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Modeling of Interactive Effects of Rainfall, Evaporation, Soil Temperature, and Soil Fertility for Sustainable Productivity of Sorghum + Cowpea and Cotton + Black Gram Intercrops under Rotation Trials in a Rain-Fed Semi-arid Vertisol

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Long-term effects of the different combinations of nutrient-management treatments were studied on crop yields of sorghum + cowpea in rotation with cotton + black gram. The effects of rainfall, soil temperature, and evaporation on the status of soil fertility and productivity of crops were also modeled and evaluated using a multivariate regression technique. The study was conducted on a permanent experimental site of rain-fed semi-arid Vertisol at the All-India Coordinated Research Project on Dryland Agriculture, Kovilpatti Centre, India, during 1995 to 2007 using 13 combinations of nutrient-management treatments. Application of 20 kg nitrogen (N) (urea) + 20 kg N [farmyard manure (FYM)] + 20 kg phosphorus (P) ha^{-1} gave the greatest mean grain yield (2146 kg ha^{-1}) of sorghum and the fourth greatest mean yield (76 kg ha^{-1}) of cowpea under sorghum + cowpea system. The same treatment maintained the greatest mean yield of cotton (546 kg ha^{-1}) and black gram (236 kg ha^{-1}) under a cotton + cowpea system. When soil fertility was monitored, this treatment maintained the greatest mean soil organic carbon (4.4 g kg^{-1}), available soil P (10.9 kg ha^{-1}), and available soil potassium (K) (411 kg ha^{-1}), and the second greatest level of mean available soil N (135 kg ha^{-1}) after the 13-year study. The treatments differed significantly from each other in influencing soil organic carbon (C); available soil N, P, and K; and yield of crops attained under sorghum + cowpea and cotton + black gram rotations. Soil temperature at different soil depths at 07:20 h and rainfall had a significant influence on the status of soil organic C. Based on the prediction models developed between long-term

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yield and soil fertility variables, 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} could be prescribed for sorghum + cowpea, and 20 kg N (urea) + 20 kg N (FYM) could be prescribed for cotton + black gram. These combinations of treatments would provide a sustainable yield in the range of 1681 to 2146 kg ha^{-1} of sorghum, 74 to 76 kg ha^{-1} of cowpea, 486 to 546 kg ha^{-1} of cotton, and 180 to 236 kg ha^{-1} of black gram over the years. Beside assuring greater yields, these soil and nutrient management options would also help in maintaining maximum soil organic C of 3.8 to 4.4 g kg^{-1} soil, available N of 126 to 135 kg ha^{-1}, available soil P of 8.9 to 10.9 kg ha^{-1}, and available soil K of 392 to 411 kg ha^{-1} over the years. These prediction models for crop yields and fertility status can help us to understand the quantitative relationships between crop yields and nutrients status in soil. Because black gram is unsustainable, as an alternative, sorghum + cowpea could be rotated with cotton for attaining maximum productivity, assuring sustainability, and maintaining soil fertility on rain-fed semi-arid Vertisol soils.

Keywords Climatic parameters, crop yields, prediction models, productivity, soil fertility, regressions

Introduction

Vertisols are a predominant soil group found across the world. The majority of the acreage of Vertisols and associated soils in the world is spread in Australia (70.5 million ha), India (70 million ha), Sudan (40 million ha), Chad (16.5 million ha), and Ethiopia (10 million ha). These five countries constitute more than 80% of the total area (250 million ha) of Vertisols in the world (Dudal 1965). In India, substantial Vertisol areas are found in the states of Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, Karnataka, and Tamil Nadu (Murthy 1981). Most of these regions receive 500 to 1300 mm of annual rainfall, concentrated in a short period of 3 to 3.5 rainy months interspersed with droughts. Crop yields in these areas are miserably low and may vary from year to year. Virmani, Rao, and Srivastava (1989) have comprehensively characterized Vertisols found in India. Their textures may vary from clay to clay loam, or silty clay loam, with the clay content generally varying from 40% to 60% or more. They have high bulk density when dry (with clod density values ranging from 1.5 to1.8 g cm^{-3}), high cation exchange capacity (47 to 65 cmol kg soil^{-1}), and pH values usually above 7.5. Tropical Vertisols are low in organic matter and available plant nutrients, particularly nitrogen (N), phosphorus (P), and zinc (Zn). The dominant clay mineral is smectite. High clay content, better effective soil depth, and associated other physical properties make these soils able to store great amounts of moisture. Low organic-matter status accompanied by poor soil fertility is one of the predominant constraints in these Vertisol soils. Farmers of the rain-fed semi-arid tropical (SAT) regions, being poor, are not able to use adequate amounts of chemical fertilizers. Earlier researchers have established that the productivity of these soils can be enhanced by supplying adequate nutrient inputs (Virmani, Rao, and Srivastava 1989; Willey, Singh, and Reddy 1989; Burford, Sahrawat, and Singh 1989). Based on numerous agronomic experiments, it has been found that supplementation of N, P, and Zn through fertilizer is inevitable to ensure satisfactory crop production in SAT soils especially in Vertisols (Kanwar 1972; Randhawa and Tandon 1982). Despite many efforts, there is a slow adoption of fertilizers in rain-fed crops, which could probably be attributed to many reasons including inability of the farmers to purchase fertilizers, erratic and uncertain rainfall leading to risk of crop failures, and uncertainty and variability in crop responses (Jha and Sarin, 1984; Kanwar et al. 1973).

A key factor in maintaining long-term production in Vertisols of Kovilpatti regions of southern India are adequate moisture availability, balanced application of nutrients, and improvement of organic matter in soil. Further, the predominant cropping systems in these regions include sorghum + cowpea and cotton + black gram. These two systems are followed in rotation. The productivity of these systems is very low because of climatic and soil-related constraints. Earlier Sharma et al. (2005, 2008, 2009), through long-term experiments, studied the effects of conservation agricultural practices consisting of several components such as reduced tillage, integrated nutrient management, and residue application on crop yields, sustainability yield indices (SYI), and soil quality under different crops and cropping systems in rain-fed Alfisol soils of southern India. Not as much effort has been made in rain-fed Vertisol soils. Through this study, efforts were initiated to improve fertility of these soils through long-term experiments consisting of different combinations of organic and inorganic sources of nutrients. A huge database on crop yields, soil related climatic parameters, and soil fertility variables was created through experimentation for 13 years for these Vertisol soils by spending huge amount of money. By capitalizing this huge database, an attempt was made to model the changes in soil organic carbon (C), N, P, potassium (K), and crop productivity through rainfall, soil temperature, and evaporation parameters and to assess the sustainability of nutrient-management treatments for productivity of sorghum, cowpea, cotton, and black gram for a semi-arid Vertisol. Hence, the study was conducted with the objectives (i) to assess the long-term influence of nutrient-management treatments on crop yields and changes in organic C and soil fertility variables; (ii) to study the effects of soil temperature, crop seasonal rainfall, and fertilizer treatments on soil organic C and available soil N, P, and K; and (iv) to select an efficient nutrient-management treatment suitable for attaining sustainable crop productivity and maintenance of maximum soil fertility over the years.

Materials and Methods

Field experiments were conducted for a sorghum (*Sorghum bicolor* L. Moench) + cowpea (*Vigna unguiculata*) intercropping system rotated with a cotton (*Gossypium hirsutum*) + black gram (*Vigna mungo*) intercropping system in a permanent site in a semi-arid Vertisol at Kovilpatti center during 1995 to 2007 situated amid the Vertisol belt in the southern zone of Tamil Nadu uplands and leeward flanks of South Sahayadri and Deccan (Karnataka) Plateau, between 8° 43′ and 9° 20′ N latitude and 77° 4′ and 28° 25′ E longitude at 90 m above mean sea level. The climate is hot and semi-arid with a mean annual rainfall of 743 mm and potential evapotranspiration of 812 mm. The experiment was laid out in a randomized block design with 13 conjunctive nutrient-use treatments in three replications. Sorghum and cowpea as intercrops were grown during 1995, 1997, 1999, 2001, 2003, 2005, and 2007, whereas cotton and black gram intercrops were grown during 1996, 1998, 2000, 2002, 2004, and 2006. The conjunctive nutrient-use treatments were the (i) control; (ii) 20 kg N ha^{-1} (urea); (iii) 40 kg N ha^{-1} (urea); (iv) 20 kg N ha^{-1} (urea) + single superphosphate (SSP) at 10 kg P ha^{-1}; (v) 40 kg N (urea) + 20 kg P ha^{-1} (SSP); (vi) 20 kg N ha^{-1} farmyard manure (FYM); (vii) 40 kg N ha^{-1} (FYM); (viii) 20 kg N (FYM) + 10 kg P ha^{-1} (SSP); (ix) 40 kg N (FYM) + 20 kg P ha^{-1} (SSP); (x) 10 kg N (urea) + 10 kg N ha^{-1} (FYM); (xi) 20 kg N (urea) + 20 kg N ha^{-1} (FYM); (xii) 10 kg N (urea) + 10 kg N ha^{-1} (FYM) + 10 kg P ha^{-1} (SSP); and (xiii) 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} (SSP). Nitrogen was applied through FYM (N content 0.5%) and urea, while P was applied through SSP. Treatments were randomized during the first year, and subsequently the same treatments were applied to the same plots every year.

