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Long-Term Fertilizer Experiments in Red and Lateritic Soils: Practical Lessons on Sustainable Agriculture

P. Mahapatra, B.K. Agarwal, D.K. Shahi and A.K. Sarkar
Birsa Agricultural University, Ranchi, Jharkhand

Abstract

Indiscriminate exploitation of natural resources without taking into account their carrying capacity and injudicious use of nutrient inputs over the years to realise higher crop yields pose serious threats to sustenance of crop productivity and soil health. Impact of continuous cropping, fertilizer, manure and lime application on crop productivity, profitability and soil health was studied for two on-going permanent experiments *viz.*, Permanent Manurial Trial (PMT) with maize-wheat sequence (in progress since 1956) and ICAR-All India Coordinated Research Project (AICRP) on Long Term Fertilizer Experiment (LTFE) with soybean-wheat sequence (in progress since 1972) under a set of different nutrient management practices. About half century sustained research has shown that the carrying capacity of the red and lateritic soils is low, but these can sustain around 6 to 8 t ha^{-1} yr^{-1} of wheat equivalent grain yield (WEY) under best nutrient and crop management practices. This is 50 to 100% higher than the current level of crop production. The present paper collates the results of detailed soil and crop based analysis for the past five to six decades of research on the subject and brings out the salient conclusions. Results suggest that sustainable higher crop yields in these soils without any adverse effect on soil quality are possible by supplementing lime and organic manures with periodic soil test-based balanced nutrient use.

Key words : Long term fertilizer experiments, soil health, crop yields, sustainability.

Introduction

Fertilizer is the key agricultural input for farmers. It has significantly contributed towards enhancing agricultural productivity in India. In recent years, quantum of fertilizer use has shown a somewhat decreasing trend, primarily due to supply-side constraints, policies on subsidy, rising costs, etc. This has also changed the ratio of nutrient use in many states skewed against primarily, P and K fertilizers. It is likely to have an adverse effect on soil health in the long run.

Long-term fertilizer experiments under different cropping systems are designed to identify the best management practices for achieving higher yield targets, sustaining soil health and maximizing farm profits. It helps us to assess the yield gain (or loss) due to the presence or absence of different nutrient sources and their levels used with or without organics and amendments, such as lime in acid soils. Information generated over the years, thus is extremely valuable scientific resource for planners, extension agencies, scientists and farmers. Farmers visiting such experimental fields are able to comprehend the merits of appropriate nutrient management practices for their crops with assured benefit in monetary terms. The present paper gives an overview of two such experiments running currently at Birsa Agricultural University, Ranchi, Jharkhand, namely the Permanent Manurial Trial (PMT), started in 1956 and ICAR-AICRP on LTFE, started in 1972 under maize-wheat and soybean-wheat cropping systems, respectively.

aksarkarranchi@gmail.com

Historical Background

Inspired by Rothamsted Classical Experiments started in 1843, a series of long-term agronomic experiments were started in India. A chronology of such experiments initiated up to 1956 are Cawnpore (Now Kanpur) (1905), Pusa (1908), Coimbatore (1909), Padegaon (1933), Shahjahanpur (1935), Attari (1942), Ambala (1946), Jhansi (1946), Jullundur (1946), Muzzafarnagar (1948), Cuttack (1948), Berhampur (1950), Anakapalle (1950) and Ranchi (1956). Unfortunately, by 1980, all except the plots at Coimbatore and Ranchi were lost to posterity for one reason or the other. These experiments are valuable treasures/resources for our quest towards sustainable agriculture.

Experimental details

Permanent Manurial Trial (PMT) Started in 1956

This experiment is in progress since 1956 at the experimental research farm, BAU, Ranchi, with maize-wheat cropping sequence. Experiment was started with 13 treatments each replicated thrice in randomized block design (RBD). Fourteenth (14^{th}) treatment consisting of lime + N as ammonium sulphate was introduced in *kharif* 1977. The levels of fertilizers applied were of 44 kg ha^{-1} each of N, P_2O_5 and K_2O through ammonium sulphate, single superphosphate (SSP) and muriate of potash (MOP), respectively. In the year 1969 during *kharif* the fertilizer dose was revised upward to 100:60:40 kg ha^{-1} for N:P_2O_5:K_2O, respectively, and it was further enhanced to 110 kg N, 90 kg P_2O_5 and 70 kg K_2O ha^{-1} in 1976 and the same has been continuing till date. From 1994 onwards, urea has replaced ammonium sulphate as N source for both the crops. Lime is applied as per lime requirement in three treatments *viz.*, T_{12}, T_{13} & T_{14} once in four years. Farmyard manure (FYM) supplying full dose of N is added 15 days before sowing of each crop. Phosphorus and

Table 1. Treatment details of the permanent manurial trial

Tr. No.	Treatments	Source of nutrients through chemical fertilizers			Level of nutrients added (kg ha^{-1})		
		N	P	K	N	P_2O_5	K_2O
T_1	Control	-	-	-	0	0	0
T_2	N	Urea	-	-	110.0	0	0
T_3	N $P_X K_Y$	Urea	SSP	MOP	110.0	68.8	54.2
T_4	FYM	FYM	-	-	0	0	0
T_5	½ (N+FYM) + $P_{X/2}$ + $K_{Y/2}$	FYM and urea	SSP	MOP	55.0	34.4	27.1
T_6	NP	Urea	SSP	-	110.0	90.0	0
T_7	FYM + $P_{(A-X)}$	FYM	SSP	-	0	21.2	0
T_8	½ (N+FYM) + $P_{(A-X/2)}$	FYM and urea	SSP	-	55.0	55.6	0
T_9	NPK	Urea	SSP	MOP	110.0	90.0	70.0
T_{10}	FYM + $P_{(A-X)}$ + $K_{(B-Y)}$	FYM	SSP	MOP	0	21.2	15.8
T_{11}	½ (N+FYM) + $P_{(A-X/2)}$ + $K_{(B-Y/2)}$	FYM and urea	SSP	MOP	55.0	55.6	42.9
T_{12}	Lime + NPK	Urea	SSP	MOP	110.0	90.0	70.0
T_{13}	Lime + FYM + $P_{(A-X)}$ + $K_{(B-Y)}$	FYM	SSP	MOP	0	21.2	15.8
T_{14}	Lime + N	Urea	-	-	110.0	0	0

Subscripts A and B stand for full dose of P and K *i.e.* 90 kg P_2O_5 and 70 kg K_2O ha^{-1}, respectively. X and Y represent the amount of P and K present in full dose of FYM applied on N basis to meet 110 kg N ha^{-1}.

potassium are applied as basal and nitrogen is applied in splits for both the crops. Details of the treatments are presented in **Table 1**.

A fixed crop rotation of maize in *kharif* and wheat in *rabi* has been followed since 1956 but the varieties of both the crops have been changed from time to time depending on their potential. Experiment was initiated in 1956 with maize variety Kalimpong and wheat variety BR 319. After 15 cycles of cropping, the Kalimpong and BR 319 were replaced by Ganga Safed-2 and S 227, respectively. In the year 1980-81, wheat variety S 227 was replaced by RR-21. In the year 1990-91 Suwan (Composite) variety of maize replaced Ganga Safed–2. In the year 1992-93 the wheat variety was changed to HD 2902, followed by HW 2045 from 2000-01 to 2005-06, K 9107 from 2006-07 to 2015-16, and to HD 2967 during the year 2016-17. Thus currently Suwan (Composite) and HD 2967 are the maize and wheat varieties, respectively being grown. At present, there are 14 treatments representing different nutrient management practices *viz*., organic, inorganic and their combinations. Initial soil characteristics are presented in **Table 2**.

