an urgent need for more precise fertilizer requirement calibration.

Recognizing the reported lack of correlation between soil test and crop response to fertilizer in multi-location agronomic trials in the past and the need for refinements in fertilizer prescriptions for varying soil test values for economic crop production, Ramamoorthy (1968) designed a novel field experimentation methodology for STCR correlation studies and initiated the All India Coordinated Research Project of the Indian Council of Agricultural Research (ICAR) in 1967-1968. In the 'inductive approach' of STCR field experimentation, the required variation in soil fertility level is obtained - not by selecting soils at different locations as in earlier agronomic trials - but by creating it in the same field in order to reduce heterogeneity in the soil (types and units) studied, adopted management practices, and climatic conditions. Ramamoorthy and Velayutham (1971; 1972) and Velayutham *et al.* (1985a) have elaborated this inductive approach, and the STCR field design has also been recognized and accepted abroad (Black, 1993).

A field design for creating simultaneous heterogeneity of soil fertility that combines chemical fertilization and organic manure has been developed. The manure variation (organic sources) is created by three parallel strips, each of which is applied with a different level of organic manure (OM_0, OM_1, and OM_2) using FYM (farm-yard manure), slurry, or compost about one month before sowing of the test crop. Four strips of selected nitrogen (N) fertiliser levels are set in a perpendicular direction to the OM set. Twelve combinations of phosphorus (P) and potassium (K) levels are selected according to a predetermined soil fertility status and scattered among the N levels. The full set of 24 fertilizer treatments are allotted in each of the three strips (Fig.1).

	OM_0	OM_1	OM_2
N_0	$P_0 K_1$	$P_2 K_2$	$P_1 K_2$
	$P_1 K_2$	$P_0 K_0$	$P_2 K_2$
	$P_0 K_0$	$P_0 K_1$	$P_0 K_0$
	$P_2 K_2$	$P_1 K_2$	$P_0 K_1$
N_1	$P_1 K_1$	$P_2 K_1$	$P_1 K_2$
	$P_2 K_1$	$P_2 K_2$	$P_2 K_2$
	$P_1 K_2$	$P_1 K_1$	$P_2 K_1$
	$P_2 K_2$	$P_1 K_2$	$P_1 K_1$
N_2	$P_1 K_1$	$P_1 K_2$	$P_2 K_1$
	$P_0 K_2$	$P_2 K_1$	$P_2 K_0$
	$P_1 K_2$	$P_1 K_1$	$P_2 K_3$
	$P_2 K_2$	$P_2 K_3$	$P_0 K_2$
	$P_2 K_1$	$P_3 K_2$	$P_3 K_3$
	$P_2 K_0$	$P_2 K_2$	$P_3 K_2$
	$P_2 K_3$	$P_3 K_3$	$P_1 K_1$
	$P_3 K_2$	$P_2 K_0$	$P_2 K_2$
	$P_3 K_3$	$P_0 K_2$	$P_1 K_2$
N_3	$P_1 K_1$	$P_2 K_2$	$P_2 K_1$
	$P_2 K_1$	$P_3 K_2$	$P_3 K_1$
	$P_2 K_2$	$P_1 K_1$	$P_2 K_3$
	$P_3 K_1$	$P_3 K_3$	$P_3 K_2$
	$P_3 K_2$	$P_2 K_3$	$P_3 K_3$
	$P_2 K_3$	$P_3 K_1$	$P_1 K_1$
	$P_3 K_3$	$P_2 K_1$	$P_2 K_2$

Fig. 1. An example of STCR experimental design. Three strips of different organic manure (OM) levels are set in a perpendicular direction to N fertilizer gradient of four levels. Twelve combinations of P and K levels are selected according to a predetermined soil fertility status and scattered among the N levels. Overall, 24 different N-P-K fertilizer combinations are simultaneously examined in each strip of OM level.