Crop Sowing Dates

The data pertaining to the descriptive statistics of date of sowing (DOS), date of harvest, and crop duration during 1995 to 2007 are given in Table 1. Because the experiments

Table 1
Date of sowing and harvest of crops and monthly rainfall during crop-growing period at Kovilpatti during 1995 to 2007

	Sorghum			Cowpea		
Year	DOS	DOH	CD	DOS	DOH	CD
1995	28 Sep.	10 Jan.	105	28 Sep.	10 Jan.	105
1997	10 Oct.	31 Jan.	114	10 Oct.	31 Jan.	114
1999	28 Sep.	21 Jan.	116	28 Sep.	15 Dec.	79
2001	26 July	19 Jan.	178	26 July	23 Jan.	182
2003	4 Oct.	6 Jan.	95	4 Oct.	15 Dec.	73
2005	1 Oct.	15 Feb.	138	1 Oct.	3 Jan.	95
2007	17 Oct.	12 Feb.	119	17 Oct.	7 Jan.	83
Mean			124			104
CV			22.2			35.6
	Cotton			Black gram		
1996	24 Sep.	11 Feb.	141	24 Sep.	2 Jan.	101
1998	3 Nov.	26 Mar.	144	3 Nov.	12 Jan.	71
2000	21 Sep.	10 Apr.	192	21 Sep.	12 Jan.	114
2002	18 Sep.	19 Mar.	183	18 Sep.	8 Jan.	113
2004	1 Oct.	23 Mar.	174	1 Oct.	15 Dec.	76
2006	27 Sep.	17 Apr.	203	16 Oct.	29 Dec.	75
Mean			173			92
CV			14.7			21.8

Notes. DOS, date of sowing; DOH, date of harvest; CD, crop duration (days); CRF, crop seasonal rainfall (mm); and CV, coefficient of variation (%).

were conducted under rain-fed conditions, the DOS of sorghum and cowpea varied from 26 July in 2001 to 17 October in 2007. In the case of cotton and blackgram, the DOS varied from 18 September in 2002 to 3 November in 1998. The dates of harvest (DOH) for sorghum crop were spread in between 6 January in 2003 to 15 February in 2005, whereas for cowpea, it was between 15 December in 1999 and 2003 to 31 January in 1997. The DOH for cotton varied between 11 February in 1996 to 17 April in 2006, whereas for black gram it varied between 15 December in 2004 to 12 January in 1998 and 2000. The crop duration ranged from 95 (2003) to 178 days (2001) for sorghum with a variation of 22.2%, whereas it ranged from 73 (2003) to 182 days (2001) for cowpea with a variation of 35.6% over years. Similarly, the crop duration ranged from 141 (1996) to 203 days (2006) for cotton with a variation of 14.7%, whereas it ranged from 71 (1998) to 114 days (2000) for black gram with a variation of 21.8% over the years.

Measurement of Climatic and Soil Parameters

Monthly rainfall was measured using rain gauge. The soil temperature was measured each day by a specialized soil temperature measuring probe in depths of 5–7.5, 10–15 and 20–30 cm at 07:20 and 14:20 h in September to February during the study period. The daily evaporation rates were recorded using a universal pan evaporimeter. Among the soil parameters, soil organic C (%) and available N, P, and K were estimated in each plot during 1995 to 2007. Soil organic C was measured by the standard procedure described by Walkley and Black (1934), available soil N by the alkaline permanganate method (Subbaiah and Asija, 1956), and soil P by Olsen's P method (Olsen et al. 1954), whereas soil K was measured by the method given by Jackson (1973).

Statistical Analysis

Regression models were developed to predict the effects of rainfall, temperature, and evaporation on soil organic C and available N, P, and K. In addition, the regressions models were also developed to predict the crop yields using organic C and available N, P, and K nutrients using the long-term data (Draper and Smith 1998; Maruthi Sankar 1986; Solaiappan, Subramanian, and Maruthi Sankar 2007).

Changes in Organic C and N, P, and K Nutrients over Years

The regression model for prediction of organic C (OC) and soil-available N (SN), P (SP), and K (SK) could be postulated as follows:

$$\begin{aligned} OC = &\pm \alpha \pm \beta 1\,(STI) \pm \beta 2\,(ST2) \pm \beta 3\,(ST3) \pm \beta 4\,(ST4) \pm \beta 5\,(ST5) \\ &\pm \beta 6\,(ST6) \pm \beta 7\,(RF) \pm \beta 8\,(EV) \end{aligned} \tag{1}$$

$$\begin{aligned} SN = &\pm \alpha \pm \beta 1\,(ST1) \pm \beta 2\,(ST2) \pm \beta 3\,(ST3) \pm \beta 4\,(ST4) \pm \beta 5\,(ST5) \\ &\pm \beta 6\,(ST6) \pm \beta 7\,(RF) \pm \beta 8\,(EV) \end{aligned} \tag{2}$$

$$\begin{aligned} SP = &\pm \alpha \pm \beta 1\,(ST1) \pm \beta 2\,(ST2) \pm \beta 3\,(ST3) \pm \beta 4\,(ST4) \pm \beta 5\,(ST5) \\ &\pm \beta 6\,(ST6) \pm \beta 7\,(RF) \pm \beta 8\,(EV) \end{aligned} \tag{3}$$

$$\begin{aligned} SK = &\pm \alpha \pm \beta 1\,(ST1) \pm \beta 2\,(ST2) \pm \beta 3\,(ST3) \pm \beta 4\,(ST4) \pm \beta 5\,(ST5) \\ &\pm \beta 6\,(ST6) \pm \beta 7\,(RF) \pm \beta 8\,(EV) \end{aligned} \tag{4}$$

In models 1 to 4, α is intercept and βs are regression coefficients of soil temperature indicated by ST1 (5–7.5 cm), ST2 (10–15 cm), and ST3 (20–30 cm) observed at 07:20 h and ST4 (5–7.5 cm), ST5 (10–15 cm), and ST6 (20–30 cm) observed at 14:20 h. Rainfall (RF) and evaporation (EV) variables were observed during September to February in each year.

From these models, the changes in soil OC, N, P, and K observed in each treatment could be assessed for superiority based on the significance of regression coefficients, coefficient of determination (R^2), and prediction error (Φ) derived under each model.

Changes in Crop Productivity over Years

The regression models for predicting yield could be postulated as

$$Y = \pm \alpha \pm \beta 1\,(OC) \pm \beta 2\,(SP) \pm \beta 3\,(SK) \tag{5}$$

$$Y = \pm \alpha \pm \beta1\,(SN) \pm \beta2\,(SP) \pm \beta3\,(SK) \quad (6)$$

In models 5 and 6, α is intercept and βs are regression coefficients of OC and soil P and K. The effect of treatments on yield could be assessed by the coefficient of determination (R^2) and prediction error (Φ) measured under each model. The superiority of a treatment for attaining a level of sustainable yield could be assessed as a "ratio of difference between mean yield and prediction error based on a regression model and maximum yield attained over years" as described by Vittal et al. (2003), Maruthi Sankar et al. (2006), Behera et al. (2007), Sharma et al. (2009), and Nema, Maruthi Sankar, and Chauhan (2008).

Results

Variations in Rainfall, Evaporation, and Temperature

The data pertaining to the descriptive statistics monthly rainfall from September to February received in different years and crop seasonal rainfall received in each year during 1995 to 2007 are given in Table 2. The rainfall during 1995 to 2007 ranged from 4.6 to 181.0 mm with a mean of 67.8 mm (variation of 84.4%) in September, 20.8 to 412.2 mm with a mean of 184.1 mm (54.0%) in October, 14.0 to 269.4 mm with a mean of 129.4 mm (63.1%) in November, 0 to 212.3 mm with a mean of 72.6 mm (89.0%) in December, 0 to 37.6 mm with a mean of 9.5 mm (117.0%) in January, and 0 to 73.2 mm with a mean of 20.1 mm (106.5%) in February over the years. In the cases of sorghum and cowpea, the

Table 2
Date of sowing and harvest of crops and monthly rainfall during crop-growing period at Kovilpatti during 1995 to 2007

	Rainfall (mm)						
Year	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Crop seasonal rainfall (mm)
1995	80.0	82.4	14.0	0.0	4.8	10.4	191.6
1997	17.0	134.2	262.2	212.3	2.8	0.0	628.5
1999	67.8	273.1	69.6	35.2	0.4	28.4	474.5
2001	181.0	155.8	86.6	63.8	14.6	37.4	539.2
2003	24.0	224.9	88.0	4.6	0.0	19.8	361.3
2005	28.2	216.0	154.2	98.6	0.6	26.8	524.4
2007	10.8	228.0	110.8	85.4	21.8	0.6	457.4
Mean	58.4	187.8	112.2	71.4	6.4	17.6	453.8
CV	102.9	35.1	70.0	101.8	131.8	81.8	31.2
1996	145.8	412.2	94.2	37.0	4.2	4.6	698.0
1998	71.6	20.8	269.4	162.2	7.6	0.0	531.6
2000	145.2	72.6	87.2	129.6	37.6	73.2	545.4
2002	37.4	215.6	67.0	6.6	1.4	38.6	366.6
2004	4.6	173.2	249.1	35.4	18.8	0.0	481.1
2006	67.8	184.1	129.4	72.6	8.4	21.7	481.4
Mean	80.9	178.9	153.4	74.2	13.9	23.3	524.5
CV	78.5	84.8	63.5	91.1	106.3	138.5	22.8

crop seasonal rainfall ranged from 191.6 to 628.5 mm with a mean of 453.3 mm and variation of 34.3% in 7 years whereas in the case of cotton and black gram, rainfall varied from 366.6 to 698.0 mm with a mean of 524.5 mm and variation of 22.8% during the 6-year period. The daily evaporation rate, which was measured using the universal pan evaporimeter, ranged from 5.2 to 10.7 mm in September, 3.9 to 6.2 mm in October, 2.6 to 4.7 mm in November, 2.6 to 4.8 mm in December, 3.0 to 5.7 mm in January, and 3.5 to 7.5 mm in February with means (variations) of 7.8 (24.3%), 5.3 (13.8%), 3.4 (17.3%), 3.7 (24.4%), 4.2 (21.2%), and 5.3 mm (21.8%) in different months, respectively.