ICAR-AICRP on Long-Term Fertilizer Experiment (AICRP-LTFE).

Indian Council of Agricultural Research (ICAR), New Delhi in September 1970 launched the All India Coordinated Research Project on Long-term Fertilizer Experiments (LTFE) with Ranchi as one of the participating centers. Under this project, a permanent fixed treatment experiment was initiated in 1972 at the Research Farm of the Department of Soil Science and Agricultural Chemistry, Birsa Agricultural University, Ranchi. Soil characteristics determined in 1972 just before the start of the experiment are presented in **Table 3**.

Table 2. Initial characteristics of soil under permanent manurial trial (PMT)

Physical properties	
Sand (%)	45.5
Silt (%)	15.3
Clay (%)	36.4
Textural class	Clay loam
Bulk density (Mg m^{-3})	1.45
Particle density (Mg m^{-3})	2.67
Total pore space (%)	46.15
Physico-chemical properties	
pH	5.50
CEC [cmol(p^+)kg^{-1}]	10.50
Exchangeable Ca [cmol(p^+)kg^{-1}]	6.00
Exchangeable Mg [cmol(p^+)kg^{-1}]	2.50
Exchangeable K [cmol(p^+)kg^{-1}]	1.16
Electrical conductivity (dS m^{-1})	0.03
Chemical properties	
Organic carbon (g kg^{-1})	5.2
Total N (%)	0.067
Available N (kg ha^{-1})	313.6
Available P (mg kg^{-1})	7.5
1*N* NH_4OAc-K (mg kg^{-1})	360

Table 3. Initial soil characteristics of AICRP-LTFE, Ranchi

Soil type and soil local name	Red loam
Soil order, sub-order, sub-group :	Order - Alfisol; Sub-order - Ustalf; Great group Paleustalf; Subgroup - Typic Paleustalf; Family - Hyperthermic mixed Typic Paleustalf
Soil texture	Sandy clay loam
Coarse sand (%)	14.81
Fine sand (%)	51.42
Silt (%)	9.40
Clay (%)	25.40
Bulk density (Mg m^{-3})	1.36
Cation exchange capacity [cmol(p^+)kg^{-1}]	7.80
Hydraulic conductivity (cm hr^{-1})	5.82
Soil pH (Soil: water::1:2)	5.30
Organic carbon (g kg^{-1})	4.20
Available N (kg ha^{-1})	295.0
Available P (kg ha^{-1})	12.6
Available K (kg ha^{-1})	157.7
Available Ca (kg ha^{-1})	2150.4 or 4.8 cmol(p^+)kg^{-1}
Available Mg (kg ha^{-1})	201.6 or 0.75 cmol(p^+)kg^{-1}
Available Zn (mg kg^{-1})	1.1 (2.46 kg ha^{-1})
Available Cu (mg kg^{-1})	2.0 (4. 48 kg ha^{-1})
Available Fe (mg kg^{-1})	47.0 (105.28 kg ha^{-1})
Available Mn (mg kg^{-1})	57.0 (127.68 kg ha^{-1})

Table 4. Details of cropping systems followed and changes in varieties of crops over a period of time at AICRP-LTFE, Ranchi

Period	Sequence followed	Varieties
1972 to 79	Soybean-Potato-Wheat	***Soybean*:** Bragg (1972 to 75)*, Punjab-1 (1976 to 79) ***Potato*:** Kufri Chandramukhi (1972 to 79) ***Wheat*:** SS 227 (1972 to 79)
1980 to 85	Soybean-*Toria*-Wheat	***Soybean*:** Punjab-1 (1980), Birsa soybean (1981 to 83), Punjab-1 (1984 to 85) **Toria:** BR-23 (1980 to 85): ***Wheat*:** RR 21 (1980-85)
Continuing since 1986)		***Soybean*:** Punjab-1 (1986 to 2004), JS-335 (since 2005) ***Wheat*:** RR 21 (1986 to 92), HD 2402 (1993 to 2002), HW 2045 (2003 to 05), K 9107 (2006 to 2015) and HD 2967 (2016).

* Figures in parenthesis represent the calendar year.

The experiment was laid out in an acidic red loam soil with 10 treatments each replicated four times in RBD. Optimal fertilizer dose ($N:P_2O_5:K_2O$) based on the initial soil test values was 25:60:40, 80:60:40, 100:80:120 and 25:30:20 kg ha^{-1} for soybean, wheat, potato and *toria*, respectively. Fertilizer dose for soybean and wheat was calculated based on soil test values with the help of the following equations:

	Soybean	Wheat
N	FN= 1.73xT-0.04xSN	FN=4.84xT-0.36xSN
P	FP_2O_5=5.86xT-1.22xSP_2O_5	FP_2O_5=2.94xT-1.63xSP_2O_5
K	FK_2O=2.6xT-0.25xSK_2O	FK_2O=2.01xT-0.16*SK_2O

Where T is target in q ha^{-1}; S is the soil test value in kg ha^{-1}; FN, FP_2O_5 and FK_2O are the fertilizer doses computed as FN, FP_2O_5 and FK_2O, respectively.

Experiment was started with soybean-potato-wheat cropping system in 1972. It was changed to soybean-*toria*-wheat in 1980. In 1986, *toria* was dropped owing to difficulties faced in land preparation for next crop after *kharif* and overlapping of crop cycle and availability of irrigation water during the critical crop growth stages and 1986 onwards, soybean-wheat system has been practiced and the same continues. Details of the crops and varieties followed at the AICRP-LTFE Ranchi Centre are presented in **Table 4**. Soybean is grown as rainfed crop in *kharif* and wheat is raised in *rabi* season under irrigated conditions.

Application of *Rhizobium* culture is followed for soybean. Taking into account a large build-up of P in the soil, P_2O_5 level was reduced by 50% with effect from the year 2008-09 *i.e.*, the fertilizer dose was readjusted to 25:30:40 and 80:30:40 kg $N:P_2O_5:K_2O$ for soybean and wheat, respectively. The level of N was raised from 80 kg ha^{-1} to 120 kg ha^{-1} for wheat from 2009-10 onwards. Currently the $N:P_2O_5:K_2O$ dose is 25:30:40 and 120:30:40 kg ha^{-1} for soybean and wheat, respectively. Treatment

Table 5. Treatment details of LTFE

Tr. No.	Description
T_1	50% Optimal NPK + Weedicide
T_2	100% Optimal NPK + Weedicide
T_3	150% Optimal NPK + Weedicide
T_4	100% Optimal NPK + Hand weeding
T_5	100% Optimal NPK + Lime @ 1/10th LR+ Weedicide (Lime @ 4.0 q ha^{-1} from the year 2005-06 onward) to *kharif* crop
T_6	100% Optimal NP + Weedicide
T_7	100% Optimal N + Weedicide
T_8	100% Optimal NPK + FYM @ 10 t ha^{-1} + Weedicide
T_9	100% Optimal N(S)PK + Weedicide
T_{10}	Control ($N_0P_0K_0$) (without any fertilizer or manure or lime)

Imazethapyr (pre-emergence) and 2,4-D (post emergence) are applied for soybean and wheat, respectively for all the treatments except in T_4 where hand-weeding is practiced and in absolute control T_{10}. Urea, DAP and MOP are used as the fertilizers for N, P and K except in treatment T_9 where SSP is used as P source.

