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Modeling of soybean yield for sustainability based on rainfall and soil and plant relationships under semi-arid Vertisols in central India

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Abstract : Based on permanent manurial experiments of soybean conducted with 9 fertilizer treatments during rainy seasons of 1992 to 2006 (June to October) in a semi-arid Vertisol at Indore, an attempt has been made in this paper to model the sustainability of yield based on rainfall received during crop growing period, soil and plant-nutrient relationships. The fertilizer treatments comprised control, 20 kg N (urea) + 13 kg P ha^{-1}, 30 kg N (urea) + 20 kg P ha^{-1}, 40 kg N (urea) + 26 kg P ha^{-1}, 60 kg N (urea) + 35 kg P ha^{-1}, 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1}, 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1}, FYM @ 6 t ha^{-1} and crop residue @ 5 t ha^{-1} and were tested on the same site for 15 years. Based on analysis of variance, the F-test indicated that the fertilizer treatments differed significantly in influencing the yield, soil and plant N, P, K and S in both individual years and also when pooled over 15 years. An assessment of relationship of yield with rainfall received during crop growing period, plant and soil nutrients was made for each treatment based on Pearson correlation coefficients derived for the pooled data over years. Based on regression models of yield through rainfall, plant and soil nutrients, the treatments were assessed for predictability of yield, prediction error and sustainable yield index over years. Ranks were assigned to fertilizer treatments for mean and variation of yield, plant and soil nutrients apart from prediction error and sustainable yield index measured under different regression models of yield. The rank sum indicated that 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} was the most efficient treatment with a minimum rank sum for different parameters. This treatment attained a maximum sustainable yield index and predictability of yield with minimum prediction error over years, apart from providing a maximum mean yield and uptake of N, P, K and S by plant with minimum variation over 15 years. The study indicated that this treatment significantly improved the soil fertility status of N, P, K and S compared to other treatments tested under semi-arid Vertisols.

Additional key words: *Plant and soil nutrients, crop growing period, correlation, regression, prediction error, sustainability yield index*

Introduction

Soybean is an important oilseed grown as rainfed crop (80% area) during *kharif* season (June to October) in the semi-arid Malwa region of Madhya Pradesh. The farmers usually apply a lower dose of fertilizer for soybean under rainfed conditions. In order to attain a maximum productivity of the crop, apart from maintaining soil fertility status of different nutrients, a balanced fertilizer dose is essential. Under rainfed conditions, the soybean yield is significantly influenced by soil fertility, rainfall and its distribution and applied nutrients. However, fertilizer efficiency is influenced by rainfall and its distribution during crop growth period under rainfed conditions (Maruthi Sankar and Vanaja 2003).

Prihar and Gajri (1988) examined usefulness of fertilization of rainfed crops and described strategies for rationalizing fertilizer application in relation to seasonal water supply and innate soil fertility. In another study, Singh *et al.* (1975) examined the effect of N fertilizer on yield and water use efficiency of dryland winter wheat as affected by stored water and rainfall. Venkateswarlu and Singh (1982) described responses of different rainfed crops to applied nutrients under limited water conditions. Permanent manurial trials with organic and inorganic fertilizer treatments for different crops are being conducted in All India Coordinated Research Project for Dryland Agriculture at different research centers. Precise information on an efficient and sustainable fertilizer treatment is lacking for soybean grown under rainfed conditions. At one of the research centers of the project at Indore, a permanent manurial study with 9 fertilizer treatment combinations of N and P were conducted for soybean during the last 15 years. An attempt is made in this paper to identify an efficient fertilizer treatment for attaining a maximum sustainable yield index, predictability of yield with minimum prediction error and maintenance of soil fertility of N, P, K and sulphur under semi-arid Vertisols.

Materials and Methods

Fifteen field experiments of soybean were conducted on a permanent site during *kharif* season (June to October) of 1992 to 2006 in a semi-arid Vertisol at the research farm of College of Agriculture (JNKVV), Indore. The study was conducted under All India Coordinated Research Project for Dryland Agriculture funded by Indian Council of Agricultural Research. The research center at Indore is located at a latitude of 20°43' N and longitude of 76°54' E. The experiments were conducted with a set of 9 fertilizer treatments which are combinations of urea, farmyard manure (FYM) and crop residue superimposed to the same plots in each season. The treatment combinations tested were (i) control (ii) 20 kg N (urea) + 13 kg P ha^{-1} (iii) 30 kg N (urea) + 20 kg P ha^{-1} (iv) 40 kg N (urea) + 26 kg P ha^{-1} (v) 60 kg N (urea) + 35 kg P ha^{-1} (vi) 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} ha (vii) 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} (viii) FYM @ 6 t ha^{-1} and (ix) Crop residue @ 5 t ha^{-1}. The crop residue contained 0.75% N, 0.045 P and 0.14% K, whereas FYM contained 0.66% N, 0.45% P and 0.50% K. The field experiments were conducted in a net plot size of 9.0 m x 6.4 m with a row spacing of 30 cm. The fertilizer treatments were randomized and superimposed to plots in a Randomized Block Design with 4 replications. FYM was applied 10 days prior to sowing, whereas crop residue was applied as surface mulch after emergence of the crop in the prescribed treatments. Before superimposing fertilizer treatments, initial soil samples were collected from each plot at a soil depth of 0–30 cm and analyzed for available soil N by alkaline permanganate method (Subbaiah and Asija 1956), soil P based by Olsen's method (Olsen *et al.* 1954), soil K by ammonium acetate method (Jackson 1973) and soil sulphur by turbidity method (Chesnin and Yien 1950) in each season.

The regression methodology described by Maruthi Sankar (1986) and Draper and Smith (1998) and sustainability yield index measurement method described by Vittal *et al.* (2002 and 2003) and Maruthi Sankar *et al.* (2006) were explored for developing efficient models of soybean yield and selection of superior fertilizer treatment.

Rainfall and its distribution during crop growing period in different years

The earliest date of sowing of soybean was on 17th June in 2004, whereas the farthest was on 20th July in 1996. The earliest date of harvest of soybean was on 1st October in 2001, as against the farthest on 29th October in 1996. The crop had a minimum growing period of 91 days in 1992 compared to a maximum of 117 days in 2004 and had a mean of 106 days and variation of 6.6% during 15 years. The lowest crop seasonal rainfall of 354.1 mm (64.9% of annual rainfall) occurred in 2002, whereas the highest of 1308.3 mm (98.3% of annual rainfall) occurred in 1996 with a mean of 840.9 mm and variation of 30.2% over years.