The descriptive statistics of monthly soil temperature observed in three soil depths at 07:20 h and 14:20 h, rainfall, and evaporation during September to February of 1995 to 2007 are given in Table 3. The soil temperature was measured on each day by a specialized soil temperature measuring probe in depths of 5–7.5, 10–15 and 20–30 cm at 07:20 and 14:20 h during the months of September to February across the study period. The mean soil temperature at 07:20 h was greatest in the 20- to 30-cm depth, followed by depths of 10–15 and 5–7.5 cm during September to February. However, the mean soil temperature at 14:20 h was maximum in the 5- to 7.5-cm depth, followed by depths of 10–15 and 20–30 cm during all 6 months. The mean soil temperature in the surface depth of 5 to 7.5 cm ranged from 28.6 °C (variation 2.6%) to 44.6 °C (variation 7.7%) in September; 27.5 °C (variation 2.0%) to 39.9 °C (variation 4.0%) in October; 26.2 °C (variation 1.8%) to 36.6 °C (variation 8.4%) in November; 24.8 °C (variation 1.3%) to 37.2 °C (variation 11.1%) in December; 25.0 °C (variation 2.5%) to 41.7 °C (variation 8.6%) in January; and 25.7 °C (variation 2.4%) to 44.1 °C (variation 7.3%) in February over the years. The data on mean soil temperature in different soil depths indicated a decrease from September to December, whereas it tended to increase in January and February over the years.

Variation in Soil Fertility Parameters

The long-term effects of nutrient-use treatments on soil OC, N, P and K in different years are presented in Table 4 are Figure 1. Among different treatments, the unamended control resulted in the lowest mean OC of 0.31% with variation of 28%, whereas application of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} gave maximum mean carbon of 0.44% with a relatively lower variation of 17.6%. In the case of soil available N, the control plot exhibited a lowest mean N content of 106 kg ha^{-1} with a variation of 23.9%, whereas application of 40 kg N (FYM) + 20 kg P ha^{-1} gave a maximum mean N content of 136 kg ha^{-1} with a greater variation of 32.8%. The available soil P was least (6.6 kg ha^{-1}) in the control plot with a variation of 22.4%, whereas the maximum mean N content of 10.9 kg ha^{-1} was recorded in 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} with a greater variation of 29.4%. When the available soil K was assessed, the control plot gave the least mean value of 356 kg ha^{-1} with a variation of 12.1%, whereas 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} maintained the greatest mean K content of 411 kg ha^{-1} with a greater variation of 18.2% over the years.

Long-Term Effects on Crop Yields

The data on treatment range, mean, and coefficient of variation pertaining to yield of sorghum, cowpea, cotton, and black gram crops grown under sorghum + cowpea and cotton + black gram systems in rotation in alternate years during 1995 to 2007 are given in Table 5. The perusal of the data revealed that yield of sorghum ranged from 358 to

Table 3
Mean and coefficient of variation of soil temperature, rainfall, and evaporation at Kovilpatti during 1995 to 2007

Month	ST1	ST2	ST3	ST4	ST5	ST6	RF	EV
September	28.6 (2.6)	29.5 (3.0)	31.9 (5.3)	44.6 (7.7)	42.1 (8.8)	35.8 (6.7)	73.0 (81.9)	7.8 (24.3)
October	27.5 (2.0)	27.9 (1.8)	30.2 (4.1)	39.9 (4.0)	38.6 (7.0)	33.7 (7.5)	180.1 (59.9)	5.3 (13.8)
November	26.2 (1.8)	26.8 (2.4)	29.0 (3.7)	36.6 (8.4)	36.0 (9.8)	31.9 (7.9)	131.0 (68.0)	3.4 (17.3)
December	24.8 (1.3)	25.8 (3.6)	28.3 (5.5)	37.2 (11.1)	35.3 (11.3)	31.8 (11.2)	71.4 (98.9)	3.7 (24.4)
January	25.0 (2.5)	26.5 (4.0)	28.8 (6.6)	41.7 (8.6)	40.6 (26.4)	32.8 (9.8)	8.4 (135.5)	4.2 (21.2)
February	25.7 (2.4)	27.3 (4.8)	29.7 (7.2)	44.1 (7.3)	40.2 (13.1)	34.4 (11.1)	21.7 (103.8)	5.3 (21.8)

Notes. Values in parentheses are coefficients of variation (%). RF, rainfall (mm); EV, evaporation (mm). ST1, ST2, and ST3 are soil temperature (°C) observed at 7:20 am and ST4, ST5, and ST6 are soil temperature (°C) observed at 2:20 pm at depths of 5–7.5, 10–15, and 20–30 cm.

Table 4
Mean and variation of soil nutrients during 1995 to 2007 at Kovilpatti

	Organic carbon (%)		Soil N (kg/ha)		Soil P (kg ha^{-1})		Soil K (kg ha^{-1})	
Treatments	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Control	0.31	28.0	106	23.9	6.6	22.4	356	12.1
20 kg N/ha (urea)	0.34	28.1	117	29.8	7.7	24.9	374	14.0
40 kg N/ha (urea)	0.35	20.2	124	31.7	7.8	15.9	382	15.3
20 kg N (urea) +10 kg P/ha	0.38	18.0	120	28.2	8.0	21.3	387	16.0
40 kg N (urea) + 20 kg P/ha	0.39	15.9	132	29.5	9.3	21.0	388	14.9
20 kg N/ha (FYM)	0.38	26.9	125	31.9	8.3	25.9	387	16.3
40 kg N/ha (FYM)	0.44	21.7	134	29.3	9.3	26.8	411	17.3
20 kg N (FYM) + 10 kg P/ha	0.39	23.2	131	35.1	9.2	20.9	394	15.3
40 kg N (FYM) + 20 kg P/ha	0.43	18.0	136	32.8	10.6	21.3	407	17.0
10 kg N (urea) + 10 kg N/ha (FYM)	0.37	25.9	120	23.8	8.7	17.6	389	16.2
20 kg N (urea) + 20 kg N/ha (FYM)	0.41	21.5	134	29.2	9.2	23.0	408	16.9
10 kg N (urea) + 10 kg N (FYM) + 10 kg P/ha	0.37	29.3	124	26.7	9.4	22.4	399	15.6
20 kg N (urea) + 20 kg N (FYM) + 20 kg P/ha	0.44	17.6	135	33.8	10.9	29.4	411	18.2
Mean	0.38		126		8.9		392	
Sem (±)	0.009		3.3		0.41		6.6	
LSD ($P < 0.05$)	0.024		9.1		1.14		18.6	
LSD ($P < 0.01$)	0.032		12.1		1.51		24.5	
Coefficient of variation (%)	8.2		9.4		16.7		6.1	

3241 kg ha^{-1}, whereas cowpea yield ranged from 17 to 146 kg ha^{-1} under sorghum + cowpea system. The yield of cotton ranged from 214 to 826 kg ha^{-1}, whereas the yield of black gram ranged from 34 to 585 kg ha^{-1} under the cotton + black gram system. The unamended control plots gave the least mean sorghum grain yield of 1211 kg ha^{-1} with variation of 49.3%, cowpea yield of 51 kg ha^{-1} with variation of 48.9% under sorghum + cowpea, and cotton yield of 391 kg ha^{-1} with variation of 30.5% and black gram yield of 115 kg ha^{-1} with variation of 63.9% under the cotton + black gram system. Application of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} was quite promising and gave the greatest mean sorghum yield of 2146 kg ha^{-1} with variation of 46.8%, cotton yield of 546 kg ha^{-1} with variation of 25.4%, and black gram yield of 236 kg ha^{-1} with variation of 85.0%, and the fourth greatest cowpea yield of 76 kg ha^{-1} with variation of 47.8%. However, 40 kg N (FYM) + 20 kg P ha^{-1} gave the greatest cowpea yield of 88 kg ha^{-1} with a variation of 45.5% over the years. The effects of fertilizer treatments on yield of crops in different years are graphically depicted in Figure 2.