Plot size : 100 m^2**; Replications :** Four; **Design :** RBD

Superimposed treatments (from, 2002-03)

T_6	Original (S_1)	Original + Lime (S_2) (as 1/10th of LR)	Original + FYM (S_3)
T_7	Original (S_1)	Original + Lime (S_2) (as 1/10th of LR)	Original + FYM (S_3)
T_9	Original (S_1)	Original + Lime (S_2) (as 1/10th of LR)	Original + FYM (S_3)

Superimposed treatment (2005-06)

T_3	Original (S_1)	Original + FYM @ 5.0 t ha^{-1} (S_2)	Original + FYM @ 10 t ha^{-1} (S_3)

Replications: Two, Design: Nested Linear Model (Two-way interaction)

details including fertilizer rates, rate of lime/FYM application followed are presented in **Table 5**.

Productivity of the Cropping Systems

System-wise productivity is presented separately.

Maize-Wheat Cropping System

Results presented in **Figure 1** showing effects of different nutrient management practices on crop yields during the last six decades reveal that the maize-wheat cropping system has a potential for producing 6-8 t grains ha^{-1} yr^{-1} (in terms of wheat equivalent yield, WEY) in red and lateritic soil regions of Ranchi. But, such higher yield levels cannot be sustained over years without balanced and integrated use of plant nutrients. Continuous use of N and NP with or without K fertilizers caused yield reduction over the years. Interestingly, use of ammonium sulphate initially and urea later on alone as N sources reduced the grain yield of crops to a level, which was even lower than that of the unfertilized plot (with no manure/fertilizer). This was primarily due to the reduction of soil pH *per se* from 5.5 in 1956 to 4.2 in 2016, and the pH-induced direct and indirect effects on soil properties.

Application of lime or FYM along

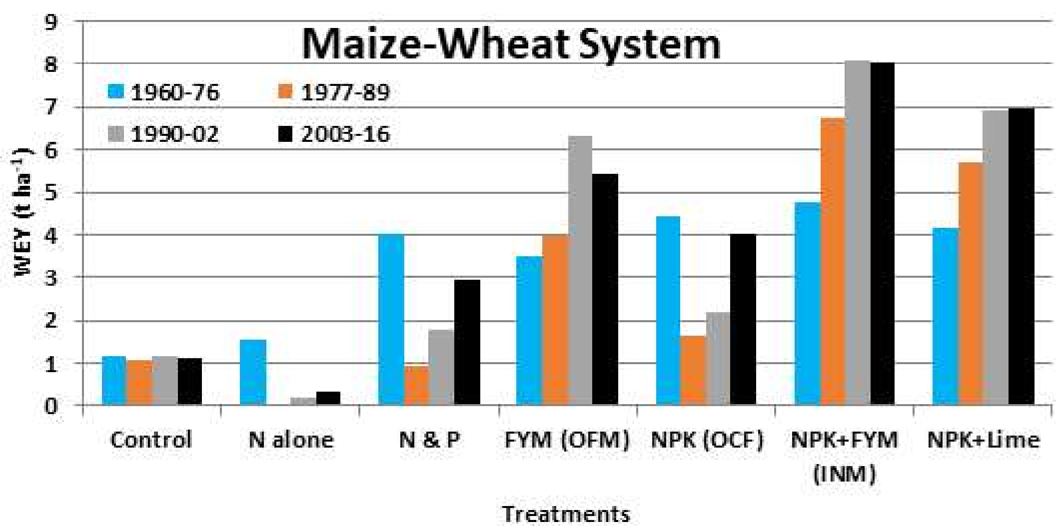

Figure 1. Wheat equivalent yield over the years under maize-wheat system
OFM: FYM only, OCF: Chemical fertilizers, INM: Integrated nutrient management.

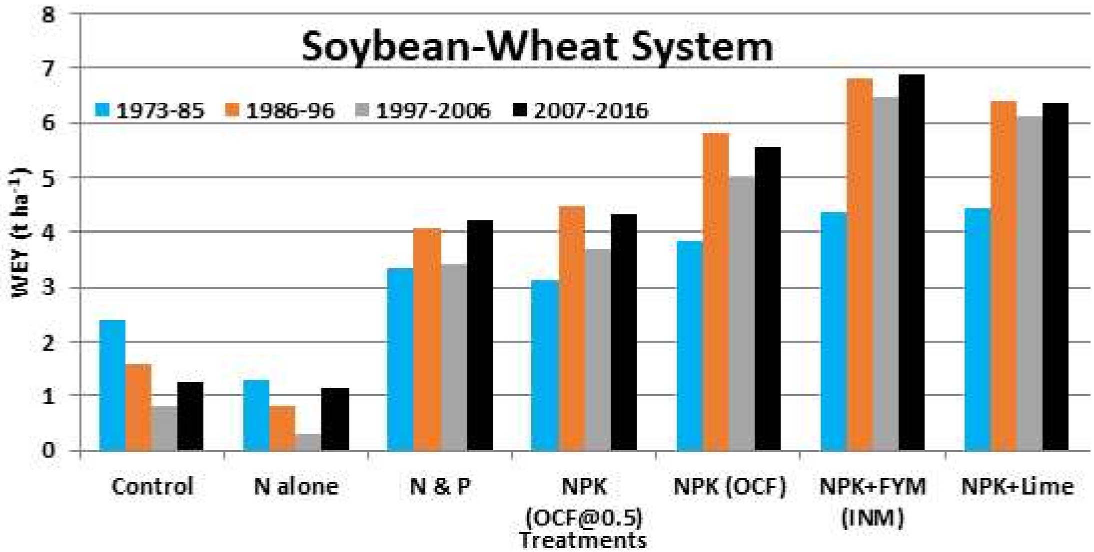

Figure 2. Wheat equivalent yield over the years under soybean-wheat system
OCF: Only chemical fertilizers, INM: Integrated nutrient management.

with NPK fertilizers sustained high crop productivity (6 to 8 t ha^{-1}) over the last 25 years and at the same time maintained the soil health. This may be attributed to the beneficial effect accruing from application of either lime (as an amendment for acidic soils) or FYM (as an amendment, buffering properties, and a nutrient source) on aggregate and structural stability, water holding capacity, availability of plant nutrients, chelating acid forming cations and improvements in biological properties of soils, etc. Interestingly, on a comparative note, NPK alone, FYM alone, NPK + lime and NPK + FYM have sustained the wheat equivalent yield at 4, 5, 7 and 8 t ha^{-1} yr^{-1}, respectively, in the soils over past three decades.

Soybean-Wheat System

In soybean-wheat system, the wheat equivalent yield (WEY) under different treatments followed the order: NPK+FYM > NPK + Lime > NPK > NP > Unfertilized > N. The NPK fertilizers used in conjunction with lime/FYM sustained the wheat yield equivalents in the range of 6-7 t ha^{-1} yr^{-1} during last three decades or so. In the absence of lime/FYM, NPK application sustained WEY at less than 5.2 t ha^{-1} yr^{-1} during the same period (**Figure 2**).