The rainfall ranged from 54.7 mm in 1996 to 329.7 mm in 2001 in June, 50.3 mm in 2002 to 676.9 mm in 1996 in July, 91.1 in 1999 to 429.7 mm in 2006 in August, 9 mm in 2000 to 350.3 mm in 2003 in September and 'no rainfall' in 1994 and 2003 to 79.8 mm in 1996 in October. A mean rainfall of 132.1 mm with a variation of 57.5% in June, 294.7 mm with a variation of 53.1% in July, 243.7 mm with a variation of 44.4% in August, 140.6 mm with a variation of 70.3% in September and 29.9 mm with a variation of 96.1% in October was received. The date of sowing (DOS) and harvest (DOH) of soybean, crop growing period (CGP) from sowing to harvest, monthly rainfall received in June, July, August, September and October, cumulative rainfall in the crop growing period or crop seasonal rainfall (CRF), percent of crop seasonal rainfall to annual rainfall in different years are given in table 1.

Assessment of rainfall, soil and plant nutrient interactions with soybean yield

The differences in the effects of fertilizer treatments could be tested using F-test based on Analysis of variance (Gomez and Gomez 1985). The test could be carried out to assess the effect of fertilizer treatments on yield, nutrient uptake and soil N, P, K, S for both individual years and also pooled over years. The relationship between any two variables could be measured based on Pearson's correlation coefficient which is determined as a ratio of covariance of variables and standard deviation of the variables (Snedecor and Cochran 1967). The treatment-wise estimates of correlation of soybean yield and uptake of N, P, K and S by plant with monthly rainfall received during June to October, crop seasonal rainfall and soil test values of N, P, K and S at sowing could be determined to assess rainfall, soil and plant relations under semi-arid Vertisols. The magnitude and direction of correlation between different pairs of variables along with their significance would provide a scope for assessing a fertilizer treatment for its selection.

Regression models of yield through rainfall, soil and plant nutrient variables

Four regression models of soybean yield attained by each treatment were calibrated over years (Draper and Smith 1998). In the first model, yield was regressed as a function of crop growing period and rainfall received in June, July, August, September and October months for assessing the effect of rainfall on yield in different years. Apart from monthly rainfall, the crop growing period would influence the yield, since the rainfall received would be utilized by the crop depending on its duration in different years. The treatment-wise regression model of yield through monthly rainfall could be postulated as

$$Y = \pm \alpha \pm \beta 1\ (CGP) \pm \beta 2\ (Jun) \pm \beta 3\ (Jul) \pm \beta 4\ (Aug) \pm \beta 5\ (Sep) \pm \beta 6\ (Oct) \quad \ldots\ldots\ldots\ldots (1)$$

In the second model, yield was regressed as a function of uptake of N, P, K and sulphur by plant to assess the contribution of plant uptake to soybean yield in different years. The uptake of nutrients would greatly influence grain yield, since a higher uptake of nutrients would provide a higher yield and *vice versa*. The treatment-wise regression model of yield through plant uptake of nutrients could be postulated as

$$Y = \pm \alpha \pm \beta 1\ (\text{uptake N}) \pm \beta 2\ (\text{uptake P}) \pm \beta 3\ (\text{uptake K}) \pm \beta 4\ (\text{uptake sulphur}) \quad \ldots\ldots (2)$$

Table 1. Dates of sowing and harvest of soybean and crop seasonal rainfall at Indore during 1992 to 2006

Year	DOS	DOH	CGP	Rainfall (mm) received in different months					CRF	CRF (%)
				Jun	Jul	Aug	Sep	Oct		
1992	16-Jul	14-Oct	91	57.6	211.9	154.6	75.9	55.0	555.0	99.9
1993	26-Jun	8-Oct	105	134.3	383.4	298.5	190.8	46.7	1053.7	96.7
1994	18-Jun	5-Oct	110	139.6	260.7	273.3	196.6	0.0	870.2	97.2
1995	1-Jul	6-Oct	98	145.2	359.5	276.6	94.3	51.5	927.1	98.6
1996	20-Jul	29-Oct	111	54.7	676.9	269.0	227.9	79.8	1308.3	98.3
1997	24-Jun	13-Oct	112	191.5	461.7	369.8	50.1	34.1	1107.2	94.0
1998	2-Jul	16-Oct	107	59.0	423.2	281.9	80.2	0.0	844.3	100.0
1999	27-Jun	18-Oct	114	251.8	172.9	91.1	244.1	72.4	832.3	100.0
2000	1-Jul	6-Oct	98	114.1	169.2	165.1	9.0	0.0	457.4	90.3
2001	22-Jun	1-Oct	102	329.7	189.6	95.1	71.8	54.6	740.8	94.3
2002	26-Jun	7-Oct	104	124.4	50.3	154.6	21.4	3.4	354.1	64.9
2003	24-Jun	11-Oct	110	103.7	349.3	137.2	350.3	0.0	940.5	96.9
2004	17-Jun	11-Oct	117	101.2	188.1	410.1	78.8	24.4	802.6	94.8
2005	28-Jun	16-Oct	111	71.4	178.4	249.0	234.2	0.0	733.0	99.0
2006	2-Jul	13-Oct	104	103.2	345.0	429.7	183.4	26.0	1087.3	92.5
Mean			106	132.1	294.7	243.7	140.6	29.9	840.9	
CV			6.6	57.5	53.1	44.4	70.3	96.1	30.2	

DOS : Date of sowing DOH : Date of harvest CGP : Crop growing period
CV : Coefficient of variation (%) CRF: Crop seasonal rainfall (mm)
CRF (%): Crop seasonal rainfall as percent of annual rainfall

In the third model, yield was regressed as a function of soil test values of N, P, K and S to assess the contribution of soil nutrients to soybean yield over years. The initial soil fertility of N, P, K and S before sowing of the crop would have a direct influence on the yield. The model is separately calibrated for organic carbon and soil N in combination with other variables. The treatment-wise regression model of yield through soil nutrient variables could be postulated as

$$Y = \pm \alpha \pm \beta 1 \text{ (soil N)} \pm \beta 2 \text{ (soil P)} \pm \beta 3 \text{ (soil K)} \pm \beta 4 \text{ (soil sulphur)} \quad \ldots\ldots (3)$$

In the fourth model, yield was regressed as a function of crop growing period, rainfall received in June, July, August, September and October months and soil N, P, K and S nutrients for assessing the effect of different variables on soybean yield over years. The treatment-wise regression model of yield through monthly rainfall and soil nutrient variables could be postulated as

$$Y = \pm \alpha \pm \beta 1 \text{ (CGP)} \pm \beta 2 \text{ (Jun)} \pm \beta 3 \text{ (Jul)} \pm \beta 4 \text{ (Aug)} \pm \beta 5 \text{ (Sep)} \pm \beta 6 \text{ (Oct)} \pm \beta 7 \text{ (soil N)} \pm \beta 8 \text{ (soil P)} \pm \beta 9 \text{ (soil K)} \pm \beta 10 \text{ (soil Sulphur)} \quad \ldots\ldots\ldots\ldots (4)$$

In models (1), (2), (3) and (4), α is intercept and β's are regression coefficients of respective variables considered in the model. The contribution of different variables measured by regression coefficients could be tested based on t-test and significance of a variable could derive at $p < 0.05$ and $p < 0.01$ level of significance. The regression models were assessed based on the estimates of coefficient of determination (R^2) and prediction error (Φ) derived under each model. A treatment which has a maximum predictability with minimum prediction error could be preferred compared to other treatments.