The ICAR supported All India Coordinated Research Project (AICRP) on STCR was initiated in 1967-68 with eight centers and has now increased to 17 centers at different agro-eco regions across the country. The STCR project has used the multiple regression approach to develop the relationship between crop yield and soil test estimates and fertilizer inputs.

Table 1 demonstrates the effect of balanced nutrition on the agricultural and economic efficiencies of fertilizer use on wheat. At a low rate of added N (50 kg N ha^{-1}), yield response was highest, 14.8 kg grains kg^{-1} added N, at the lowest P-K input (25 kg ha^{-1} of each P_2O_5 and K_2O). Elevating P-K rates at the same N level resulted in even lower grain yield.

When N dose was elevated to 90 kg ha^{-1}, yield response dropped, averaging at 10-12 kg kg^{-1}, under different P-K combinations. To return to the high response of 14.5 kg kg^{-1} at the new N level, a precise P-K combination of 75 and 50 kg ha^{-1}, respectively, was required. These results demonstrate the diminishing contribution of elevated N input, unless corrected with a new optimum P-K requirement.

Recent studies exploring the optimum nutrient balance which aimed to achieve maximum productivity or economic benefits (Boldea *et al.*, 2015) also demonstrated this principle and, furthermore, yields can be increased as long as the site-specific N-P-K optimum combination is met. Table 1 also shows that the response to absorbed N only varies within narrow limits compared to the response to added N. Thus, the varying yield response to applied fertilizers is primarily influenced by nutrient uptake restrictions but, once taken up, the efficiency of applied nutrients is nearly the same.

Targeted yield concept

Based on a large number of complex field experiments on diverse soils at STCR different centers of growing major crops, a technology for fertilizer recommendations based on soil tests for targeted yields of crops has evolved. Truog (1960) illustrated the possibility of a 'prescription method' of fertilizer use for obtaining high yields of maize using empirical values of nutrient availability from soil and fertilizer. It was generally believed that crop requirements for P and K follow the rate sufficiency concept of Mitscherlich-Baule (Baule, 1917) and of Mitscherlich and Bray (Bray, 1945). Nevertheless, Ramamoorthy *et al.* (1967) established the theoretical basis and field experimental proof and validation for the fact that Liebig's 'Law of Minimum' operates equally well for N, P, and K for the high yielding varieties of wheat, rice and pearl millet. They demonstrated the importance of P and K in determining crop response to N and the role of balanced nutrition in achieving efficient fertilizer use (Ramamoorthy *et al.*, 1967; Ramamoorthy and Pathak, 1969). Their work founded the 'targeted yield' concept for fertilizer recommendations.

Table 1. Effect of balanced nutrition on efficiency and economy in fertilizer use at Delhi with wheat Sonora 64 (1965-1966). (Ramamoorthy *et al.*, 1967).

Nitrogen dose	Associated treatment	Yield	Yield response to added N	Yield response to absorbed N
kg ha^{-1}		------*kg ha^{-1}*------	--------------*kg grain kg^{-1} N*--------------	
90	P_{75} K_{50}	5,047	14.5	38.7
	P_{50} K_{50}	4,779	11.8	38.9
	P_{50} K_{25}	4,760	11.7	40.3
	P_{50} K_{75}	4,588	9.9	42.0
	P_{25} K_{50}	4,665	10.7	40.2
50	P_{25} K_{25}	4,330	14.8	43.1
	P_{50} K_{50}	4,302	14.2	43.5
Control	P_0 K_0	3,590	-	-

The linear relationship between yield level and N-P-K uptake implied that, for obtaining a given yield, a definite quantity of nutrients (both from soil and fertilizers) must be taken up by the plant. Once this requirement is determined for a given yield, the quantity of fertilizer needed can be calculated, taking into account contribution rates from soil available nutrients and those from added fertilizers and organic manure.