With an emphasis to study the effect of ameliorants in acid soils, superimposition of ameliorants was done in 2002-03 (**Table 6**). Results suggest a positive effect of lime and FYM application on grain yield of both the crops *i.e.*, soybean and wheat, under N, NP, NPK and N(S)PK. Interestingly, FYM was more effective than lime when added to 100% NP and 100% N treatments; lime was better when added to 100% N(S)PK. Soil receiving 150% NPK fertilized additionally with 5 and 10 t FYM ha^{-1} observed 11.6 and 15.9% increase in productivity of soybean, respectively. In case of wheat increase was 14.5 and 26.2%, respectively. Based on the studies in acidic red and lateritic soils of Jharkhand and Odisha (pH <5.5 & low in organic matter), Sharma and Sarkar (2005) and Jena (2013) have shown that combined application of FYM as basal and lime @ 1/10th lime requirement (applied in furrows) are desirable for sustenance of

Table 6. Effect of lime /FYM on grain yield of crops under soybean-wheat cropping system in superimposed treatments

Treatments	Soybean		Wheat	
	Mean grain yield ($t ha^{-1}$) over the years	% increase	Mean grain yield over the years	% increase
100% NP	0.615		2.911	
100% NP +Lime	1.017	65.2	3.484	19.7
100% NP +FYM	1.675	172.1	3.774	29.7
100% N	0.239		0.354	
100% N + Lime	0.721	201.8	0.646	82.2
100% N + FYM	1.530	540.9	1.687	376.0
100% N(S)PK	0.980		1.946	
100% N(S)PK + Lime	1.936	97.6	3.339	71.6
100% N(S)PK + FYM	1.865	90.5	3.010	54.7
150% NPK	1.908		3.015	
150% NPK + 5.0 t FYM	2.129	11.6	3.451	14.5
150% NPK + 10.0 t FYM	2.213	15.9	3.806	26.2

Table 7. Effect of nutrient management practices on sustainable yield index (SYI) of crops under different cropping systems

Maize-Wheat System			Soybean-Wheat System		
Treatments	Maize	Wheat	Treatments	Soybean	Wheat
Control	0.03	0.09	Control	0.10	0.03
N alone	-0.05	-0.01	N alone	0.01	0.02
N and P	-0.02	0.10	N and P	0.21	0.28
FYM (OFM)	0.28	0.28	NPK (OCF@0.5)	0.37	0.35
NPK (OCF)	0.32	0.23	NPK (OCF)	0.48	0.25
NPK + FYM (INM)	0.43	0.38	NPK+FYM (INM)	0.62	0.42
NPK + Lime	0.50	0.32	NPK + Lime	0.60	0.41

crop production.

Sustainable Yield Index

Sustainable yield index (SYI) helps to establish the minimum guaranteed yield that can be obtained relative to maximum observed yield for a set of experiments under study. A higher value of SYI under a given practice implies that it is a more progressive management practice capable of producing high yields over the years. The nearness of the SYI to 1 implies the closeness to an ideal condition that can sustain maximum crop yields, whereas deviation from 1 indicates loss/reduction in sustainability.

Sustainable yield index (SYI) for maize and wheat, computed from the yield data are presented in **Table 7**. Highest sustainable yield index (SYI) obtained for maize was 0.50 for 100% NPK + lime treatment. Integrated use of organics and chemical fertilizers had SYI of 0.43 and it was followed by 0.28 observed with application of FYM alone. Lowest and negative SYI value of -0.05 was recorded with application of N alone. Imbalanced and continuous use of N alone produced greatest decline in yield and had deleterious effect on long-term yield sustainability, indicating that other major and micronutrients had started becoming the limiting factors in crop production and adequate response to N could not be obtained unless limitations imposed by those factors were alleviated. In wheat, sustainable yield index followed the order: NPK + FYM > NPK + Lime > FYM > NPK.

In soybean-wheat cropping system, SYI for soybean was highest (0.62) with NPK + FYM followed closely by NPK + lime (0.60). NPK application alone at the recommended level had lower SYI values of 0.48 for soybean and 0.28 for wheat, which were considerably lower than that with lime or FYM. Results strongly suggest on the use of lime for harvesting sustainable higher yields of leguminous crops, chiefly pulses in acid soils. Based on these results, it can be concluded that integrated use of lime or FYM coupled with balanced NPK is the best management practice for increasing as well as sustaining crop production in the acidic red and lateritic soils.

Nutrient Uptake by Cropping Systems

Perusal of data in **Table 8** reveals highest uptake for all the nutrients in the treatment where lime/FYM was applied along with optimal dose of NPK. Total nutrient removal was highest *i.e.*, 256.9, 38.6 and 107.0 kg ha^{-1} yr^{-1} for N, P and K, respectively in maize-wheat system under NPK + Lime treatment. In soybean-wheat system it was 259.9, 33.3 and 161.3 kg ha^{-1} yr^{-1} N, P and K, respectively under NPK + FYM. Between the two cropping systems, K removal was much higher in soybean-wheat cropping system as compared to maize-wheat cropping system.

Impact of Manuring and Fertilization on Soil Properties

Impact of manuring and fertilization on soil properties is discussed for each cropping system separately.

i) Maize-Wheat Cropping System

a) Bulk Density

Bulk density of the experimental field at the start of the experiment *i.e.*, during 1956 was 1.45 Mg m^{-3}. After harvest of maize crop during 2015-16 , it varied from 1.31 to 1.53 Mg m^{-3} depending upon the treatments (**Table 8**). Significantly higher soil bulk density was recorded under NPK + Lime

Table 8. Total uptake (kg ha^{-1}) of N, P and K by the cropping systems as affected by continuous cropping, fertilizer and manure application

Treatments	Maize-Wheat			Treatments	Soybean-Wheat		
	N	P	K		N	P	K
Control	46.8	4.9	22.5	Control	38.6	3.4	19.1
N alone	20.7	2.2	8.6	N alone	41.9	4.0	27.3
NP	100.1	11.2	38.4	NP	144.7	17.5	80.1
FYM (OFM)	184.3	23.2	85.9	NPK (OCF@0.5)	163.7	17.1	89.8
NPK (OCF)	127.7	15.2	52.6	NPK (OCF)	199.4	21.7	111.5
NPK + FYM (INM)	228.0	27.6	96.7	NPK + FYM (INM)	259.9	33.3	161.3
NPK + Lime	256.9	38.6	107.0	NPK + Lime	235.6	27.9	129.7

Table 9. Effect of 60 years of continuous cropping, fertilizers, manure and lime application on soil fertility status under maize-wheat cropping system