Table 5

Effect of fertilizer treatments on yields (kg ha^{-1}) of sorghum + cowpea and cotton + black gram rotations at Kovilpatti during 1995 to 2007

	Sorghum		Cowpea		Cotton		Black gram	
Treatment	Range	Mean (CV)	Range	Mean (CV)	Range	Mean (CV)	Range	Mean (CV)
T1	358–1785	1211 (49.3)	17–90	51 (48.9)	214–526	391 (30.5)	34–232	115 (63.9)
T2	388–2461	1523 (58.0)	18–125	69 (58.9)	264–630	456 (31.1)	43–333	146 (71.6)
T3	487–2396	1501 (58.9)	24–119	71 (54.4)	323–758	492 (35.5)	54–276	139 (58.6)
T4	487–2340	1610 (43.5)	27–146	75 (61.6)	342–595	465 (27.2)	62–410	179 (73.8)
T5	443–2623	1764 (50.7)	27–137	78 (58.0)	395–811	546 (30.3)	65–414	191 (67.0)
T6	423–2396	1500 (54.1)	33–145	74 (58.9)	265–742	452 (39.8)	47–495	173 (94.6)
T7	450–2770	1729 (50.9)	29–123	75 (50.7)	312–588	453 (27.3)	46–520	189 (93.8)
T8	578–2310	1614 (44.2)	33–141	77 (56.6)	354–662	488 (26.2)	63–512	202 (82.3)
T9	447–3038	1915 (49.7)	47–142	88 (45.5)	397–664	520 (23.4)	55–512	222 (77.1)
T10	390–2583	1700 (49.9)	26–134	72 (54.5)	356–573	462 (21.9)	67–369	166 (67.4)
T11	419–3135	1940 (52.8)	29–141	77 (55.5)	399–826	543 (30.8)	65–503	189 (85.1)
T12	442–2550	1701 (47.0)	41–122	77 (44.1)	362–664	506 (25.2)	59–471	190 (81.0)
T13	548–3241	2146 (46.8)	50–141	76 (47.8)	415–698	546 (25.4)	56–585	236 (85.0)
Mean		1681		74		486		180
Sem (±)		78		4.4		19		18.5
LSD[a]		219		12.5		54		52
LSD[b]		291		16.5		72		70
CV (%)		12.3		15.9		9.6		25.2

Notes. Values in parentheses are coefficient of variation (%).
[a]Least significant difference at $P < 0.05$.
[b]Least significant difference at $P < 0.01$.

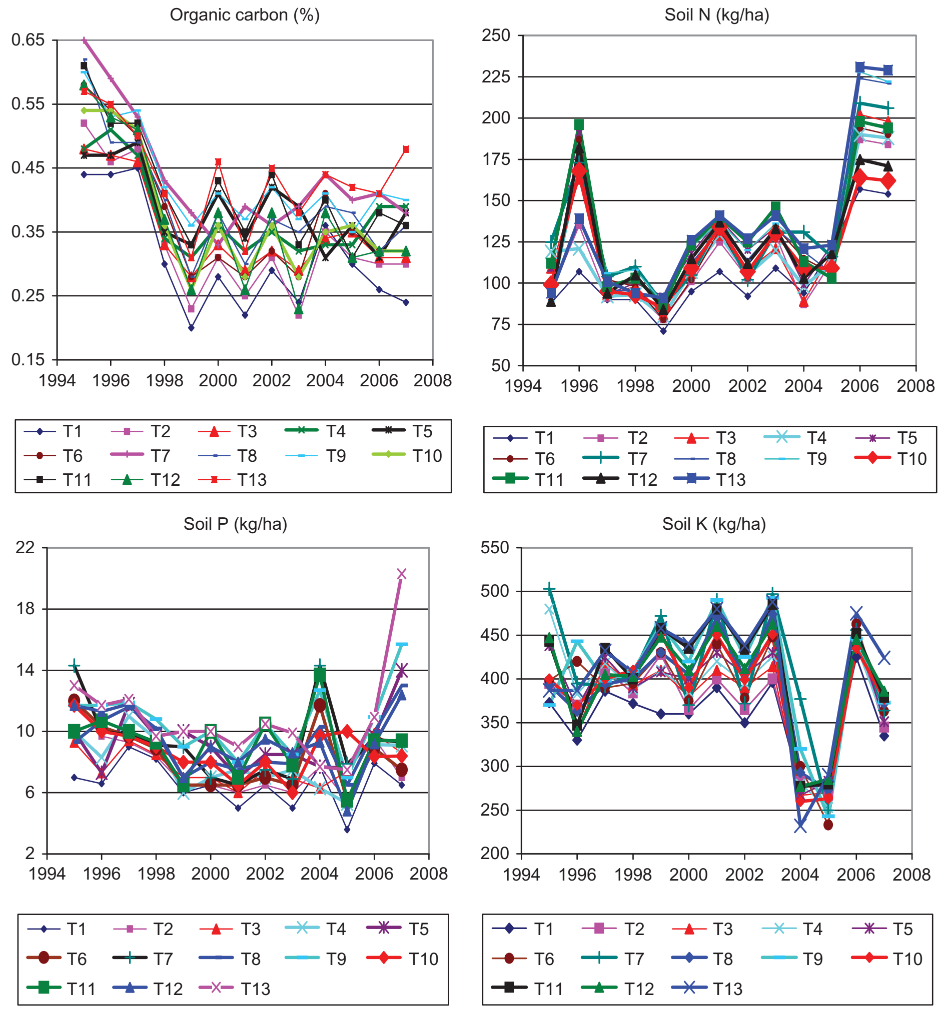

Figure 1. Effect of fertilizer treatments on soil nutrients at Kovilpatti during 1995 to 2007 (color figure available online).

Based on the pooled analysis of variance (ANOVA; Gomez and Gomez 1985), the treatments had a significant effect on yield of all the four crops. The treatments gave a mean yield of 1681 kg ha^{-1} with a variation of 12.3% in sorghum, 74 kg ha^{-1} with variation of 15.9% in cowpea, 486 kg ha^{-1} with variation of 9.6% in cotton, and 180 kg ha^{-1} with variation of 25.2% in black gram over the years. The analysis of data of 7 years of sorghum + cowpea and 6 years of cotton + black gram indicated that the treatment of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} gave a significantly greater mean yield of sorghum, cotton, and black gram, whereas 40 kg N (FYM) + 20 kg P ha^{-1} gave significantly greater yield of cowpea compared to control. Based on the least significant difference (LSD) criteria, the treatments 40 kg N (FYM) + 20 kg P ha^{-1} and 20 kg N (urea) + 20 kg N ha^{-1} (FYM) were at par with 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} in the case of sorghum; 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} was at par with 40 kg N (FYM) + 20 kg P ha^{-1} in the case of cowpea; 40 kg N (urea) + 20 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and 10 kg

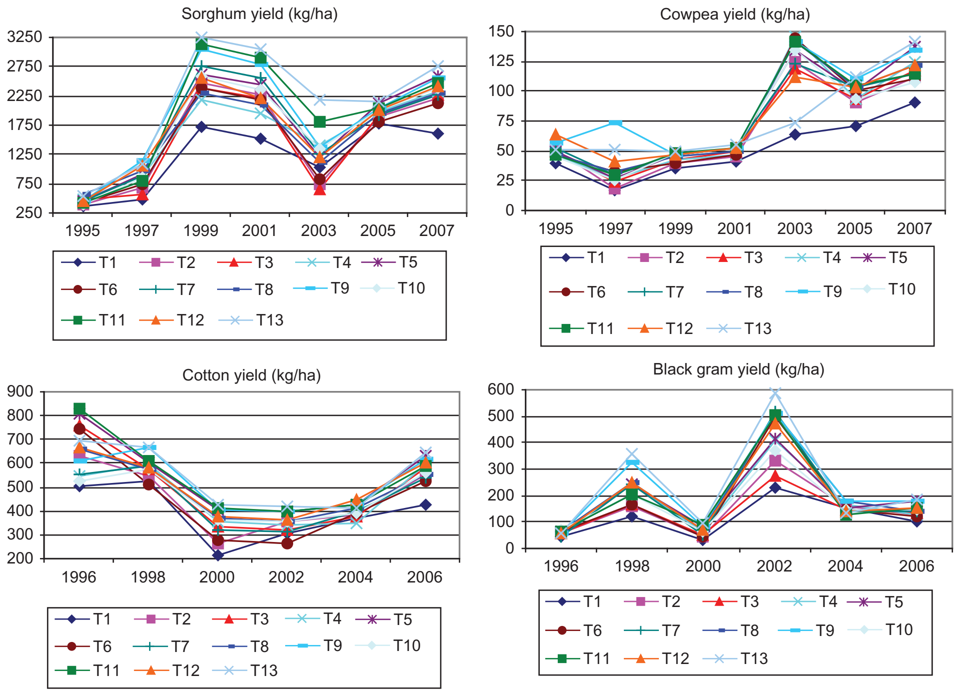

Figure 2. Effect of fertilizer treatments on yield of crops attained under sorghum + cowpea and cotton + black gram systems at Kovilpatti during 1995 to 2007 (color figure available online).

N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1} were at par with 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} in the case of cotton; whereas 40 kg N (urea) + 20 kg P ha^{-1}, 40 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1} were at par with 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} in the case of black gram over the years.