The implementation of the targeted yield concept is described in the following examples. A soil test based calibration of wheat var. WH-157 on Sierozem soil at Hissar resulted in the following fertilizer adjustment equations, in their simplest form:

$$Nf = 4.96TY - 0.63Ns;$$
$$P_2O_5f = 3.83TY - 4.63Ps;$$
$$K_2Of = 2.66TY - 0.22Ks$$

Where:
Nf, P_2O_5f and K_2Of are fertilizer doses in kg ha^{-1} respectively; TY is the yield target in q ha^{-1} (100 kg); Ns, Ps, and Ks are soil test values for available N, P, and K in kg ha^{-1}, respectively.

These simplified linear equations demonstrate the relationships between expected levels of wheat grain yield and the N-P-K doses required in site-specific variation of soil fertility (Fig. 2). Evidently, fertilizer requirements vary according to soil N-P-K availability. Fertile soils would require considerably less fertilization than poor soils. Under rain-fed conditions, differences are more relevant at lower yield levels, where relatively small changes in fertilizer input can make significant differences, turning economic failure to success. The farmer, after being informed of the particular situation of his field, may choose expected yield

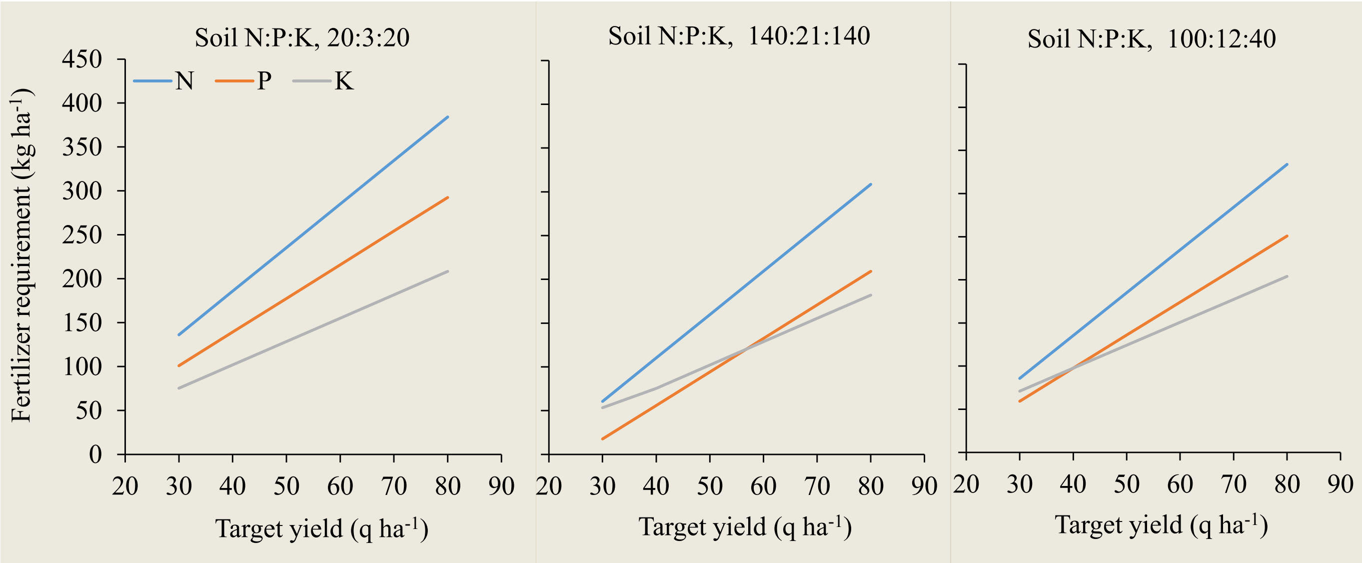

Fig. 2. Resolving fertilizer requirements as a function of the expected wheat grain yield and according to soil available N-P-K at three hypothetical situations of initial soil fertility, as determined through soil tests. Wheat cultivar: WH-157; soil type: Sierozem; location: Hissar, India.

according to fertilizer costs and available budget. According to Fig. 2, a farmer with an exhausted soil, who desires a high yield of 60 q ha^{-1} should invest in 285, 216, and 155 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. However, if too costly, this farmer might be satisfied with 40 q ha^{-1}, reducing his fertilizer expenses by 35%. Obviously, fertilizer requirements decline with the increasing initial soil fertility. Obtaining the same 60 q grains ha^{-1} requires 209, 133, and 129 kg ha^{-1} of N, P_2O_5, and K_2O, and reducing the target yield to 40 q ha^{-1} would lessen fertilizer costs by 47, 58, and 41%, respectively (Fig. 2).