Treatment	pH	EC (dS m^{-1})	Org. C (g kg^{-1})	Avail. P (kg ha^{-1})	Avail. K (kg ha^{-1})	Avail. S (mg kg^{-1})	Exch. Ca [cmol(p^+)kg^{-1}]	Exch. Mg [cmol(p^+)kg^{-1}]
Control	5.7	0.05	5.6	5.60	140.1	16.9	3.2	2.6
100% N	4.2	0.07	5.6	17.8	128.8	25.7	1.6	0.5
100% NP	4.5	0.11	6.5	389.9	112.4	64.4	2.0	0.9
100% NPK	4.8	0.06	6.6	661.4	173.2	21.8	2.2	0.9
100% NPK+ Lime	6.2	0.06	6.5	176.2	168.0	12.2	7.0	1.1
FYM	6.3	0.08	11.0	169.3	203.0	18.7	5.2	3.6
NPK + FYM	5.6	0.06	8.4	335.6	162.4	23.8	4.3	3.0
Lime + N	5.7	0.05	5.4	5.60	112.7	16.3	4.4	1.8
CD (P = 0.05)	0.265	0.01	1.4	67.3	33.01	5.97	0.6	0.5
CV (%)	2.82	10.8	11.8	17.5	12.6	13.7	9.5	14.5

treatment. Application of farmyard manure on the other hand caused reduction in the bulk density of soil. The FYM effect could be related to associated increase in organic matter content which is responsible for improvement in pore space. Higher bulk density in the lime-treated soil may be due to cementing effect induced by $CaCO_3$.

b) Soil Reaction (pH)

Long-term application of fertilizers and manures to soil is expected to effect changes in soil reaction depending upon the dose and type of fertilizers used. Data in **Table 9** revealed significant effect of treatments on soil reaction. Initial soil pH at the start of the experiment was 5.5. As is evident from the data, it was influenced by nutrient management practices. Soil pH under different treatments varied from 4.2 to 6.3 after 60 cycles of cropping. Control plot witnessed marginal increase in soil pH from 5.5 to 5.7. Drastic reduction in soil pH was observed in the plots receiving chemical fertilizers only where soil pH decreased by 0.7 to 1.4 units; maximum drop in pH was recorded due to the application of N alone either with urea or ammonium sulphate as nitrogen source. Acid-producing nature of these fertilizers is the reason for this drop. Application of lime/FYM improved or stabilized the soil pH. The plots which have been receiving lime along with NPK fertilizers, witnessed a 0.7 units rise in soil pH, which clearly demonstrates the ameliorative effect of lime on soil acidity. The FYM-amended plots had a favourable influence in stabilizing the soil pH.

c) Electrical Conductivity (EC)

Electrical conductivity of soil is a measure of the concentration of salts in soil solution. Electrical conductivity of the soil varied from 0.05 to 0.11 dS m^{-1}. Higher EC values were recorded for 100% NP treatment, followed by FYM treatment (0.08 dSm^{-1}) and it was least in the lime and N and control plots. The EC values in all treatments are so far safe for growth of all types of the crops. Higher EC values due to application of fertilizers/manures might be due to continuous addition of salts through the fertilizer materials over the years.

d) Soil Organic Carbon

An overall increase in soil organic carbon was observed in the present study under all the treatments as compared to its initial value (5.2 g kg^{-1}). The value of organic carbon varied from as low as 5.4 g kg^{-1} in Lime + N to as high as 11.0 g kg^{-1} in FYM treatment (**Table 9**). Continuous application of FYM alone or integrated use of FYM with NPK fertilizers recorded significantly higher organic carbon content over other treatments comprising of chemical fertilizers alone. This could be attributed to direct incorporation of organic matter and better root growth in the FYM-amended soils. Application of chemical fertilizers alone or in combination with lime recorded lower organic carbon in soil similar to control, which might be due to enhanced lime-induced oxidation of soil organic carbon (Sarkar and Singh, 2002).

f) Available Phosphorus

Available phosphorus in soil varied from as low as 5.6 kg ha^{-1} in control and lime + N treatment to high of 661.4 kg ha^{-1} under NPK treatment (**Table 9**). Critical examination of the data shows that the continuous application of phosphatic fertilizers in combination with N, NP, NPK, NPK + lime and NPK + FYM caused a significant build up in available P content of the soil. Substantial build-up of available P with its continuous use in these acidic soils is attributed to low crop recovery of applied P and its high stability as residual P in the acid soils. In the plots receiving treatments comprising of either FYM alone or in combination with fertilizers, there occurred a significant build up in the available P content compared to control and N-treated plots. Increase in available P content in the manured plots could be attributed to higher

Table 10. Effect of cropping and nutrient use on available micronutrient content in soil

Treatment	DTPA-Fe (mg kg^{-1})	DTPA-Cu (mg kg^{-1})	DTPA-Mn (mg kg^{-1})	DTPA-Zn (mg kg^{-1})	HWS- B (mg kg^{-1})
Control	11.75	0.34	12.10	0.63	0.64
100% N	18.21	0.43	6.00	0.57	0.56
100% NP	24.24	0.54	4.47	0.50	0.59
100% NPK	28.89	0.61	5.53	0.64	0.51
100% NPK + Lime	13.16	0.37	7.74	0.75	0.81
FYM	20.77	0.57	9.90	2.56	1.44
NPK+FYM	27.72	0.36	12.44	1.31	0.56
Lime + N	12.77	0.55	7.35	0.77	0.63
CD (P = 0.05)	5.8	0.07	0.79	0.20	0.22

mobilization of native P and higher mineralization of organic P.

g) Available Potassium

Available K content in the soil varied from 112.4 kg ha^{-1} under 100% NP treatment to 203 kg ha^{-1} under FYM treatment (**Table 9**). Critical examination of the data revealed decline in available K status in the treatments receiving chemical fertilizers devoid of K *i.e.,* N and NP treatments. This might be due to increase in release rate of native K on application of fertilizers devoid of K. Significant increase in available K content was observed in the plots amended with FYM. This might be due to supply of K from FYM, which helped in maintaining the supply of K and also releasing more indigenous K through priming action.

h) Secondary Nutrients

Calcium, magnesium and sulphur are required in relatively larger amounts for good growth of crops. Sulphur and magnesium are needed by plants in about the same quantities as phosphorus, and for many plant species, calcium requirement is greater than that of phosphorus. Available sulphur content in the soil under different treatments varied from 12.2 to 64.4 mg kg^{-1} (**Table 9**). Highest available S content was observed in the plots receiving NP treatment; this could occur probably due to reduction in yield and this yield reduction was responsible for lower S removal from the soil. Effect of continuous cropping, fertilizers, manure and lime application over the years showed that available S content of soil was just above the critical limit of 10.0 mg kg^{-1} for all the treatments probably due to use of S-impure SSP as a phosphatic fertilizer as SSP contains 12% S and is a standard fertilizer-S source.

Exchangeable Ca and Mg under different treatments varied from 1.6 to 7.0 and 0.5 to 3.6 cmol (p$^+$) kg^{-1}, respectively. Calcium and Mg are two plant nutrients, which often occur in lower amounts in acid soils. Exchangeable Ca and Mg content were lowest under N treatment, which might be due to reduction in pH created by application of acid forming N fertilizers and also due to continuous removal of these nutrients by crops. The exchangeable Ca and Mg status exhibited improvement in the plots continuously fertilized along with lime and FYM.

i) DTPA Extractable Micronutrient Cations

Red and lateritic soils of Jharkhand are fairly well supplied with the cationic micronutrients. However, in recent years, Zn deficiency has been reported from intensively cropped areas. DTPA extractable Fe, Cu, Mn and Zn varied from 11.75 to 28.89, 0.34 to 0.61, 4.47 to 12.10 and 0.50 to 2.56 mg kg^{-1}, respectively (**Table 10**). Addition of lime along with the NPK increased the availability of micronutrients in soil, which might be due to the higher organic matter content of these soils supporting enhanced microbial activity and consequent release of organic complexing substances, which could enhance the micronutrient availability. The FYM-treated plots maintained the highest level of DTPA-extractable cations, mainly due to application of organic manures over the years. Lime/FYM along with NPK application also sustained the availability of these micronutrients in acid soils (Sarkar and Singh, 2002). Plots receiving N and NP fertilizer exhibited a drop in the DTPA-Zn level in soil to less than 0.60 mg kg^{-1}, a limit used to categorize a soil as Zn-deficient.