Ranking and selection of an efficient fertilizer treatment

The sustainability of fertilizer treatments could be assessed based on a sustainable yield index measured as a function of mean yield of each treatment attained over years, maximum soybean yield attained by any treatment in the study period and prediction error based on the regression model of each treatment (Vittal *et al,* 2002 and 2003; Maruthi Sankar *et al,* 2006). Using mean yield of a treatment 'i' ($\bar{A}_i$) over 15 years; prediction error (Φ) based on the model of treatment 'i'; and maximum yield (Y_{max}) attained by any treatment, an estimate of sustainable yield index (η) of treatment 'i' could be derived as

$$\eta_i = [(\bar{A}_i - \Phi) / (Y_{max})] * 100 \quad \ldots\ldots\ldots (5)$$

The sustainable yield index of a fertilizer treatment could be derived under models (1) to (4) and examined for superiority of treatments over years. A treatment with a higher sustainable yield index would be superior compared to other treatments with a relatively lower index value.

A superior fertilizer treatment could be finally selected based on rank analysis. Ranks could be assigned to each fertilizer treatment for mean and coefficient of variation in yield, plant and soil nutrients. Ranks could also be assigned to treatments for coefficient of determination, prediction error and sustainable yield index under each model. Based on rank sum of treatments, an efficient fertilizer treatment with minimum rank sum could be selected for attaining a sustainable yield of soybean under semi-arid vertisols.

Results and Discussion

Distribution of soybean yield, plant uptake and soil test values over years

The differences between fertilizer treatments in influencing the soybean yield, nutrient uptake by plant and soil test values of N, P, K and S were tested based on F-test under Analysis of variance at 5 and 1% level of significance. The mean and coefficient of variation, critical difference for testing treatment differences at $p < 0.05$ and $p < 0.01$ for yield, nutrient uptake and soil N, P, K and S are given in table 2. The F-test indicated that the treatments were significantly different in both individual years and also when pooled over years in influencing the yield, plant and soil nutrients. The mean soybean yield ranged from 1275 kg ha^{-1} with a variation of 31.1% under control to 2095 kg ha^{-1}with a variation of 25.3% under an application of 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} over years. The superior treatment also gave a maximum potential yield of 3247 kg ha^{-1} in 2006.

Application of 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} was also superior with a maximum mean uptake N (149.6 kg ha^{-1}), uptake K (61.9 kg ha^{-1}), uptake S (16.3 kg ha^{-1}), organic carbon of 0.79%, soil N (274 kg ha^{-1}), soil P (22.2 kg ha^{-1}), soil K (741 kg ha^{-1}), and soil S (18.1 kg ha^{-1}), while 60 kg N (urea) + 35 kg P ha^{-1} gave a maximum mean uptake P of 10.3 kg ha^{-1}. Compared to these values, the control gave a minimum mean uptake N (84.5 kg ha^{-1}), uptake P (4.8 kg ha^{-1}), uptake K (36.2 kg ha^{-1}), uptake S (8.1 kg ha^{-1}), organic carbon 0.39%, soil N (178 kg ha^{-1}), soil P of 11.4 kg ha^{-1}), a, soil K of 540 kg ha^{-1}), and soil sulphur (13.6 kg ha^{-1}).

Application of 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} had a minimum variation of 20.1% for uptake N, 30.3% for soil P and 24.8% for soil S, while crop residue @ 5 t ha^{-1} had a minimum variation of 46.7% for uptake P and 26.5% for uptake S. Application of 20 kg N (urea) + 13 kg P ha^{-1} had a minimum variation of 10.7% for organic carbon, 7% for soil N and 18.1% for soil K, while application of 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} had a minimum of 52.1% for K uptake.

The control had a maximum variation of 30.6% for N uptake, 57.5% for soil P and 43.2% for soil S, while application of 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} had a maximum variation of 83.1% for P uptake and 60 kg N (urea) + 35 kg P ha^{-1} had 34.6% variation for uptake S. Application of FYM @ 6 t/ha had a maximum variation of 55.2% for K uptake, 40.4% for organic carbon and 26.2% for soil N, while crop residue @ 5 t ha^{-1} had a maximum of 31.7% for soil K.

Table 2. Mean and coefficient of variation of soybean yield, soil moisture, plant and soil nutrients*

Variable	T1	T2	T3	T4	T5	T6	T7	T8	T9	CD1	CD2
Yield	1275	1620	1774	1886	1994	2095	1790	1863	1629	110	145
	(31.1)	(29.4)	(29.5)	(27.7)	(26.4)	(25.3)	(34.0)	(30.3)	(32.6)		
Plant N	84.5	109.3	122.5	132.2	142 1	149.6	127.5	129.9	115.6	6.7	8.9
	(30.6)	(26.8)	(26.7)	(24.2)	(22.0)	(20.1)	(28.7)	(27.1)	(28.9)		
Plant P	4.8	6.6	7.6	8.5	10.3	10.0	9.7	8.6	7.4	2.7	3.5
	(58.7)	(49.5)	(51.3)	(48.2)	(70.1)	(53.8)	(83.1)	(49.5)	(46.7)		
Plant K	36.2	48.5	53.2	56.6	60.1	61.9	55.8	60.5	53.3	5.3	7.0
	(55.0)	(54.9)	(54.8)	(53.5)	(53.0)	(54.0)	(52.1)	(55.2)	(55.2)		
Plant S	8.1	11.9	12.7	13.7	15.6	16.3	13.1	13.7	11.6	1.3	1.6
	(33.5)	(32.6)	(34.5)	(31.1)	(34.6)	(33.0)	(29.1)	(31.2)	(26.5)		
OC	0.39	0.48	0.50	0.58	0.57	0.79	0.68	0.78	0.65	0.09	0.12
	(16.3)	(10.7)	(16.2)	(13.0)	(17.8)	(29.9)	(25.3)	(40.4)	(31.4)		
Soil N	178	202	206	225	224	274	254	264	239	21	28
	(8.4)	(7.0)	(10.3)	(8.4)	(11.5)	(20.3)	(18.9)	(26.2)	(23.4)		
Soil P	11.4	14.1	16.1	16.9	17.7	22.2	15.0	18.3	15.6	2.5	3.3
	(57.5)	(53.8)	(53.1)	(46.6)	(42.6)	(30.3)	(53.1)	(32.8)	(46.8)		
Soil K	540	552	585	545	629	741	642	677	629	45	59
	(22.2)	(18.1)	(25.7)	(19.0)	(25.6)	(24.3)	(23.2)	(20.9)	(31.7)		
Soil S	13.6	15.1	15.6	16.4	16.6	18.1	17.0	16.8	15.7	1.1	1.4
	(43.2)	(40.0)	(42.4)	(41.5)	(37.8)	(24.8)	(33.0)	(35.9)	(36.6)		
SMS	319.8	323.0	322.6	320.7	325 2	341.4	334.9	337.6	334.0	6.9	9.1
	(21.4)	(20.7)	(20.6)	(21.5)	(20.8)	(21.2)	(21.6)	(21.4)	(21.5)		
SMH	299.8	294.5	295.5	298.2	313 5	306.0	300.4	308.4	300.3	NS	NS
	(16.1)	(16.4)	(17.8)	(21.3)	(16.5)	(20.2)	(19.6)	(20.0)	(24.9)		
WUE	2.26	2.61	2.96	3.16	3.29	3.36	2.92	3.07	2.71	0.18	0.24
	(71.1)	(63.4)	(61.9)	(59.0)	(53.7)	(51.0)	(59.3)	(54.6)	(61.8)		