The utilization of organic manure adds a significant factor to the targeted yield equations. Santhi *et al.* (2013) documented a range of 53 soil-crop situations in Tamil Nadu, Southern India. One such example for rice grown on Noyyal soil series (typical Haplustalf) is given below, as a set of equations:

$$Nf = 4.39TY - 0.52Ns - 0.80No;$$
$$P_2O_5f = 2.22TY - 3.63Ps - 0.98Po;$$
$$K_2Of = 2.44TY - 0.39Ks - 0.72Ko$$

Where, Nf, P_2O_5f and K_2Of are fertilizer doses in kg ha^{-1} respectively; TY is the yield target in q ha^{-1} (100 kg); Ns, Ps, and Ks are soil test values for available N, P, and K in kg ha^{-1}, respectively, and No, Po, and Ko are the quantity of N, P, and K, respectively, in kg ha^{-1} supplied through FYM.

FYM use significantly reduces fertilizer requirements, but this effect is considerably greater in fertile soils (Fig. 3). Choosing relatively low targeted yield levels, farmers who use sufficient FYM may significantly reduce their expenses for chemical fertilizers. Nevertheless, the targeted yield concept also provides farmers with the opportunity to recognize possible economic benefits that might arise from rational, calculated increase of fertilizer use.

The fertilizer prescription equations have been rigorously tested and evaluated for their predictability through a series of field verification trials (follow up trials) in farmer's fields on similar soils. After evaluation in the follow-up trials, these equations are used to recommend fertilizer doses for all the major crops grown across Indian states.

The practical application of yield target for a fixed cost of fertilizer investment by the farmer or under resource (fertilizer/credit) constraints and for maintenance of soil fertility in crop rotation were documented by Velayutham (1979), Randhawa and Velayutham (1982), Velayutham *et al.* (1985b), Reddy *et al.* (1989) and Dey and Santhi (2014). STCR field experiments have been conducted at all the cooperating centers and fertilizer prescription equations were developed for various crops for advisory use, and have been documented (Anonymous, 1968-2013; Subba Rao and Srivastava, 2001; Muralidharudu *et al.*, 2012; Dey and Das, 2014). Founded on reliable field data flow (site-specific soil tests) and economically considered practice of chemical and organic fertilizers, the targeted yield concept can promote a gradual but consistent increase in crop productivity.