j) Hot Water Soluble Boron (HWS-B)

Boron deficiency to the tune of 40% has been reported in soils of Jharkhand (Singh and Ghosh, 2013). This is primarily due to leaching of soluble B from coarse textured acid upland soils and its non-application in cereal-cereal, cereal-vegetable, and cereal-pulse systems. In this experiment ammonium sulphate was used as a N source for the first 34 years; after that urea has been used. In the N, NP and NPK-amended plots, due to high soil acidity (pH 4.2 to 4.8), available boron although low but is just above the critical level of 0.5 mg kg^{-1} (**Table 10**). The NPK + lime plots maintained a higher level of this micronutrient. Application of B along with NPK+FYM is a better practice in maize-wheat cropping system than its non-application. The minimum and

Table 11. Effect of forty-five years of continuous cropping, fertilizers, manure and lime application on soil fertility status under soybean-wheat cropping system

Treatments	pH	Org. C ($g\ kg^{-1}$)	Avail. N ($kg\ ha^{-1}$)	Avail. P ($kg\ ha^{-1}$)	Avail. K ($kg\ ha^{-1}$)	Avail. S ($kg\ ha^{-1}$)	Avail. Ca ($kg\ ha^{-1}$)	Avail. Mg ($kg\ ha^{-1}$)
50% NPK + W	5.2	4.6	209.1	16.6	85.7	23.7	889.0	253.3
100% NPK + W	5.2	4.6	229.4	107.5	80.1	22.3	724.3	233.5
150% NPK + W	4.7	4.6	201.8	238.1	104.4	22.0	476.6	215.4
100% NPK +HW	5.0	4.7	209.5	111.6	88.0	21.9	727.0	270.5
100% NPK + Lime + W	6.0	**3.8**	195.6	69.6	83.5	21.5	1242.7	334.3
100% NP + W	5.3	4.6	221.0	75.4	**58.5**	21.0	833.5	228.1
100% N + W	4.6	4.6	217.2	16.0	107.9	20.4	368.5	173.4
100% NPK + FYM +W	5.2	**5.5**	248.1	216.6	88.0	22.7	826.8	313.5
100% N (S) PK + W	4.8	**5.2**	224.9	205.2	101.0	173.2	315.9	119.5
Control	5.1	3.9	181.5	15.8	102.7	22.3	947.0	246.5
CD (P = 0.05)	0.3	0.7	12.34	24.9	13.9	4.08	123.80	16.89
CV(%)	4.0	9.7	4.0	16.0	10.6	7.58	11.60	4.87

W = Weedicide, H.W. = Hand weeding

maximum content of HWS=B was 0.51 and 1.44 mg kg^{-1} in 100% NPK and FYM-treated plots, respectively.

ii) Soybean-Wheat Cropping System

a) Soil Reaction

Results in **Table 11** reveal maximum reduction in soil pH of 0.5-0.7 units under treatments namely, 100 N (S) PK+W, 100% N and 150% NPK treatments. Lime application along with recommended dose of NPK caused an increase of 0.7 units in pH after harvest of wheat crop. In superimposed treatments application of lime increased the pH of the soil while FYM application led to slight decline in pH of soil as compared to its initial value. In the fourth superimposed treatment there was no influence of FYM application on the pH of soil after harvest of crops.

b) Soil Organic Carbon

After 45 years of intensive cropping, a decline in organic carbon content in almost all the treatments was observed; exceptions were 100% N(S)PK and 100% NPK+FYM treatments (**Table 11**). Application of 10 t FYM ha^{-1} yr^{-1} during the *kharif* season along with recommended NPK could maintain the initial organic carbon content of soil. There was reduction in organic carbon content of soil in the lime-treated plots. In superimposed treatments the effect of FYM on increasing organic carbon was not appreciable.

c) Available Nitrogen

After more than four decades of intensive cropping, it was observed that in general, there was a decline in available N content of soil from the initial value of 295 kg N ha^{-1} in all treatments (**Table 11)** and the decrease varied from 58 to 96 kg N ha^{-1}.

d) Available Phosphorus

There was a build- up of P in these soils and highest P accumulation was observed in super-optimal treatment (150%NPK). It was followed by 100% NPK + FYM and 100% N(S)PK treatments. Decline in available P was noticed in the plots receiving only N fertilizer and no fertilizer (control).

e) Available Potassium

There was a decline in available K content of soil from the initial value of 157.7 kg K ha^{-1} in all the treatments. Decrease ranged from 25 to 95 kg K ha^{-1} after 45 years of cropping and highest decrease observed was under 100% NP treatment.

f) Secondary Nutrients

Analysis of post-harvest soil samples for secondary nutrients revealed that the exchangeable Ca content in the soils decreased considerably under intensive cropping and the lowest exchangeable Ca was found in the plots treated with 100%N and 100% N(S)PK.

g) Soil Carbon Pool

Active fraction of soil organic carbon (SMBC, SMBN) changed significantly (**Table 12**). There occurred a substantial decrease in these parameters under N or NP treatments as compared to balanced NPK use. A decline in active fractions of C and N after long-term cultivation led to a depletion of soil fertility through reduction of labile sources of nutrients, faster decomposition and lower bio-available nutrients (Mahapatra et al., 2007). Furthermore, continuous cultivation and lower above-ground biomass production significantly reduced the total amount of nutrients as well as soil microbial biomass, which might lead to the degradation of soil biological function. There was an extensive depletion of particulate organic carbon (POC) under imbalanced nutrient use. The POC is an indicator of soil quality for any land use management and tillage practice and its disruption rate is primarily affected by state of soil aggregation. Particulate organic carbon content was highest with

Table 12. Long-term effect of continuous cropping and fertilizer, manure and lime application on soil organic carbon fractions under different cropping systems.

Treatments (%)	Water soluble C (mg kg^{-1})	Water soluble carbohydrates (mg kg^{-1})	SMBC (mg kg^{-1})	SMBN (mg kg^{-1})	Particulate organic C as per cent of total soil organic carbon
Control	20.4	251.8	175	17	28
100% N	22.3	255.0	132	12	31
100% NP	24.4	243.8	156	14	32
100% NPK	26.3	277.9	186	18	34
100% NPK + lime	35.5	302.3	207	23	32
100% NPK + FYM	44.6	327.3	237	25	41
150% NPK	40.5	312.5	217	23	39
CD (P = 0.05)	7.3	26.3	8.8	1.4	NS

application of NPK + FYM or NPK + Lime. Redistribution of SOM from labile to more humified fractions was observed due to cropping. Thus, long-term N or NP fertilizer application with simultaneous and continuous removal of crop residues reduced the quantity of POM. Balanced plant nutrition (NPK + FYM or NPK + Lime) was necessary to increase the total amount of POC in the red and lateritic soil under soybean-wheat system (**Table 12**).