*During 1992-2006
Values in parentheses are coefficient of variation (%) OC: Organic carbon (%) N: Nitrogen (kg/ha)
P: Phosphorus (kg ha^{-1}) K: Potassium (kg ha^{-1}) S: Sulphur (kg ha^{-1})
CD1: Critical difference ($p < 0.05$) CD2: Critical difference ($p < 0.01$) T1: Control
T2: 20 kg N (urea) + 13 kg P ha^{-1} T3: 30 kg N (urea) + 20 kg P ha^{-1} T4: 40 kg N (urea) + 26 kg P ha^{-1}
T5: 60 kg N (urea) + 35 kg P ha^{-1} T6: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1}
T7: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} T8: FYM @ 6 t ha^{-1} T9: Crop residue @ 5 t ha^{-1}

Correlation of soybean yield and plant nutrients with crop seasonal rainfall and soil nutrients

Treatment-wise estimates of correlation of soybean yield and plant uptakes of N, P, K and S with monthly rainfall of June to October received during crop growing period, soil N, P, K and S during 15 years are given in table 3. The soybean yield had a significant and positive correlation with uptake N under all the 9 fertilizer treatments. It ranged from 0.90** for 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} to 0.97** for control. The yield had a significant negative correlation with organic carbon (-0.53*) and soil N (-0.56*) under FYM @ 6 t ha^{-1}. The control yield had a significant negative correlation with crop growing period (-0.54*). The uptake of N had a significant negative correlation with crop growing period under control (-0.59*) and 40 kg N (urea) + 26 kg P ha^{-1} (-0.51*) treatments. It had a significant negative correlation with organic carbon and soil N under 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} (-0.59* and –0.61*), 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} (-0.59* and –0.58*), FYM @ 6 t ha^{-1} (-0.60* and –0.61*) and crop residue @ 5 t ha^{-1} (-0.57* and –0.61*) treatments. The uptake of K had a significant negative correlation with rainfall received in August for all the 9 treatments. It ranged from –0.60** for 60 kg N (urea) + 35 kg P ha^{-1} to –0.72** for control. The uptake of K had a significant negative correlation with rainfall during crop season for control, 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} and crop residue @ 5 t ha^{-1} with estimates of –0.57*, -0.52* and -0.58* respectively. The S uptake by plant had a significant positive correlation with rainfall received in June for FYM @ 6 t ha^{-1} (0.64**) and July for 20 kg N (urea) + 13 kg P ha^{-1} (0.65**), 30 kg N (urea) + 20 kg P ha^{-1} (0.59*), 40 kg N (urea) + 26 kg P ha^{-1} (0.54*), 60 kg N (urea) + 35 kg P ha^{-1} (0.54*) and 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} (0.54*) treatments. A significant positive correlation of sulphur uptake by plant with rainfall received in October was observed for all treatments except FYM @ 6 t/ha and crop residue @ 5 t/ha and the estimates ranged from 0.56* for 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} to 0.69** for control. Similarly, it had a significant positive correlation with rainfall during crop season for all treatments except control and FYM @ 6 t ha^{-1} and ranged from 0.51* for 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} to 0.70** for 20 kg N (urea) + 13 kg P ha^{-1} application.

Regression models of soybean yield through rainfall received during crop growing period

The regression models of soybean yield were calibrated as a function of crop growing period and monthly rainfall received during June to October in different years. The estimates of regression coefficients (β) of crop growing period and monthly rainfall, coefficient of determination (R^2) and prediction error (Φ) were determined for each treatment (Table 4). The rainfall received in August and September had a significant positive effect on soybean yield by all treatments, while June rainfall had a significant effect for all treatments except yield in plot control. The rainfall received in July and crop growing period were found to have a significant negative effect on yield in all treatments. The rainfall received in October had no significant influence on soybean yield in different treatments. The coefficient of determination ranged from 0.73* for control to 0.93** for 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1}, while the prediction error ranged from 202 kg ha^{-1} for 60 kg N (urea) + 35 kg P ha^{-1} to 274 kg ha^{-1} for control. The study indicated that maximum rate of change in soybean yield for an unit change in rainfall of July, August and September and crop growing period have occurred for 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1}, while the lowest rate was in control for crop growing period and rainfall of June, August and September months. The maximum rate of change in yield for June rainfall occurred for FYM @ 6 t ha^{-1} and October rainfall for control, whereas the lowest rate of October rainfall occurred for crop residue @ 5 t ha^{-1} in the study.

Regression models for prediction of soybean yield through nutrients uptake by plants

Based on model (2), the regression models of soybean yield were calibrated as a function of uptake of N, P, K and S to assess the influence of uptake of nutrients on crop yield under different treatments during 15 years. The estimates of regression coefficients (β) of for uptake of nutrients, coefficient of determination and prediction error for each treatment are given in table 5. Among N, P, K and S, the uptake of N was found to have a significant positive effect on soybean yield for all the 9 treatments. The uptake of K had a significant negative effect on yield with 30 kg N (urea) + 20 kg P ha^{-1} and 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} treatments. The analysis indicated that uptake of P and sulphur had no significant influence on soybean yield. The coefficient of determination ranged

Table 3. Correlation coefficients of soybean yield and plant uptake with crop seasonal rainfall and soil nutrients