Relationships of Crop Yields with Rainfall and Soil Nutrients

The estimates of correlation of yield of base crop sorghum under sorghum + cowpea and cotton under cotton + black gram system with monthly rainfall, OC, and available soil N, P, and K are given in Table 6. From these relationships, it was understood that the sorghum grain yield had a significant negative correlation with OC (r = –0.77* to –0.88*) in all treatments except 20 kg N ha^{-1} (urea), 40 kg N ha^{-1} (urea), 20 kg N ha^{-1} (FYM), and 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1} (r = –0.68 to –0.75). Interestingly, crop yields reflected a positive but nonsignificant correlation with soil N (r = 0.14 to 0.43) and negative correlation with soil P (r = –0.02 to –0.72) in all the treatments. In the case of soil K, the yield had nonsignificant negative correlations (r = –0.11 to –0.61) in the case of 20 kg N (FYM) + 10 kg P ha^{-1} and 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1}, whereas it had positive correlations (r = 0.01 to 0.34) in the cases of 40 kg N (FYM) + 20 kg P ha^{-1}, 10 kg N (urea) + 10 kg N ha^{-1} (FYM), 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} treatments. Growing season rainfall is one important factor for ensuring good crop yield in rain-fed Vertisol soils. This

Table 6
Correlation of yield with rainfall and soil nutrients at Kovilpatti

Treatment	RF-S	RF-O	RF-N	RF-D	RF-J	RF-F	OC	SN	SP	SK
Sorghum + cowpea										
T1	0.11	0.80*	−0.10	−0.12	0.11	0.84*	−0.85*	0.37	−0.70	−0.57
T2	0.29	0.66	−0.10	−0.02	0.34	0.81*	−0.68	0.29	−0.69	−0.22
T3	0.28	0.64	−0.14	−0.05	0.35	0.80*	−0.71	0.33	−0.54	−0.43
T4	0.05	0.82*	−0.03	−0.03	0.19	0.77*	−0.77*	0.33	−0.67	−0.61
T5	0.21	0.74	−0.06	−0.01	0.30	0.80*	−0.88*	0.43	−0.02	−0.46
T6	0.29	0.68	−0.10	−0.02	0.32	0.81*	−0.72	0.26	−0.72	−0.12
T7	0.32	0.73	−0.12	−0.07	0.30	0.84*	−0.84*	0.14	−0.63	−0.14
T8	0.18	0.73	−0.04	0.02	0.29	0.77*	−0.84*	0.39	−0.15	−0.11
T9	0.29	0.73	−0.05	−0.01	0.30	0.79*	−0.81*	0.35	−0.16	0.21
T10	0.22	0.77*	−0.08	−0.05	0.27	0.82*	−0.86*	0.35	−0.55	0.01
T11	0.32	0.77*	−0.19	−0.19	0.26	0.87*	−0.86*	0.23	−0.68	0.01
T12	0.15	0.77*	0.01	0.05	0.25	0.75	−0.75	0.42	−0.44	−0.22
T13	0.28	0.79*	−0.15	−0.17	0.25	0.84*	−0.86*	0.40	−0.07	0.34
Cotton + black gram										
T1	−0.02	0.25	0.49	0.12	−0.67	−0.87*	0.44	0.20	0.57	0.10
T2	0.18	0.45	0.21	0.01	−0.68	−0.74	0.57	0.53	0.94**	0.44
T3	0.44	0.51	0.07	0.08	−0.49	−0.59	0.69	0.64	0.42	0.15
T4	0.28	0.08	0.26	0.39	−0.46	−0.52	0.43	0.50	0.96**	0.54
T5	0.48	0.56	0.01	0.04	−0.49	−0.55	0.26	0.72	−0.15	0.19
T6	0.38	0.58	0.13	−0.01	−0.47	−0.66	0.81	0.75	0.57	0.51
T7	0.17	0.14	0.44	0.32	−0.48	−0.71	0.66	0.59	0.23	0.71
T8	0.39	0.40	0.19	0.18	−0.49	−0.63	0.49	0.48	0.81	0.15
T9	0.25	0.07	0.35	0.40	−0.48	−0.60	0.37	0.45	0.07	0.41
T10	0.21	0.06	0.35	0.38	−0.46	−0.60	0.20	0.46	0.36	0.44
T11	0.51	0.58	−0.01	0.04	−0.48	−0.54	0.59	0.67	−0.29	−0.13
T12	0.30	0.39	0.24	0.14	−0.49	−0.67	0.38	0.72	0.69	−0.03
T13	0.40	0.26	0.16	0.29	−0.50	−0.54	0.18	0.28	0.58	0.32

*Significant at $P < 0.05$.
**Significant at $P < 0.01$.

was reflected by the fact that rainfall in September, October, January, and February had positive correlations of r = 0.05 to 0.32, 0.64 to 0.82**, 0.11 to 0.35, and 0.75 to 0.87*, whereas the rainfall of November and December had negative correlations of –0.03 to –0.19 and –0.01 to –0.19 respectively across the treatments with sorghum yield over years. However, the relations were significant for all treatments except in cases of 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1} in the case of February rainfall and 20 kg N ha^{-1} (urea), 40 kg N ha^{-1} (urea), 40 kg N (urea) + 20 kg P ha^{-1}, 20 kg N ha^{-1} (FYM), 40 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, and 40 kg N (FYM) + 20 kg P ha^{-1} with October rainfall.

When the relationships of cotton yield over years were studied with soil fertility parameters, it was observed that OC and soil N had positive correlations with yield attained under all the treatments, whereas soil P had a positive correlation with yield obtained under all the treatments except in the cases of 40 kg N (urea) + 20 kg P ha^{-1} and 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and soil K had positive correlations with the yield of all the treatments except in cases of 20 kg N (urea) + 20 kg N ha^{-1} (FYM) and 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1}. In cotton, the estimates of correlation were nonsignificant with soil fertility parameters in most of the cases except with the yield attained with 20 kg N ha^{-1} (urea) and 20 kg N (urea) + 10 kg P ha^{-1} where the significant positive correlations of the magnitude of r = 0.94* and 0.96* with soil P, respectively, were observed. Similarly, when the long-term cotton yield data from different nutrient-management treatments were correlated with rainfall, the yield attained by the control had a significant negative correlation of r = –0.87* with rainfall received in February. In the rest of the cases, across the treatments, cotton yield had positive correlations with the rainfall received in September (r = 0.02 to 0.48), October (r = 0.06 to 0.58), November (r = 0.01 to 0.49), and December (r = 0.01 to 0.39), whereas there were negative correlations with the rainfall received in January (r = –0.46 to –0.68) and February (r = –0.52 to –0.87*).

Prediction of Rates of Changes in Soil Fertility as a Function of Time

The prediction functions of the status of nutrient and time in years were developed to study the trend of changing soil fertility over the years under the two intercropping systems in rotation. The prediction equations depicting the rate of change in soil OC and available soil N, P, and K over the years along with other descriptive statistics are given in Table 7. From the data, it was found that the rate of change was positive for soil N, whereas it was negative for OC, soil P (except for 20 kg N (FYM) + 10 kg P ha^{-1}and 40 kg N (FYM) + 20 kg P ha^{-1} treatments), and soil K. This indicated that soil N tended to increase over years, while OC and soil P and K had decreased over the years. The rate of change/year as indicated by the slope of the equations ranged from 0.007% (20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}) to 0.019% (10 kg N (urea) + 10 kg N ha^{-1} (FYM) + 10 kg P ha^{-1}) for OC; 3.02 kg ha^{-1} (10 kg N (urea) + 10 kg N ha^{-1} (FYM)) to 8.46 kg ha^{-1} (20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}) for soil N; 0.03 kg ha^{-1} (40 kg N ha^{-1} (urea)) to 0.27 kg ha^{-1} (20 kg N ha^{-1} (urea)) for soil P; and 2.05 kg ha^{-1} (20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}) to 7.92 kg ha^{-1} (20 kg N ha^{-1} (urea) + 10 kg P–ha^{-1}) for soil K. These data revealed that the rate of change in OC (%) was significant within all treatments except in 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. The rate of change in soil N (kg ha^{-1}) was significant with an application of 20 kg N ha^{-1} (urea), 20 kg N ha^{-1} (urea) + 10 kg P ha^{-1}, 20 kg N (FYM) + 10 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}, and control treatments, whereas the rates of change in soil P and K were not significant in any of the 13 treatments applied over the years.

The coefficient of determination (R^2) ranged from 0.14 (20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}) to 0.54 (20 kg N (urea) + 20 kg N ha^{-1} (FYM)) for predicting OC; whereas it ranged from 0.14 (20 kg N (urea) + 20 kg N ha^{-1} (FYM)) to 0.59 (20 kg N ha^{-1} (urea) + 10 kg P ha^{-1}) for soil N; 0.01 (40 kg N ha^{-1} (urea)) to 0.29 (20 kg N ha^{-1} (urea)) for soil P; and 0.01 (20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}) to 0.25 (20 kg N ha^{-1} (urea) + 10 kg P ha^{-1}) for soil K based on the models. The prediction error based on models was in a range of 0.05% (40 kg N (urea) + 20 kg P ha^{-1}) to 0.08% (20 kg N ha^{-1} (urea), 20 kg N ha^{-1} (FYM), 10 kg N (urea) + 10 kg N ha^{-1} (FYM) + 10 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}) for OC; 18.2 kg ha^{-1} (control) to 39.5 kg ha^{-1} (20 kg N (FYM) + 10 kg P ha^{-1}) for soil N; 1.29 kg ha^{-1} (40 kg N ha^{-1} (urea)) to 3.34 kg ha^{-1} (20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}) for soil P; and 44.0 kg ha^{-1} (control) to 77.6 kg ha^{-1} (20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}) for soil K.