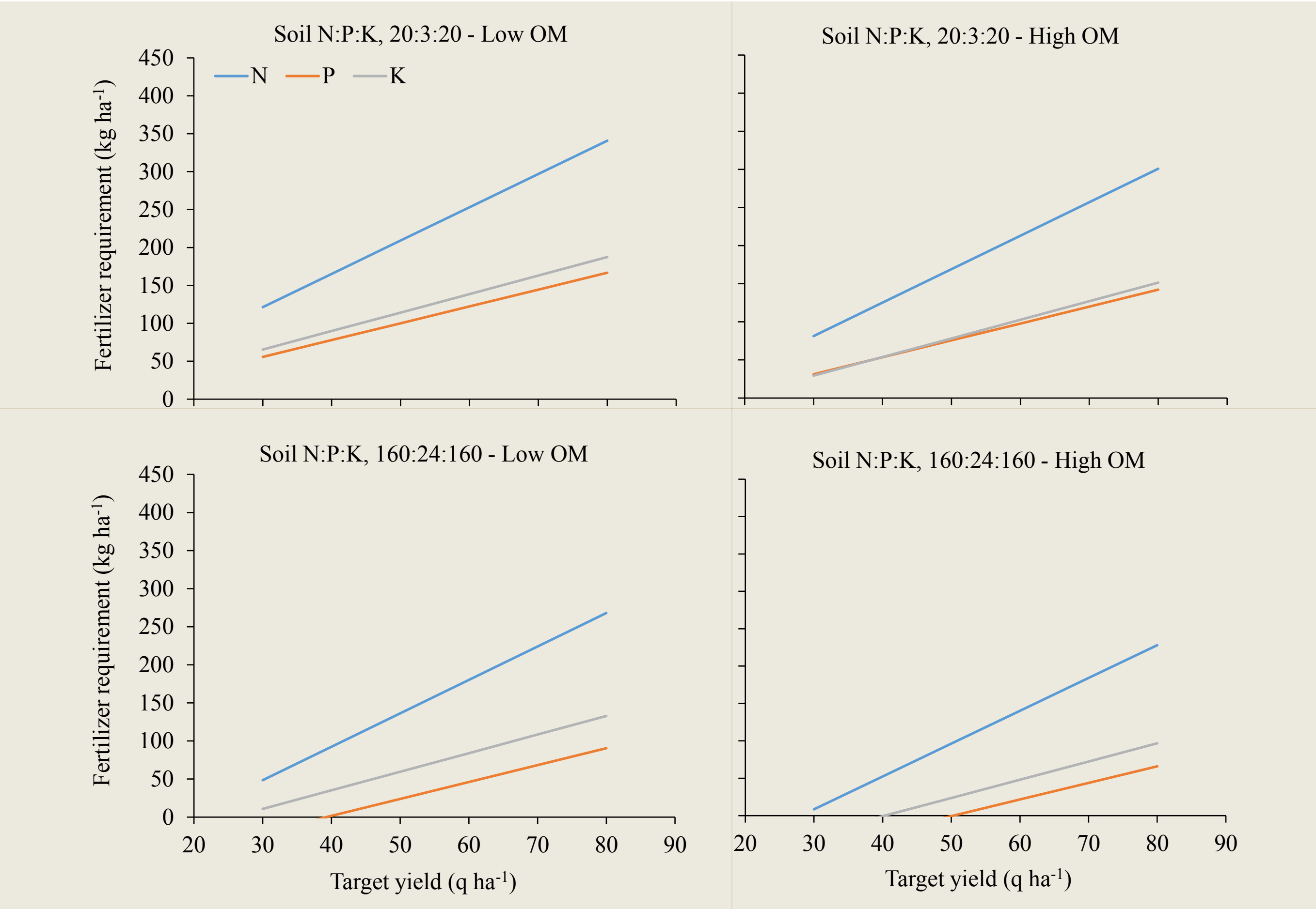

Fig. 3. Resolving fertilizers' requirements as a function of expected rice yield and according to soil + FYM available N-P-K. Soil type: Typic Haplustalfs; location: Tamil Nadu, India.

Yield targeting and maintenance of soil fertility

Among the various methods for formulating fertilizer recommendations, the one based on yield targeting is unique in the sense that, beyond a defined fertilizer dose for the desired yield level, it ensures considerable maintenance of soil fertility, taking into account nutrient removal by the crop for a given yield level (Velayutham, 1979; Velayutham and Tandon, 2014).

Using the fertilizer prescription equations for rice at a fixed field site since 1998 (Tamil Nadu Agricultural University, Coimbatore, Southern India), the yield targeting block demonstration has amply shown the value of soil test-based integrated plant nutrition system (IPNS) (Velayutham and Santhi, 2013) for obtaining high yields (6 to 7 tonnes ha^{-1} of paddy yield). These results from 15 years of continuous cropping (Maragatham *et al.*, 2015) were consistent with profitable fertilizer use and maintenance of long-term soil fertility (Tables 2 and 3). Velayutham (1979) illustrated that, by choosing appropriate yield targets of crops in rotation, soil fertility can be maintained and even upgraded.