V1	V2	T1	T2	T3	T4	T5	T6	T7	T8	T9
GY	Jun	0.13	0.06	0.01	-0.01	-0.05	0.03	-0.01	0.01	0.04
GY	Jul	-0.27	-0.04	0.02	0.01	0.01	0.06	-0.07	0.01	-0.11
GY	Aug	-0.09	0.13	0.14	0.12	0.20	0.25	0.17	0.24	0.07
GY	Sep	0.07	0.28	0.30	0.32	0.34	0.38	0.36	0.36	0.34
GY	Oct	0.18	0.15	0.15	0.16	0.13	0.16	0.05	0.08	0.05
GY	CRF	-0.12	0.18	0.21	0.19	0.22	0.31	0.17	0.26	0.11
GY	CGP	-0.54*	-0.40	-0.43	-0.42	-0.37	-0.25	-0.33	-0.28	-0.37
GY	OC	0.37	0.25	0.03	-0.26	-0.15	-0.45	-0.46	-0.53*	-0.42
GY	SN	0.40	0.20	-0.01	-0.16	-0.10	-0.48	-0.47	-0.56*	-0.49
GY	SP	0.05	0.17	0.21	0.18	0.18	-0.23	0.30	0.17	0.23
GY	SK	-0.24	-0.20	-0.25	-0.49	-0.28	-0.11	-0.21	-0.26	-0.09
GY	SS	-0.16	-0.11	0.01	0.06	0.01	0.08	-0.02	-0.03	-0.23
GY	UN	0.97**	0.95**	0.94**	0.94**	0.94**	0.90**	0.93**	0.95**	0.95**
GY	UP	0.27	0.22	0.21	0.29	0.19	0.21	0.23	0.26	0.40
GY	UK	0.12	-0.03	0.05	0.14	-0.02	0.08	-0.01	0.01	0.07
GY	US	-0.13	-0.07	-0.14	-0.17	-0.15	-0.12	0.02	-0.02	-0.19
UN	Jun	0.09	0.02	0.11	0.04	0.06	0.06	0.16	0.03	0.05
UN	Jul	-0.29	-0.10	-0.10	-0.19	-0.18	-0.18	-0.23	-0.07	-0.24
UN	Aug	-0.22	-0.04	-0.13	-0.10	-0.05	-0.01	-0.11	0.05	-0.15
UN	Sep	0.08	0.30	0.32	0.24	0.31	0.35	0.30	0.38	0.34
UN	Oct	0.19	0.13	0.13	0.12	0.06	0.07	0.03	0.04	-0.03
UN	CRF	-0.19	0.06	0.05	-0.04	0.01	0.04	-0.02	0.14	-0.06
UN	CGP	-0.59*	-0.47	-0.47	-0.51*	-0.43	-0.32	-0.42	-0.37	-0.42
UN	OC	0.48	0.27	-0.11	-0.38	-0.30	-0.59*	-0.59*	-0.60*	-0.57*
UN	SN	0.49	0.30	-0.12	-0.30	-0.29	-0.6**	-0.58*	-0.61*	-0.60**
UP	Jun	-0.02	0.01	-0.05	0.03	-0.12	0.03	-0.16	0.09	-0.03
UP	Jul	-0.40	-0.39	-0.28	-0.31	-0.38	-0.33	-0.30	-0.37	-0.26
UP	Aug	-0.30	-0.27	-0.30	-0.33	-0.20	-0.26	-0.09	-0.31	-0.33
UP	Sep	0.15	0.15	0.23	0.29	0.40	0.33	0.33	0.21	0.38
UP	Oct	0.08	0.16	0.08	0.14	-0.19	0.14	-0.19	0.13	0.10
UP	CRF	-0.31	-0.28	-0.22	-0.19	-0.22	-0.17	-0.17	-0.24	-0.15
UP	CGP	-0.04	-0.14	-0.13	-0.02	0.17	0.10	0.17	-0.07	-0.04
UP	SP	-0.25	-0.30	-0.25	-0.22	0.18	-0.12	0.14	-0.16	-0.17
UK	Jun	0.31	0.26	0.25	0.28	0.20	0.31	0.34	0.39	0.28
UK	Jul	-0.46	-0.33	-0.34	-0.32	-0.35	-0.39	-0.44	-0.42	-0.48
UK	Aug	-0.72**	-0.64**	-0.65**	-0.65**	-0.60**	-0.63**	-0.69**	-0.68**	-0.68**
UK	Sep	-0.24	-0.17	-0.08	-0.07	-0.11	-0.05	-0.16	-0.19	-0.23
UK	Oct	0.13	0.15	0.14	0.18	0.06	0.20	0.04	0.11	0.03
UK	CRF	-0.57*	-0.45	-0.43	-0.39	-0.44	-0.41	-0.52*	-0.49	-0.58*
UK	CGP	-0.43	-0.43	-0.38	-0.36	-0.31	-0.34	-0.41	-0.42	-0.42
UK	SK	0.04	-0.30	-0.12	-0.33	-0.33	-0.42	-0.10	-0.31	-0.05
US	Jun	0.41	0.19	0.25	0.33	0.24	0.33	0.26	0.64**	0.33
US	Jul	0.37	0.65**	0.59*	0.54*	0.54*	0.39	0.54*	0.15	0.47
US	Aug	-0.19	0.11	-0.01	0.01	0.09	0.04	0.02	-0.12	-0.01
US	Sep	0.19	0.33	0.13	0.28	0.28	0.24	0.38	-0.01	0.24
US	Oct	0.69**	0.66**	0.61**	0.65**	0.57*	0.58*	0.56*	0.47	0.49
US	CRF	0.42	0.70**	0.55*	0.61**	0.61**	0.51*	0.62**	0.29	0.53*
US	CGP	0.18	0.22	0.07	0.27	0.28	0.31	0.17	0.04	0.11
US	SS	0.40	0.49	0.37	0.26	0.30	0.24	0.32	-0.10	0.24

* & ** indicate significance at $p < 0.05$ & $p < 0.01$ respectively, V1 and V2 are variables, GY- Grain yield, OC- Organic carbon, UN- Uptake N UP- Uptake P UK- Uptake K, US- Uptake sulphur, SN- Soil N, SP- Soil P, SK- Soil K, SS- Soil sulphur, CRF- Crop seasonal rainfall, CGP- Crop growing period,

T1: Control, T2: 20 kg N (urea) + 13 kg P ha^{-1}, T3: 30 kg N (urea) + 20 kg P ha^{-1}, T4: 40 kg N(urea)+26 kg P ha`1, T5: 60 kg N(urea)+35 kg P ha^{-1}, T6: 20 kg N(urea)+13 kg P+FYM @ 6 t ha^{-1}, T7: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1}, T8: FYM @ 6 t ha^{-1}, T9: Crop residue @ 5 t ha^{-1}

Table 4. Regression models of soybean yield through rainfall received during crop growing period

	T1	T2	T3	T4	T5	T6	T7	T8	T9
α	6174**	7681**	8785**	8753**	8659**	7876**	9395**	8481**	8370**
β1 (Jun)	1.50	2.95*	3.14**	2.65*	2.61*	3.35**	3.66**	3.71**	3.28*
β2 (Jul)	-1.47*	-1.29*	-1.12*	-1.29*	-1.48**	-1.35*	-1.84**	-1.50**	-1.54*
β3 (Aug)	2.35*	4.01**	4.29**	4.14**	4.62**	4.88**	5.39**	5.29**	4.16**
β4 (Sep)	2.91**	4.88**	5.44**	5.45**	5.70**	5.75**	6.86**	6.27**	5.85**
β5 (Oct)	3.01	0.72	0.18	1.10	0.96	0.84	-1.15	-0.97	-1.33
β6(CGP)	-53.9**	-72.9**	-83.7**	-81.3**	-80.1**	-73.7**	-91.9**	-82.7**	-79.9**
R^2	0.73*	0.88**	0.91**	0.89**	0.92**	0.88**	0.93**	0.92**	0.88**
Φ	274	221	212	230	202	241	215	214	248
η	30.8	43.1	48.1	51.0	55.2	57.1	48.5	50.8	42.5