Table 7

Regression models for predicting changes in soil nutrients over years at Kovilpatti

Treatment	Organic carbon (%)	R^2	E	Soil N (kg/ha)	R^2	E	Soil P (kg/ha)	R^2	E	Soil K (kg/ha)	R^2	E
Control	OC = 0.40** – 0.013* T	0.36*	0.07	SN = 72.9** + 4.70** T	0.52**	18.2	SP = 7.4** – 0.12 T	0.10	1.46	SK = 371.8** – 2.20 T	0.04	44.0
20 kg N/ha (urea)	OC = 0.44** – 0.015* T	0.39*	0.08	SN = 79.7** + 5.34* T	0.36*	29.2	SP = 9.6** – 0.27 T	0.29*	1.69	SK = 405.8** – 4.54 T	0.11	51.4
40 kg N/ha (urea)	OC = 0.44** – 0.012** T	0.45**	0.06	SN = 90.2** + 4.86 T	0.23	36.1	SP = 8.0** – 0.03 T	0.01	1.29	SK = 412.3** – 4.26 T	0.08	58.4
20 kg N/ha (urea) + 10 kg P/ha	OC = 0.44** – 0.009* T	0.30*	0.06	SN = 83.7** + 5.12* T	0.59*	28.4	SP = 9.1** – 0.17 T	0.15	1.63	SK = 442.1** – 7.92 T	0.25	56.2
40 kg N (urea) + 20 kg P/ha	OC = 0.46** – 0.015* T	0.41*	0.05	SN = 102.6** + 4.14 T	0.17	36.8	SP = 8.9** – 0.05 T	0.01	2.03	SK = 425.6** – 5.30 T	0.13	56.6
20 kg N/ha (FYM)	OC = 0.49** – 0.016* T	0.38*	0.08	SN = 93.8** + 4.51 T	0.19	37.5	SP = 9.9** – 0.23 T	0.18	2.03	SK = 420.6** – 4.78 T	0.09	62.8
40 kg N/ha (FYM)	OC = 0.55** – 0.016** T	0.45**	0.07	SN = 100.4** + 4.74 T	0.22	35.9	SP = 10.4** – 0.16 T	0.06	2.53	SK = 454.4** – 6.20 T	0.12	70.1
20 kg N (FYM) + 10 kg P/ha	OC = 0.50** – 0.015* T	0.41*	0.07	SN = 84.1** + 6.70* T	0.32*	39.5	SP = 9.2** + 0.002 T	0.01	2.02	SK = 409.0** – 2.16 T	0.02	62.3

40 kg N (FYM) + 20 kg P/ha	OC = 0.53** – 0.014** T	0.50**	0.06	SN = 86.1** + 7.13* T	0.39*	36.5	SP = 10.4** + 0.03 T	0.01	2.36	SK = 437.3** – 4.32 T	0.06	70.3
10 kg N (urea) + 10 kg N/ha (FYM)	OC = 0.49** – 0.017** T	0.45**	0.07	SN = 99.1** + 3.02 T	0.17	27.3	SP = 9.8** – 0.16 T	0.16	1.47	SK = 419.9** – 4.42 T	0.08	63.2
20 kg N (urea) + 20 kg N/ha (FYM)	OC = 0.53** – 0.017** T	0.54**	0.06	SN = 107.8** + 3.69 T	0.14	37.9	SP = 9.7** – 0.07 T	0.02	2.20	SK = 438.6** – 4.37 T	0.06	69.8
10 kg N (urea)+ 10 kg N/ha (FYM)+ 10 kg P/ha	OC = 0.50** – 0.019** T	0.46**	0.08	SN = 99.8** + 3.53 T	0.17	31.5	SP = 10.7** – 0.18 T	0.11	2.09	SK = 424.2** – 3.66 T	0.05	63.3
20 kg N (urea)+20 kg N (FYM) + 20 kg P/ha	OC = 0.49** – 0.007 T	0.14	0.08	SN = 76.0** + 8.46** T	0.52**	33.1	SP = 10.3** – 0.09 T	0.01	3.34	SK = 424.9** – 2.05 T	0.01	77.6

Effect of Soil Temperature, Crop Seasonal Rainfall, and Evaporation on Soil Nutrients

To study the effects of soil temperature measured at different soil depths (5–7.5, 10–15, and 20–30 cm) at 07:20 and 14:20 h, crop seasonal rainfall, and evaporation, multiple regression models were fitted and calibrated. The regression diagnostics (viz., estimates of regression coefficients of soil temperature, rainfall, and evaporation variables; coefficient of determination or predictability of a dependent variable (R^2); and prediction error of a dependent variable based on a model) are given in Table 8. The predictability of OC was significant for all treatments (R^2 0.91* to 0.97**) except the control, 40 kg N ha^{-1} (urea), 40 kg N (urea) + 20 kg P ha^{-1}, 20 kg N (FYM) + 10 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N ha^{-1} (FYM) ($R^2 = 0.81$ to 0.89). The soil temperature measured at 5–7.5 cm deep at 07:20 h had a significant negative effect on OC observed in the plot with an application of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}; whereas the soil temperature measured 10–15 cm deep at 07:20 h had a significant positive effect on the status of OC observed in plots with an application of 40 kg N (urea) + 20 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, 10 kg N (urea) + 10 kg N ha^{-1} (FYM), 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. The evaporation had a significant negative effect on OC observed in the plot with an application of 20 kg N ha^{-1} (FYM) and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. The soil temperature, rainfall, and evaporation variables had no significant effect on available soil N in either of the nutrient management treatments practiced. In the case of soil P, the soil temperature at 5–7.5 cm deep measured at 07:20 h had a significant negative effect in the case of 40 kg N ha^{-1} (FYM), 10 kg N (urea) + 10 kg N ha^{-1} (FYM), and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}, whereas the soil temperature at 5–7.5 cm deep measured at 14:20 h had a significant negative effect in the plots treated with 20 kg N ha^{-1} (FYM) and 40 kg N ha^{-1} (FYM). The soil temperature at 10–15 cm measured at 07:20 h had a significant positive effect on soil P in the plot with an application of 20 kg N (urea) + 10 kg P ha^{-1}, whereas the soil temperature measured at 20–30 cm at 07:20 h had a significant positive effect with an application of 40 kg N ha^{-1} (FYM). In the case of soil K, the crop seasonal rainfall had a significant positive effect in the plots with an application of 20 kg N (FYM) + 10 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM); whereas evaporation had a significant effect on soil K observed in the plots with an application of 20 kg N (FYM) + 10 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, 20 kg N (urea) + 20 kg N ha^{-1} (FYM), 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} over the years.

Prediction Models for Crop Yields as Function of Soil Nutrients

Sorghum + Cowpea System. Treatment-wise regression models of yield through combinations of (i) soil OC and available soil P and K and (ii) available soil N, P, and K were calibrated to predict yields of sorghum and cowpea under sorghum + cowpea and cotton and black gram under cotton + black gram system over the years. Estimates of regression coefficients, coefficient of determination, and prediction error are given in Tables 9 and 10 for sorghum + cowpea and cotton + black gram systems, respectively. Under sorghum + cowpea system, with combination of OC, soil P, and soil K variables, the sorghum yield predictability ranged from 0.50 for 20 kg N ha^{-1} (urea) to 0.99 for 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}, whereas the cowpea yield predictability ranged from 0.16 for 20 kg N (FYM) + 10 kg P ha^{-1} to 0.75 for 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. The prediction error varied from 91 kg ha^{-1} for 20 kg N (urea) + 20 kg N (FYM) +

Table 8

Regression models for predicting changes in soil nutrients through soil temperature, rainfall, and evaporation at Kovilpatti