Potassium and the 'Law of Optimum'

Among the essential plant nutrients, K assumes greater significance since it is required in relatively larger quantities by plants and, besides increasing yield, it improves the quality of crop produce, as well as improving N and P use efficiency (Rao *et al.*, 2014). Potassium has many roles in plant physiology: it activates enzymes involved in photosynthesis and in carbohydrate and protein metabolism; it assists in synthesis and translocation of carbohydrates, protein synthesis, membrane permeability, and stomatal regulation; it regulates water utilization; it improves N uptake and utilization; and, it enhances plants' tolerance to abiotic stresses and diseases (Mengel and Kirkby, 1987).

Efficiency of K soil uptake differs among crops and is influenced by many factors, such as crop type, crop growth stage, plant root density and distribution, soil type, soil moisture status, etc. Dynamic equilibrium among different pools of soil K also has a significant influence on crop uptake efficiency. Soil K status and its distribution among different pools is governed by its

Table 2. Yield targeting in rice and efficiency of fertilizer use (mean of 15 crops per season) on an Alfisol (Maragatham *et al.*, 2015). AE - agricultural efficiency; IPNS - integrated plant nutrition system.

Treatments	Kharif season (1998-2013)			Rabi season (1998-2013)		
	Target yield	Grain yield	AE	Target yield	Grain yield	AE
	--------*Mg ha^{-1}*--------		*kg kg^{-1}*	--------*Mg ha^{-1}*--------		*kg kg^{-1}*
General agronomic recommendation		5.37	12.0		4.95	11.4
STCR - NPK alone	6	5.72	13.7	5	5.10	15.2
STCR - NPK alone	7	6.52	14.4	6	5.90	15.7
STCR - IPNS	7	6.74	16.0	6	6.05	17.5
Absolute control		2.80	-		2.78	-

Table 3. Yield targeting and maintenance of soil fertility status after 30 crops of rice on an Alfisol (Maragatham *et al.*, 2015).

Treatments	Targeted yield	Soil organic carbon	Available nutrients		
			N	P	K
	Mg ha^{-1}	*g kg^{-1}*	----------------*kg ha^{-1}*----------------		
General agronomic recommendation		6.0	210	19.8	472
STCR-NPK alone	6	7.0	218	21.5	492
STCR- NPK alone	7	7.4	260	27.0	498
STCR - IPNS	7	8.6	268	28.5	550
Absolute control		5.2	165	15.1	412
Initial status (1998 Kharif)		4.6	280	20.2	670

mineralogy. There are three major soil K pools: exchangeable, non-exchangeable, and organic. The exchangeable pool contains the K^+ ions which adhere to the negatively charged surface layer of the finest soil particle fraction. This pool maintains a steady equilibrium with the soil water solution, is affected by soil pH, and interacts with other dissolved ions. The exchangeable K pool is considered the most available K resource in the soil. However, due to its high solubility, exchangeable K is extremely mobile in the soil, being strongly affected by the dynamics of water status and movement in the soil.

The non-exchangeable K pool is present within the soil particles, as an inherent element of their chemical composition. The size of this pool depends on the soil mineral composition. The availability of this K pool to the plant depends on the type and rate of soil weathering processes. While definitely not immediately available, this pool may contribute significant portions of K crop requirements (Rao *et al.*, 2014). Nevertheless, this availability is very difficult to estimate hence the non-exchangeable K pool is not taken into account in regular assessments of fertilizer requirements. In a similar way, the K availability incorporated in organic soil material is difficult to assess.