* & ** indicate significance at $p < 0.05$ & $p < 0.01$ respectively R^2 : Coefficient of determination
α : Intercept β: Regression coefficient Φ: Prediction error (kg ha^{-1}) η: Sustainable yield index

Table 5. Regression models of soybean yield through plant uptake of nutrients

	T1	T2	T3	T4	T5	T6	T7	T8	T9
α	150	0.76	-87	-262	-328	-537	-90	-32	-164
β1 (UN)	15.01**	15.49**	15.66**	16.37**	16.29**	17.52**	16.29**	15.16**	15.10**
β2 (UP)	1.95	8.61	21.00	5.50	5.47	10.15	8.27	11.17	19.63
β3 (UK)	-2.15	-3.41	-5.51*	-3.52	-2.73	-4.50	-5.47**	-2.92	-3.57
β4 (US)	-9.14	2.85	5.94	9.87	7.38	11.51	2.15	0.37	7.95
R^2	0.95**	0.92**	0.93**	0.91**	0.91**	0.88**	0.94**	0.92**	0.93**
Φ	109	159	158	182	188	218	180	191	169
η	35.9	45.0	49.8	52.5	55.6	57.8	49.6	51.5	45.0

* & ** indicate significance at $p < 0.05$ & $p < 0.01$ respectively R^2 : Coefficient of determinationα : Intercept
β: Regression coefficient Φ: Prediction error (kg ha^{-1}) η: Sustainable yield index

from 0.88** for 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} to 0.95** for control, while the prediction error ranged from 109 kg ha^{-1} for control to 218 kg ha^{-1} for 20 kg N (urea) + 13 kg P + FYM @ 6 t/ha based on the regression models. A maximum rate of change in soybean yield of 17.52 occurred in 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} compared to a minimum of 15.01 in control for N uptake. The rate of change ranged from 1.95 in control to 21.0 in 30 kg N (urea) + 20 kg P ha^{-1} for P uptake, -5.51 in 30 kg N (urea) + 20 kg P ha^{-1} to –2.15 in control for K uptake and –9.14 in control to 11.51 in 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} for S uptake based on the regression models of yield calibrated as a function of nutrient uptake by plants over years.

Regression models for prediction of soybean yield through soil nutrients

Based on model (3), the regression models of soybean yield were calibrated as a function of soil N, P, K and S to assess the influence of soil nutrients on yield under different treatments during 15 years. The estimates of regression coefficients (β) of soil nutrients, coefficient of determination and prediction error for each treatment are given in table 6. The soil parameters including organic carbon, soil N, soil P, soil K and soil S were found to have non-significant effect on soybean yield for all the 9 treatments tested. The coefficient of determination ranged from 0.09 for 30 kg N (urea) + 20 kg P ha^{-1} to 0.40 for FYM @ 6 t ha^{-1}, whereas prediction error ranged from 390 kg/ha for

Table 6. Regression models of soybean yield through soil nutrients

	T1	T2	T3	T4	T5	T6	T7	T8	T9
Organic carbon									
α	948	-97	1995	3322*	3611*	2040	4251	3748*	2963
$\beta 1$ (OC)	3103	5430	136	713	-1867	-1559	-1350	-860	-1130
$\beta 2$ (SP)	-4.95	3.56	9.64	4.04	9.96	4.11	10.71	12.72	-4.88
$\beta 3$ (SK)	-0.64	-0.49	-0.72	-3.02	-1.32	0.23	-1.94	-1.81	-0.61
$\beta 4$ (SS)	-34.72	-44.08	-1.38	-16.48	5.84	56.57	-27.02	-13.42	-8.99
R^2	0.31	0.24	0.09	0.27	0.19	0.33	0.32	0.40	0.21
Φ	390	492	591	529	560	515	592	519	559
η	27.3	34.7	36.4	41.8	44.2	48.7	36.9	41.4	33.0
Soil N									
α	-689	-826	3065	2003	3967	3338	4694*	4461**	3737*
$\beta 1$ (SN)	14.65	16.19	-4.50	13.07	-5.74	-5.78	-5.08	-4.31	-6.78
$\beta 2$ (SP)	1.82	9.17	6.01	0.78	11.02	-0.15	8.12	9.35	-15.06
$\beta 3$ (SK)	-0.49	-0.75	-0.97	-4.26	-1.38	-0.27	-1.97	-1.99	-0.59
$\beta 4$ (SS)	-29.11	-36.15	6.90	-45.47	-0.67	30.12	-27.82	-16.50	7.49
R^2	0.32	0.20	0.09	0.30	0.18	0.32	0.33	0.45	0.30
Φ	386	503	589	516	566	518	590	496	526
η	27.4	34.4	36.5	42.2	44.0	48.6	37.0	42.1	34.0

α, $\beta 1$, $\beta 2$, $\beta 3$ and $\beta 4$ are regression constants, R^2 -coefficient of regression, Φ -prediction error, η-sustainable yield index

control to 592 kg ha^{-1} for 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} based on the models calibrated with the combination of organic carbon, soil P, K and S. The models indicated that a maximum rate of change of 5430 in soybean yield occurred for 20 kg N (urea) + 13 kg P ha^{-1} compared to a minimum of -1867 in 60 kg N (urea) + 35 kg P ha^{-1} for organic carbon. The rate of change ranged from 4.95 in control to 12.72 in FYM @ 6 t ha^{-1} for soil P, -3.02 in 40 kg N (urea) + 26 kg P ha^{-1} to 0.23 in 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} for soil K and –44.08 in 20 kg N (urea) + 13 kg P ha^{-1} to 56.57 in 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} for soil S based on the regression models of yield calibrated through soil nutrients.

The coefficient of determination ranged from 0.09 for 30 kg N (urea) + 20 kg P ha^{-1} to 0.45 for FYM @ 6 t ha^{-1}, whereas prediction error ranged from 386 kg ha^{-1} for control to 590 kg ha^{-1} for 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} based on the models calibrated with the combination of soil N, P, K and S variables. The models indicated that a maximum rate of change of 16.19 in soybean yield occurred for 20 kg N (urea) + 13 kg P ha^{-1} compared to a minimum of –6.78 for crop residue @ 5 t ha^{-1} in case of soil N. The rate of change ranged from –15.06 in crop residue @ 5 t ha^{-1} to 11.02 in 60 kg N (urea) + 35 kg P ha^{-1} for soil P, -4.26 in 40 kg N (urea) + 26 kg P ha^{-1} to -0.27 in 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} for soil K and –45.47 in 40 kg N (urea) + 26 kg P ha^{-1} to 30.12 in 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} for soil S based on the regression models of yield calibrated through soil nutrients during 15 years.