Var	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13
Organic carbon (%)													
α	4.4	4.7	3.6	2.8	−1.6	6.1	3.7	3.2	0.29	2.4	−2.4	2.1	5.7
ST1	−0.22	−0.24	−0.19	−0.18	−0.08	−0.25	−0.15	−0.20	−0.09	−0.20	−0.02	−0.18	−0.28*
ST2	0.10	0.14	0.10	0.10	0.16*	0.07	0.04	0.14	0.13*	0.16*	0.18*	0.17	0.12*
ST3	−0.01	−0.05	−0.03	−0.04	−0.07	−0.01	0.001	−0.05	−0.06	−0.06	−0.10	−0.08	−0.03
ST4	−0.01	0.011	0.011	0.016	0.046	−0.015	−0.03	0.016	0.017	0.029	0.038	0.035	0.019
ST5	0.003	−0.004	0.006	0.005	−0.01	0.012	0.025	0.001	−0.005	−0.009	−0.027	−0.024	−0.009
ST6	0.013	0.008	0.001	0.003	0.001	0.014	0.012	0.007	0.014	0.016	0.032	0.030	0.011
RF	0.001	0.001	0.001	0.001	0.001	0.001	−0.001	0.001	−0.001	−0.001	0.001	0.001	0.001
EV	−0.15	−0.15	−0.10	−0.07	0.04	−0.22*	−0.16	−0.11	−0.05	−0.09	0.01	−0.10	−0.12*
R^2	0.83	00.92*	0.89	0.97**	0.81	0.94*	0.91*	0.87	0.93*	0.91*	0.88	0.91*	0.96**
Error	0.06	0.04	0.04	0.02	0.05	0.04	0.05	0.06	0.04	0.05	0.05	0.06	0.02
Soil N (kg/ha)													
α	2588	1804	2162	2614	1585	2231	3554	3375	3070	1358	949	678	3737
ST1	−83.7	−63.9	−76.7	−82.1	−57.6	−69.4	−97.8	−100.7	−94.3	−42.1	−36.8	−26.3	−113.4
ST2	1.5	4.8	5.0	8.5	−3.5	−15.2	−20.7	−15.1	−11.1	−7.2	−1.4	−3.2	−7.7
ST3	9.6	4.3	−0.06	−0.65	−0.47	16.8	19.7	16.6	16.2	4.0	−0.30	0.69	14.6
ST4	−8.0	−7.3	−5.3	−8.1	−4.8	−19.4	−23.6	−18.6	−15.3	−11.3	−9.5	−7.0	−14.4
ST5	6.3	6.5	4.6	5.8	3.1	9.1	11.5	8.5	6.6	5.1	2.7	2.0	7.7
ST6	−8.5	−4.4	−0.62	−7.5	5.9	5.7	0.02	0.34	−1.1	5.2	11.2	8.3	−8.1
RF	−0.21	−0.07	−0.05	−0.21	0.09	0.03	−0.18	−0.15	−0.14	0.07	0.13	0.16	−0.27
EV	−28.6	−8.6	−15.2	−18.7	0.21	−25.6	−53.8	−37.1	−32.4	−0.15	8.6	11.7	−30.0
R^2	0.21	0.14	0.16	0.17	0.29	0.36	0.28	0.20	0.19	0.43	0.36	0.38	0.18
Error	39	56	62	53	57	55	57	71	70	37	54	45	72

(Continued)

Table 8
(Continued)

Var	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13
Soil P (kg/ha)													
α	−48	22	22	−100	165	128	373*	139	224	196	69	−27	231
ST1	1.3	−1.4	−2.2	1.2	−6.1	−2.8	−8.7*	−4.5	−6.4	−6.2*	−1.5	−0.64	−8.9*
ST2	1.3	1.5	2.1	4.0*	1.1	−0.74	−3.8	0.64	−0.39	−0.04	0.11	3.1	1.9
ST3	−0.13	−0.64	−0.37	−1.45	0.79	1.1	3.0*	1.1	1.4	0.46	0.48	−0.97	0.05
ST4	−0.15	−0.08	0.54	0.27	0.16	−1.6*	−2.3*	−1.12	−1.15	−0.06	−1.08	−0.18	0.12
ST5	−0.29	0.07	0.03	−0.01	0.64	0.29	0.92	0.39	0.17	0.07	−0.59	−0.18	0.62
ST6	0.43	0.42	−0.36	−0.05	−1.37	0.81	0.098	0.038	0.24	−0.097	1.40	0.62	−0.98
RF	−0.003	−0.003	−0.01	0.001	−0.02	−0.014	−0.04*	−0.016	−0.026	−0.02*	−0.013	−0.003	−0.023
EV	−1.5	−2.5	−1.8	0.09	−4.6	−5.1*	−9.9*	−4.9	−6.1	−5.0*	−2.4	−1.1	−4.7
R^2	0.58	0.89	0.72	0.86	0.53	0.89	0.91*	0.64	0.53	0.88	0.65	0.63	0.26
Error	1.7	1.1	1.1	1.1	2.3	1.3	1.3	2.0	2.7	0.9	2.2	2.2	4.8
Soil K (kg/ha)													
α	−6879	−7444	−8158	−9455	−9937	−10201	−7362	−10770	−13146	−11755	−11607	−10042	−12716
ST1	184	214	211	250	253	316	287	323	412	345	318	288	329
ST2	88	57	113	115	131	42	−9	77	43	80	126	98	134
ST3	−60	−51	−81	−93	−99	−56	−30	−75	−69	−80	−105	−88	−108
ST4	25	27	40	38	48	16	−19	27	22	40	49	41	63
ST5	−4.3	−0.9	−7.4	−9.1	−12.9	−2.2	17.0	−6.5	−10.9	−9.0	−10.7	−7.8	−13.7
ST6	−0.58	3.2	−2.5	11.4	4.6	23.3	12.8	8.3	33.1	9.6	−1.9	−1.4	0.17
RF	0.57	0.76	0.60	0.83	0.86	1.14	0.79	1.01*	1.46*	1.11*	0.98	0.82	1.23
EV	136	125	153	179	205	185	132	232*	267*	225	260*	216*	284*
R^2	0.67	0.59	0.68	0.78	0.74	0.65	0.84	0.75	0.73	0.74	0.78	0.80	0.68
Error	43	58	57	50	51	65	49	53	63	55	57	49	73

*Significant at $P < 0.05$.
**Significance at $P < 0.01$.

Table 9
Regression models for predicting yield of sorghum and cowpea through soil nutrients at Kovilpatti

	$Y = \pm\alpha \pm \beta1$ (OC) $\pm \beta2$ (SP) $\pm \beta3$ (SK)						$Y = \pm\alpha \pm \beta1$ (SN) $\pm \beta2$ (SP) $\pm \beta3$ (SK)					
Treatments	α	OC	SP	SK	R^2	Error	α	SN	SP	SK	R^2	Error
Sorghum												
T1	5258*	−4928*	38.6	−7.80*	0.96	177	3514	2.13	−187.7	−3.88	0.56	555
T2	4092	−3743	−66.1	−2.22	0.50	879	3057	1.72	−254.1	0.43	0.48	898
T3	5133	−8659	142.0	−4.33	0.60	796	4836	7.35	−341.3	−3.98	0.48	894
T4	5851	−10403	201.9	−5.01	0.75	488	2934	8.77	−226.5	−1.40	0.68	559
T5	6653	−14284	138.0	−1.56	0.92	357	3200	9.25	−52.6	−5.29	0.32	1042
T6	7883	−23192	952.0	−13.06	0.66	663	3124	1.62	−250.1	0.30	0.52	787
T7	4694	−11140	177.0	0.91	0.77	592	3387	2.40	−208.5	−0.16	0.40	962
T8	4997	−5957	53.5	−3.73	0.84	398	2368	11.52	−176.1	−1.52	0.39	783
T9	4295	−8763	87.9	1.14	0.72	712	930	13.03	−154.0	2.20	0.34	1094
T10	3567	−9612	216.0	−0.58	0.82	497	7015	−0.86	−343.7	−5.65	0.43	901
T11	4004	−7398	−45.9	3.01	0.77	687	2767	12.78	−506.5	3.86	0.71	770
T12	4580	−5203	60.4	−3.86	0.63	681	1351	12.68	−146.0	0.47	0.43	851
T13	8058*	−13804*	156.2*	−4.40	0.99*	91	−317	17.69	−163.9	4.85	0.49	1007

(*Continued*)

Table 9
(Continued)

	$Y = \pm \alpha \pm \beta 1$ (OC) $\pm \beta 2$ (SP) $\pm \beta 3$ (SK)						$Y = \pm \alpha \pm \beta 1$ (SN) $\pm \beta 2$ (SP) $\pm \beta 3$ (SK)					
Treatments	α	OC	SP	SK	R^2	Error	α	SN	SP	SK	R^2	Error
Cowpea												
T1	192	−88	−1.2	−0.30	0.50	25	25	0.69	−4.2	−0.06	0.87	13
T2	317	−567	23.9	−0.63	0.61	36	72	0.66	−3.2	−0.15	0.60	36
T3	159	−459	21.0	−0.23	0.49	39	102	0.66	−5.5	−0.17	0.59	35
T4	264	−606	19.3	−0.29	0.31	54	38	0.89	−8.6	−0.01	0.50	46
T5	227	−210	4.4	−0.27	0.28	54	48	0.93	−2.2	−0.16	0.64	38
T6	293	−660	26.0	−0.44	0.26	53	78	0.59	−5.7	−0.07	0.47	45
T7	184	−252	4.1	−0.08	0.30	44	77	0.54	−4.4	−0.07	0.49	38
T8	170	−155	3.0	−0.14	0.16	56	94	0.86	−9.4	−0.10	0.56	41
T9	173	−238	6.2	−0.11	0.35	46	65	0.70	−3.3	−0.08	0.54	38
T10	352	−14	−15.1	−0.36	0.48	40	203	0.59	−10.5	−0.27	0.59	36
T11	172	−392	15.9	−0.15	0.52	42	93	0.83	−9.4	−0.10	0.59	39
T12	218	−202	8.3	−0.35	0.53	33	55	0.75	−0.4	−0.15	0.62	29
T13	283	−271	8.4	−0.45	0.75	25	108	0.70	−0.6	−0.27	0.94	12

*Significant at $P < 0.05$.