Soil Quality

Principal component analysis (PCA) was performed on soil attributes. The first seven principal components (PC) accounted for more than 80% of the variability of the data. The PCs with eigen values (variance accounted for >1) were examined. The first PC, which explained 24.8% of the variance, had high *positive loadings* on DHA (dehydrogenase), magnesium (avail. Mg), pH, Ca (avail. Ca) and potentially mineralizable N (PMN) and *negative loadings* on total acidity (t_a), and hot water soluble B (HWS-B), indicating the inverse relationship between (total acidity) and HWS-B with other five variables. Among these attributes, total acidity was found to be very well correlated with other variables and had the highest correlation sum (absolute values) among these variables. The second PC, which explained 11.7% of the variance, had high positive loading on available Cu, fungi and soil microbial biomass nitrogen (SMBN). The third PC, which explained 11.5% of the variance, had high positive loading on SMBC and available S, and negative loadings on DTPA-Ni). The fourth PC, which explained 8.9% of the variance, had high positive loading on DTPA -Cd. The fifth PC, which explained 8.5% of the variance, had high positive loading on available Zn and negative loading on DTPA -Co. The sixth PC, which explained 7.6% of the variance, had high positive loading on mineral N, total N and $CaCO_3$. The seventh PC, which explained 7.5% of the variance, had high positive loading on labile C.

Under a particular PC, only the variables with high positive factor loading were retained for development of SQI where high factor loadings were defined as having absolute value within 10% of the highest factor loading in the respective PC. When more than one variable was retained under a single PC, multivariate correlations were implied to determine if the variables could be considered redundant and therefore, eliminated from the soil quality index (SQI). If the highly loaded factors were not correlated, then each was considered important and thus, retained for estimation of SQI. Among well correlated variables, the variable with the highest factor loading (absolute) value was chosen for development of SQI. It was observed that pH, exchangeable Ca^{2+}, DHA (dehydrogenase), PMN (potentially mineralizable nitrogen), soil microbial biomass carbon (SMBC), SMBN (soil microbial biomass nitrogen), total N, mineral-N, labile carbon, organic carbon and available sulphur were the key indicators for soil health under this situation. Each PC explained a certain amount of variation (%) in the total dataset and the percentage provided the weight for variables chosen under a given PC. Variables which had higher factor loading were considered as the best representative indicators. Values of key soil quality indicators were transformed into unitless score (between 0 to 1) using linear transformation. The most sensitive indicators in descending order of importance as revealed by PCA and correlation studies were as follows: soil pH > dehydrogenase > potentially mineralizable N > SMBN> SMBC. Soil quality index was developed using additive model, SQI =Wi×Si. The index developed varied from 0.18 to 0.72 (**Table 13**). Relative soil quality index was calculated as the percentage of the highest SQI observed for the set of experiment. Lower SQI values were observed under imbalanced fertilizer use. Application of N fertilizer alone reduced the quality of soil by 70% as compared to the best management practices and the situation was worse under maize-wheat than soybean-wheat cropping system.

The higher index values, relative SQI (RSQI) and sustainable yield index (SYI) under balanced and integrated nutrient supply system suggest that these nutrient management options are good in maintaining better soil health and sustaining higher crop productivity in acid soils. Therefore, sustained efforts are

Table 13. Long-term effect of continuous cropping and fertilizer, manure and lime application on soil quality under different cropping systems

PMT (Maize-Wheat)	SQI	RSQI	LTFE (Soybean-Wheat)	SQI	RSQI
Control	0.34	0.55	Control	0.54	0.75
N	0.18	0.29	100%N	0.38	0.53
NP	0.19	0.31	100%NP	0.39	0.54
NPK	0.39	0.63	50%NPK	0.39	0.54
FYM	0.40	0.65	100% NPK	0.40	0.56
Lime + NPK	0.42	0.68	150% NPK	0.51	0.71
Lime + N	0.52	0.84	100% NPK+lime	0.72	1.00
100% NPK+FYM	0.62	1.00	100% NPK+FYM	0.72	1.00

Table 14. Partial factor productivity of nutrients under different cropping systems

Treatments	1960-76	1977-89	1990-02	2003-16
Maize-Wheat Cropping System				
Control	-			
N alone (kg kg^{-1} N)	13.27	4.93	5.34	5.04
NP (kg kg^{-1} NP)	24.40	0.19	0.54	1.00
FYM (OFM) (kg t^{-1} FYM)	91.65	21.06	40.30	66.70
NPK (OCF) (kg kg^{-1} NPK)	35.26	9.62	15.16	13.01
NPK+FYM (kg kg^{-1} NPK)	88.93	7.85	10.56	19.33
NPK + Lime (kg kg^{-1} NPK)	47.71	16.24	19.44	19.39
Soybean-Wheat Cropping System				
	1973-85	**1986-96**	**1997-2006**	**2007-2016**
Control	-			
N alone (kg kg^{-1} N)	22.78	14.99	7.77	8.59
NP (kg kg^{-1} NP)	8.26	5.07	1.94	6.79
NPK (OCF @0.5) (kg kg^{-1} NPK)	14.90	18.20	15.20	17.76
NPK (OCF) (kg kg^{-1} NPK)	27.81	39.94	33.14	36.33
NPK + FYM (kg kg^{-1} NPK)	17.19	25.92	22.45	23.49
NPK + Lime (kg kg^{-1} NPK)	19.54	30.36	28.95	28.88

Table 15. Agronomic efficiency of nitrogen under different cropping systems

Treatments	1960-76	1977-89	1990-02	2003-16
Maize-Wheat Cropping System				
Control	-			
N alone (kg kg^{-1} N)	4.25	-4.67	-4.61	-3.68
N & P (kg kg^{-1} NP)	32.55	-0.72	2.72	8.30
FYM (kg t^{-1} FYM)	53.59	66.12	116.35	97.61
NPK (kg kg^{-1} NPK)	37.26	2.47	4.62	13.20
NPK + FYM (kg kg^{-1} NPK)	40.94	51.43	62.68	63.11
NPK + Lime (kg kg^{-1} NPK)	33.97	21.06	26.18	26.65
Soybean-Wheat Cropping System				
	1973-85	**1986-96**	**1997-2006**	**2007-2016**
Control	-			
N alone (kg kg^{-1} N)	-10.39	-7.38	-4.87	-0.66
NP (kg kg^{-1} NP)	9.01	23.84	24.66	23.83
NPK (OCF @0.5) (kg kg^{-1} NPK)	6.89	27.62	27.57	24.60
NPK (OCF) (kg kg^{-1} NPK)	13.89	40.32	40.11	34.73
NPK + FYM (kg kg^{-1} NPK)	18.91	49.77	53.99	44.97
NPK + Lime (kg kg^{-1} NPK)	19.31	45.98	50.42	40.91

needed to improve and maintain soil resource base through judicious integration of chemical fertilisers, lime, organic and green manures, crop residues and bio-fertilizers such that it nourishes intensive cropping without getting irreversibly damaged in the process.