Regression models for prediction of yield through crop seasonal rainfall and soil nutrients

Based on model (4), the combined regression models of soybean yield as a function of monthly rainfall received during June to October, crop growing period, soil N, P, K and S separately for organic carbon and soil N variables were calibrated to assess the increase in predictability of yield and also the effects of different variables on yield for different treatments during 15 years. The estimates of regression coefficients (β) of rainfall received in different months, crop growing period, soil N, P, K and S, coefficient of determination and prediction error of each treatment are given in table 7.

Table 7. Regression models of soybean yield through monthly rainfall during crop growing period and soil nutrients

	T1	T2	T3	T4	T5	T6	T7	T8	T9
Organic carbon									
α	1502	5666	11005**	9560**	6315*	6754**	8856**	8030**	8834**
β1(CGP)	-8.39	-73.49*	-87.4**	-65.79*	-111.8*	-74.8**	-95.6**	-71.7**	-58.05*
β2 (Jun)	-9.06	3.42	2.19	-0.11	9.65	3.66	2.88	3.68	-1.97
β3 (Jul)	0.91	-1.41	-2.75*	-0.82	-4.54	-3.29**	-2.97**	-1.46	-0.80
β4 (Aug)	-0.87	3.83	7.12**	4.02*	9.26*	7.59**	6.97**	5.34*	3.69
β5 (Sep)	0.88	4.80*	7.35**	5.51**	9.09**	7.96**	8.23**	6.18**	5.58*
β6 (Oct)	24.22	-0.09	-0.21	4.01	-22.85	-6.97	-3.86	-3.57	6.99
β7 (OC)	7614	2711	-5359*	1042	1588	1411	-934*	-331	-786
β8 (SP)	-25.75	9.71	-26.31	-27.83	-10.27	-58.05*	-28.68*	-16.82	-36.11
β9 (SK)	1.40	1.07	0.14	-2.76	2.69	0.71	1.84	-0.32	-0.32
β10 (SS)	-184.64	7.29	56.15	-56.29	147.74	40.06	45.52	8.54	-73.94
R^2	0.86	0.91	0.98**	0.94*	0.96**	0.97**	0.98**	0.95*	0.92
Φ	275	265	139	236	188	176	127	230	289
η	30.8	41.7	50.4	50.8	55.6	59.1	51.2	50.3	41.3
Soil N									
α	-1926	4065	12409*	9645**	7728	5223*	9248**	8225**	8794**
β1(CGP)	-14.6	-77.9**	-77.8**	-61.1*	-86.5*	-77.0**	-94.5**	-69.9**	-53.5
β2 (Jun)	-6.83	3.68	2.04	-0.02	5.24	4.87	2.75	3.54	-2.19
β3 (Jul)	0.15	-1.63	-2.49	-0.78	-2.98	-3.48*	-2.81**	-1.47	-0.81
β4 (Aug)	0.35	4.22*	6.72*	4.02*	7.33*	7.36**	6.71**	5.29*	3.44
β5 (Sep)	1.65	5.07**	7.01**	5.61**	7.93*	7.68**	8.12**	6.11**	5.34*
β6 (Oct)	17.90	-1.24	-0.34	4.95	-10.65	-7.30	-3.21	-3.71	7.98
β7 (SN)	31.07	13.81	-21.23	-2.79	-2.36	4.45	-3.44*	-1.54	-3.33
β8 (SP)	-7.17	13.30	-33.95	-27.40	-20.25	-40.98	-28.15*	-18.94	-38.17
β9 (SK)	1.81	1.64	-0.48	-2.16	1.17	1.27	1.64	-0.47	-0.38
β10 (SS)	-125.04	16.54	46.23	-41.05	76.68	87.68	37.85	5.45	-73.22
R^2	0.81	0.94*	0.95*	0.94*	0.96**	0.96**	0.98**	0.95*	0.91
Φ	320	215	216	238	191	187	130	225	290
η	29.4	43.3	48.0	50.8	55.5	58.8	51.1	50.4	41.2

Based on the regression model of yield with rainfall and soil nutrient variables with the combination of organic carbon, the effect of crop growing period on yield attained by all treatments was found significant except for control. July rainfall had a significant effect on yield attained by 30 kg N (urea) + 20 kg P ha^{-1}, 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} and 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} treatments, while August rainfall had a significant effect on yield attained by all treatments except control, 20 kg N (urea) + 13 kg P ha^{-1} and crop residue @ 5 t ha^{-1}. September rainfall had a significant effect on yield by all treatments except control, based on the model. Among soil nutrients, organic carbon had a significant influence on yield by 30 kg N (urea) + 20 kg P ha^{-1} and 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1}, while soil P had a significant influence on the yield attained by 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} and 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} treatments. The coefficient of determination ranged from 0.86 for control to 0.98 for 30 kg N (urea) + 20 kg P ha^{-1} and 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1}, while prediction error ranged from 127 kg ha^{-1} for 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} to 289 kg/ha for crop residue @ 5 t ha^{-1} based on the models. The regression models indicated that a maximum rate of change of 7614 in soybean yield occurred for a unit change in organic carbon in control compared to a

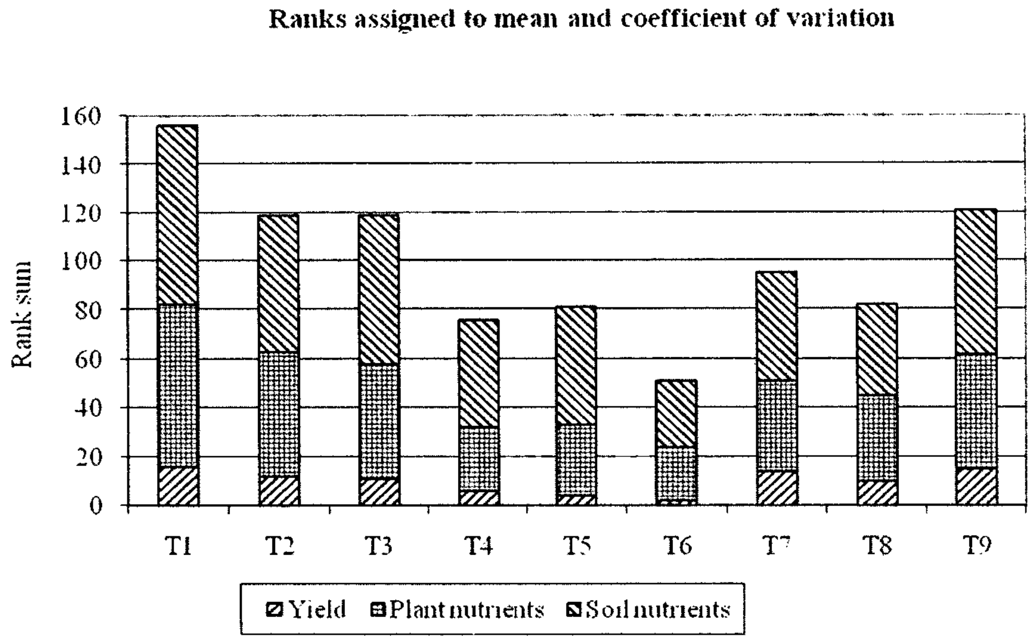

Fig.1. Rank sum of treatments for mean and coefficient of variation of soybean yield, nutrient uptake and soil nutrients