Soil available K status is therefore a consequence of contradictory flow rates; crop K uptake and K leaching both reduce soil K status, while soil weathering and mineralization of organic matter enrich the soil with K. Under intensive agriculture, soil available K might be rapidly exhausted due to over-exploitation by successive crops, and where soil weathering becomes soil erosion, as fine-textured soil particles are removed by water and wind. Consequently, soil K balance may be severely depleted, resulting in yield reduction, insufficient revenue for farmers, and reduced food security. Unfortunately, the present trend of fertilizer use in the majority of Indian states is not sufficient and is dominated by mainly NP fertilization; this has led to a negative K balance in most of the soils across India (Rao *et al.*, 2014).

Potassium fertilization is therefore a necessity. However, restoring soil's K balance means much more than a one-time replenishment of absent K. Soil's capacity to store K is limited, as it depends on the soil's cation exchange capacity (CEC). Similarly, crop K uptake rate is limited, depending on crop type, growth rate, and stage of plant development. Excess K application can be lost through leaching, particularly under prolonged or heavy rains (e.g. during monsoons). Therefore, a wise approach to K application should be adopted, accounting for the current crop requirements, weather conditions, and the present and future soil K status. Here, the 'Law of Optimum', and the approaches deriving from this law, provide an excellent strategy and practical means for soil fertility restoration and for the upkeep of sustainable, highly productive agricultural systems. Annual soil tests will determine the current soil K status, CEC, and potential K contribution by non-exchangeable K. Adding organic manure enriches the soil with slow-release nutrients, increases soil CEC and water retention, thus preserving future soil fertility. Crop type and targeted yield determine K requirements of the crop cycle. Then, using the 'Law of Optimum' equations, a fertilization prescription can be determined for the required nutrient dose. However, the distribution of K application during the cropping season should be carefully planned taking into consideration the limits of K uptake and soil capacity. A single basal application, although easiest for the farmer, is the least preferred option in most cases. The predetermined K dose should preferably be divided into several applications distributed throughout the cropping season, considering the current stage of crop development (and K requirements) and expected rainfall events. Where irrigation is employed, K should be applied with the irrigation water.

Concluding remarks

Although India's economy has experienced remarkable progress during recent decades, 70% of the population live in rural areas and are still agriculture-dependent. The ever-increasing demands for food, feed, and fibers with limited arable land necessitate preserving, managing, and enriching the natural resources, and furthermore, scaling up their use efficiency. Soil forms the basis for any crop production activity and is the most precious natural resource. Declining soil fertility is one of the important factors that directly affect crop productivity. Therefore, soil fertility management is crucial to ensure productivity and nutritional security, while maintaining soil health and sustainability. Fertilizers are one of the costly inputs in agriculture, yet their use is key to ensuring soil productivity. It has been proved, however, that imbalanced use of fertilizer not only causes deterioration in soil quality but also afflicts nutrient use efficiency. To achieve maximum benefit, enhanced nutrient use efficiency and reduced nutrient losses, fertilizers must be applied in the right quantity, from the right sources and in the right combination at the right time using the right methods (Dey, 2015; Singh, 2016).

Based on a large number of complex field experiments on diverse soils at different centers of STCR growing major crops, a technology for fertilizer recommendations based on soil tests for targeted yields of crops has evolved. During the last 15 years, the different AICRP centers on STCR developed prediction equations by using the targeted yield equation for different cropping systems. The predicted values can be utilized for recommending fertilizer doses for succeeding crops, thus lessening the need for recurrent expensive soil tests. Financial returns vary across soils, crops and locations. However, many demonstrations confirmed an increase in benefit/cost ratios through STCR technology over the control, or farmer's practices, or application of a general recommended dose (Majumdar *et al.*, 2014). Moreover, the targeted yield concept enables farmers to adjust their fertilizer inputs to anticipated yield levels, thus having better financial and economic control.

Thus, the 'Law of Optimum' enables farmers to optimize their farm management by providing a competent method to precisely fulfil site-specific crop nutrient requirements while preserving, and even ameliorating soil fertility. The expected resulting increases in farmers' income and in national agricultural productivity, while maintaining soil fertility, may altogether bring about more sustainable agriculture in India.

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