Nutrient Use Efficiency

Improvement in the efficiency of one single component may or may not be effective in increasing the efficiency of the system. Efficiency gains in the short-term may sometimes be at the expense of those in the long-run. Short-term reductions in application rates may increase nutrient use efficiency. Nutrient use efficiency is measured in different ways depending upon the perspective in which it is computed and considered. Agronomic indices commonly used to describe nutrient use efficiency are partial factor productivity (PFP, kg crop yield per kg nutrient applied); agronomic efficiency (AE, increase in crop yield kg per kg nutrient applied) and apparent recovery efficiency (RE, increase in kg nutrient taken up per kg nutrient applied). Influence of cropping and fertilization on these parameters is described below:

Partial Factor Productivity (PFP_{NPK})

Data on partial factor productivity presented in **Table 14** shows that PFP_{NPK} values showed reductions as compared to the initial years in the treatments receiving imbalanced doses of fertilizer nutrients. Use of lime or FYM along with NPK improved the PFP for both the cropping systems. Decline in factor productivity and the growth rate of productivity of major crops as well as rate of response of crops to added fertilizers under intensive cropping systems possibly resulted from the deterioration in physical, chemical and biological fertility of the soils.

Agronomic Efficiency of N (AE_N)

Agronomic efficiency for N under

Table 16. Apparent recovery efficiency (%) of nutrients by the system as affected by continuous cropping, fertilizer and manure application

Treatments	Maize-wheat			Treatments	Soybean-wheat		
	N	P	K		N	P	K
Control	-	-	-	Control	-	-	-
N alone	-9.5	-	-	N alone	2.3	-	-
NP	44.5	16.3	-	NP	73.1	26.9	-
FYM (OFM)	-	-	-	NPK (OCF@0.5)	86.2	26.2	14.7
NPK (OCF)	60.1	18.8	13.7	NPK (OCF)	110.9	34.8	47.2
NPK + FYM (INM)	101.0	33.6	50.3	NPK+FYM (INM)	152.6	56.9	121.9
NPK + Lime	117.9	50.2	60.2	NPK+Lime	135.9	46.7	74.5

maize-wheat and soybean-wheat cropping system (**Table 15**) was lower as compared to the initial years for the treatments receiving imbalanced rates of fertilizer nutrients. Use of ameliorant or FYM along with NPK improved agronomic efficiency of N in both the cropping systems.

Apparent Recovery Efficiency of N, P and K Nutrients (RE_N)

Apparent recovery efficiency of nutrient (RE_N) refers to the increase in nutrient uptake by plant (above ground parts) per unit of nutrient applied. Nutrient use efficiency is generally high at a low yield level, because any small amount of nutrient applied could give a large yield response. If nutrient use efficiencies were the only goal, it would be achieved with a low level of fertilizer. In acid soils, application of N alone had deleterious effect on grain yield of crops. The use efficiency of N and P increased with application of NP and NPK fertilizers, which further improved with use of ameliorants along with fertilizers (**Table 16**). The soil-water-crop management practices that promote crop productivity at same level of fertilizer use are expected to enhance the nutrient use efficiency. Similarly, all the management practices that minimize nutrient/ fertilizer requirement while achieving desired productivity targets would also lead to increase in the nutrient use efficiency.

Factors that contribute to low nutrient uptake efficiencies in the acid soils are low soil pH and the poor organic carbon content coupled with low inherent levels of most essential plant nutrients and unfavourable soil conditions. The essence of good nutrient management and fertilizer use is to ensure that the necessary quantities of the essential crop nutrients are available when required for uptake by the crop. This would minimize the loss of nutrients to the environment. Application of a nutrient as fertilizer is normally justified where the supply of the nutrient from all other sources is expected to be insufficient to meet the crop requirement. Any application of fertilizer which exceeds the crop nutrient requirement or which is not properly applied will result in wastage of money and environmental degradation.

Research Output from the Experiments in a Nutshell

- Continuous cropping with use of urea (N) and urea + SSP/DAP without potassic fertilizers caused deleterious effect on crop yields. Wheat equivalent yield under the cropping systems followed the order: Lime/FYM +NPK > NPK > FYM > NP> N.
- Application of FYM alone resulted in lower yield of maize, wheat and soybean compared to NPK + FYM or NPK + Lime during the last 4 to 6 decades of experimentation.
- Response of crops in red and lateritic soils to added phosphatic fertilizers was higher in *rabi* than that in *kharif* season. On the other hand, potassic fertilizers benefitted *kharif* crops more than the *rabi* crops, especially in legume-based cropping sequences.
- Lime application (1/10th of lime requirement as furrow application) and/or well decomposed organic manure used in conjunction with balanced NPK fertilizers proved to be the *best management practice* for crop production in acidic red and lateritic soils of eastern India.
- Conservation of soil organic matter is a critical component for long-term management of soil health. Imbalanced nutrient use (N, NP fertilizers) reduced the active fractions of soil organic carbon (SMBC, SMBN). This means that a reduction in the labile pool of nutrients adversely affected the soil health. Particulate organic carbon, an indicator of soil quality, decreased with imbalanced nutrient use. Lime and organic manures helped in conservation of both these fractions in the soil.
- Soil quality index values were low in the N- and NP- treated soils. This was highest with NPK + FYM followed by NPK + Lime use, showing the need of practicing integrated plant nutrient management for sustenance crop production and maintenance or aggregation of soil health.

Practical Lessons on Sustainable Agriculture

Sustainable Food Production

This is a challenge being faced by farmers across the country. There are yield differences varying from year to year and season to season, mainly due to prevalence of abrasive weather conditions and faulty management practices. LTFE results suggest that soil test based integrated plant nutrient management is prescription to achieve surmounting food security challenges with assurance for good soil health.

Best Management Practices

Soil-related constraints to achieve high crop production targets need to be addressed before resorting to nutrient use. Best management practices (BMP) are those, which balance the soil supply and crop requirements for essential plant nutrients. Among the external nutrient sources (N, NP, NPK, organic manure, NPK + FYM, NPK + lime), integrated use of lime/FYM with balanced NPK is the best option for yield enhancement and nutrient conservation in red and lateritic soils.

Sustaining Soil Organic Matter

Lower fertilizer use, decline in soil organic matter (SOM) and scant attention to crop nutrient needs contribute to decline in soil fertility and food production in the long run. LTFE results focus on the need to improve the SOM levels for having conducive soil-crop environment.

Improving Nutrient Use efficiency

Higher nutrient use efficiency can be achieved if we can manage a higher yield at a lower level of input use. Integrated use of plant nutrients in red and lateritic soils with measures for soil acidity correction makes nutrient uptake more efficient. It must be borne in mind that application of fertilizers, which exceeds the crop requirements, will be wastage of money and may lead to environmental pollution.

Learning Tool for Farmers

LTFE is an educational tool for farmers. This demonstrates the impact of balanced or imbalanced nutrient use on crop production over the years. Farmers also learn about the profitable use of inputs for sustainable farming. The participation of farmers is a key factor in promoting BMPs. LTFE also serves as a tool to remind the state administrators of their role not only for supply and distribution of inputs, but also on the need to provide critical inputs to farmers in remote areas and regulate the market for new fertilizer products, biofertilizers, micronutrients and quality organic manures.

Conclusions

The current level of food grain production in the country needs to be increased by about 6 Mt yr^{-1} to address food security concerns of the growing population. With decreasing/fast-depleting land resources and increasing number of small and marginal farmers, there is no option, but to raise crop productivity level per unit of land. In such a situation, imbalanced use of plant nutrients will lead to colossal losses in crop yields, cause irreversible damage to soil fertility/ health, and finally become the prime cause of farm distress. Results offer useful leads and emphasize on the need for large scale adoption of integrated and balanced use of nutrient sources based on soil tests for sustenance of soil health and harnessing the potential yields.

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