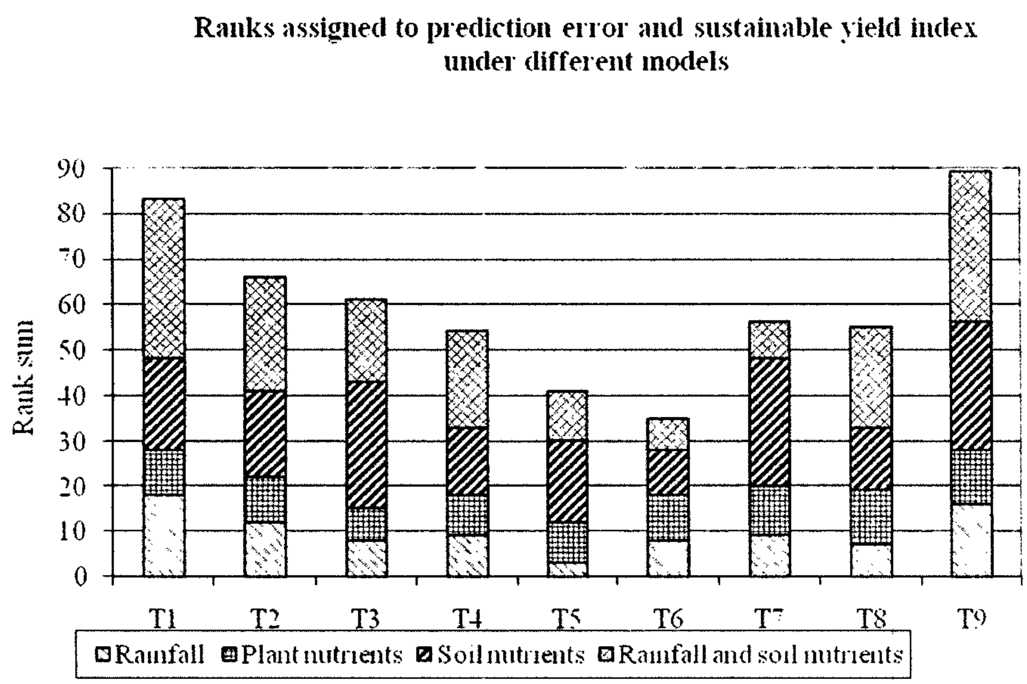

Fig.2. Rank sum of treatments for prediction error and sustainable yield index based on regression models of yield through rainfall, nutrient uptake and soil nutrients

minimum of -5359 in 30 kg N (urea) + 20 kg P ha^{-1}. The rate of change ranged from –58.05 in 20 kg N (urea) + 13 kg P + FYM @ 6 t/ha to 9.71 in 20 kg N (urea) + 13 kg P ha^{-1} for soil P, -2.76 in 40 kg N (urea) + 26 kg P ha^{-1} to 2.69 in 60 kg N (urea) + 35 kg P ha^{-1} for soil K and –184.64 in control to 147.74 in 60 kg N (urea) + 35 kg P ha^{-1} for soil S based on the regression models of yield through rainfall and soil nutrients examined.

Based on the regression model with combination of soil N, the crop growing period had a significant effect on yield attained by all treatments except control and crop residue @ 5 t/ha. July rainfall had a significant effect on yield attained by 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} and 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1}, while August rainfall had a significant effect on yield attained by all treatments except control and crop residue @ 5 t ha^{-1}. September rainfall had a significant effect on yield attained by all treatments except control based on the model. Among soil nutrients, soil N and P had a significant influence on yield attained by 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1}. The coefficient of determination (R^2) ranged from 0.81 for control to 0.98 for 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1}, while prediction error ranged from 130 kg ha^{-1} for 20 kg N (urea) + 13 kg P + FYM @ 5 t ha^{-1} to 320 kg ha^{-1} for control based on the models calibrated with the combination of soil N variable. The regression models indicated that maximum rate of change in yield of 31.07 for a unit change in soil N and 1.81 for soil K occurred in control compared to a minimum of –21.23 in 30 kg N (urea) + 20 kg P ha^{-1} and –2.16 in 40 kg N (urea) + 26 kg P ha^{-1} for the two soil nutrients respectively. The yield attained by 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} had a minimum rate of change for soil P and maximum rate of change for soil sulphur, while 20 kg N (urea) + 13 kg P ha^{-1} had a maximum rate of change for soil P and control had a minimum rate of change for soil S based on the regression models calibrated for the data.

Sustainability of fertilizer treatments over years

The sustainable yield index 'η' of 9 fertilizer treatments was measured based on model (5) using the prediction error of the respective treatment under models (1) to (4). The estimate of 'η' was found to range from 30.8 to 57.1% under model (1); 35.9 to 57.8% under model (2); 27.3 to 48.7% with organic carbon and 27.4 to 48.6% with soil N variable under model (3); 30.8 to 59.1% with organic carbon and 29.4 to 58.8% with soil N variable under model (4) for control and 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} treatments respectively. Ranks were assigned to each fertilizer treatment for mean yield and coefficient of variation of yield, plant and soil nutrients over years. Ranks were also assigned to fertilizer treatments for prediction error based on models (1) to (4) and sustainable yield index based on (5). The rank sum of different fertilizer treatments are shown (Fig.1) for mean and coefficient of variation and fig.2 depicts prediction error and sustainable yield index. Based on the rank sum, 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} was found to be the most efficient treatment with a minimum rank sum for mean and coefficient of variation of yield, plant and soil nutrients and estimates of prediction and sustainable yield index over 15 years. The treatment 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} was also superior with a maximum available mean soil N, P, K and S at the end of 15 year study. Application of 40 kg N (urea) + 26 kg P ha^{-1} was the second best treatment based on mean and coefficient of variation of yield, plant and soil nutrients, while application of 60 kg N (urea) + 35 kg P ha^{-1} was the second best based on prediction error and sustainable yield index based on models (1) to (4) calibrated for the data. Based on the study, 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} could be recommended for large scale adoption under farmer's fields for attaining maximum sustainable yields and maintenance of soil fertility of N, P, K and S under semi-arid Vertisols in central India.

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