Table 10
Regression models for predicting yield of cotton and black gram through soil nutrients at Kovilpatti

Treatments	$Y = \pm\alpha \pm \beta 1\ (OC) \pm \beta 2\ (SP) \pm \beta 3\ (SK)$						$Y = \pm\alpha \pm \beta 1\ (SN) \pm \beta 2\ (SP) \pm \beta 3\ (SK)$					
	α	OC	SP	SK	R^2	Error	α	SN	SP	SK	R^2	Error
Cotton												
T1	−1453	1779	104.3	1.47	0.89	61	−201	0.38	85.7	−0.20	0.33	154
T2	−454	480	76.7	0.34	0.90	72	−567	−2.08	115.6*	0.91	0.95	51
T3	−1049*	2483*	150.2*	−1.33	0.97*	46	278	2.37	90.3	−2.13	0.55	185
T4	−282	368	103.5*	−0.55	0.94*	29	−166	0.78	105.6*	−0.77	0.97*	31
T5	1022	−439	−118.3	1.87	0.20	234	193	3.48	33.9	−1.10	0.57	172
T6	−1079*	1203*	31.5	2.04*	0.98*	37	−1292	−0.64	80.4	2.87	0.82	122
T7	−768	779	−2.5	2.30	0.79	89	−829	−0.41	10.9	3.12	0.55	131
T8	−1373*	1096*	87.5*	1.55*	0.99*	3	−995	−0.33	108.8	1.27	0.85	78
T9	−1681	−772	117.5	3.00	0.42	147	−1274	0.01	80.5	2.19	0.39	151
T10	−1642*	−836*	182.4*	2.14*	0.99*	16	−1233	−0.25	120.1	1.76	0.79	73
T11	2926	1094	−148.1	−3.28	0.78	125	3210*	2.19*	−146.5*	−3.65*	0.98*	40
T12	−1077	−2012	249.9	−0.14	0.72	107	−387	1.72	67.3	0.03	0.66	118
T13	523	−2996	238.8	−2.59	0.66	128	−101	0.28	82.1	−0.55	0.39	172

(Continued)

Table 10
(Continued)

Treatments	$Y = \pm\alpha \pm \beta1$ (OC) $\pm \beta2$ (SP) $\pm \beta3$ (SK)						$Y = \pm\alpha \pm \beta1$ (SN) $\pm \beta2$ (SP) $\pm \beta3$ (SK)					
	α	OC	SP	SK	R^2	Error	α	SN	SP	SK	R^2	Error
Black gram												
T1	587	−697	8.7	−0.88	0.27	98	68	−0.69	18.9	−0.04	0.07	110
T2	511	−524	−16.6	−0.13	0.22	145	328	−0.09	−33.2	0.26	0.18	149
T3	422	−732	2.8	−0.12	0.26	110	−3	−1.28	38.3	0.02	0.27	109
T4	645	1227	81.7	2.02	0.30	174	109	−1.86	−21.5	1.22	0.20	187
T5	−147	53	34.2	0.05	0.07	193	258	−2.34	−51.6	1.84	0.37	159
T6	772	−309	−23.9	−0.69	0.18	233	540	−0.91	−21.5	−0.13	0.18	233
T7	834	−599	−9.5	−0.75	0.18	253	−290	−3.23	−6.1	2.48	0.28	237
T8	1183	−630	−57.6	−0.48	0.24	229	604	−1.05	−41.3	0.35	0.26	226
T9	990	−1348	−22.2	0.15	0.18	244	836	−1.36	−39.9	0.06	0.19	242
T10	669	−232	−44.1	−0.06	0.19	158	484	−1.40	−27.6	0.26	0.29	148
T11	−2044	404	90.1	2.82	0.30	212	−1294	−1.21	67.2	2.41	0.38	199
T12	−105	−1323	70.3	0.34	0.17	221	−442	−2.76	52.1	1.28	0.37	191
T13	731	−1817	21.6	0.28	0.22	278	372	−1.63	−61.1	1.78	0.29	265

*Significant at $P < 0.05$.

20 kg P ha^{-1} to 879 kg ha^{-1} for 20 kg N ha^{-1} (urea) in sorghum, whereas it ranged from 25 kg ha^{-1} for 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} and control to 56 kg ha^{-1} for 20 kg N (FYM) + 10 kg P ha^{-1} in cowpea based on the models. However, with available soil N, P, and K variables, the sorghum yield predictability ranged from 0.32 for 40 kg N (urea) + 20 kg P ha^{-1} to 0.71 for 20 kg N (urea) + 20 kg N ha^{-1} (FYM), whereas the cowpea yield predictability ranged from 0.47 for 20 kg N ha^{-1} (FYM) to 0.94 for 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. The prediction error ranged from 555 kg ha^{-1} for the control to 1094 kg ha^{-1} for 40 kg N (FYM) + 20 kg P ha^{-1} in sorghum, whereas it ranged from 12 kg ha^{-1} for 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} to 46 kg ha^{-1} for 20 kg N (urea) + 10 kg P ha^{-1} in cowpea based on the models.

In the case of regression models with OC, soil P, and K variables, the OC and soil K had negative effects, whereas soil P had a positive effect on yield of sorghum and cowpea crops. However, the effects were significant in sorghum crop only in the case of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. When the regression models with soil N, P, and K variables were critically observed, soil N had a positive effect on sorghum yield in the case of all the nutrient managements treatments except 10 kg N (urea) + 10 kg N ha^{-1} (FYM), whereas soil P had a negative effect in all treatments. However, soil K had a negative effect in the cases of only 7 treatments—control, 40 kg N ha^{-1} (urea), 20 kg N (urea) + 10 kg P ha^{-1}, 40 kg N (urea) + 20 kg P ha^{-1}, 40 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM)—on sorghum yield. In the case of cowpea, soil N had a positive effect, whereas soil P and K had a negative effect on yield attained by all the treatments.

Cotton + Black Gram System. Perusal of the data presented in Table 10 revealed that under the cotton + black gram system, with models based on OC, soil P, and soil K variables, the cotton yield predictability ranged from 0.20 for 40 kg N (urea) + 20 kg P ha^{-1} to 0.99* for 20 kg N (FYM) + 10 kg P ha^{-1}, whereas the black gram yield predictability ranged from 0.07 for 40 kg N (urea) + 20 kg P ha^{-1} to 0.30 for 20 kg N (urea) + 10 kg P ha^{-1} and 20 kg N (urea) + 20 kg N ha^{-1} (FYM). Based on the models, the prediction error ranged from 3 kg ha^{-1} for 20 kg N (FYM) + 10 kg P ha^{-1} to 234 kg ha^{-1} for 40 kg N (urea) + 20 kg P ha^{-1} in cotton, and it ranged from 98 kg/ha for control to 278 kg ha^{-1} for 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} in black gram. Based on the models fitted with available soil N, soil P, and soil K variables, the cotton yield predictability ranged from 0.33 for control to 0.98* for 20 kg N (urea) + 20 kg N ha^{-1} (FYM), whereas the black gram yield predictability ranged from 0.07 for the control to 0.38 for 20 kg N (urea) + 20 kg N ha^{-1} (FYM). The prediction error ranged from 31 kg ha^{-1} for 20 kg N (urea) + 10 kg P ha^{-1} to 185 kg ha^{-1} for 40 kg N ha^{-1} (urea) in cotton, whereas it ranged from 109 kg ha^{-1} for 40 kg N ha^{-1} (urea) to 265 kg ha^{-1} for 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} in black gram. Based on the regression models fitted with OC, soil P, and soil K variables, OC had a positive effect on cotton yield in all treatments except 40 kg N (urea) + 20 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, 10 kg N (urea) + 10 kg N ha^{-1} (FYM), 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}, whereas soil P had a positive effect in all treatments except 40 kg N (urea) + 20 kg P ha^{-1}, 40 kg N ha^{-1} (FYM), and 20 kg N (urea) + 20 kg N ha^{-1} (FYM); and soil K had a positive effect in all treatments except 40 kg N ha^{-1} (urea), 20 kg N (urea) + 10 kg P ha^{-1}, 20 kg N (urea) + 20 kg N ha^{-1} (FYM), 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. However, the effects were significant for OC only in 40 kg N ha^{-1} (urea), 20 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM); for soil P in 40 kg N ha^{-1} (urea), 20 kg N (urea) + 10 kg P ha^{-1}, 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM); and for soil K in 20 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM) treatments. In the case of black gram, the effects of OC on yield were negative in all treatments except 20 kg N (urea) + 10 kg P ha^{-1}, 40 kg N (urea) + 20 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N ha^{-1} (FYM); whereas the effect of soil P was negative on the yield attained by 20 kg N ha^{-1} (urea), 20 kg N ha^{-1} (FYM), 40 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM); and soil K was negative on the yield attained by the control, 20 kg N ha^{-1} (urea), 40 kg N ha^{-1} (urea), 20 kg N ha^{-1} (FYM), 40 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM) treatments.

With models based on soil N, P, and K variables, the effect of soil N was positive on cotton yield attained by all treatments except 20 kg N ha^{-1} (urea), 20 kg N ha^{-1} (FYM), 40 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM), whereas the effect of soil P was positive on yield of all treatments except 20 kg N (urea) + 20 kg N ha^{-1} (FYM) and soil K was positive in all treatments except the control, 40 kg N ha^{-1} (urea), 20 kg N (urea) + 10 kg P ha^{-1}, 40 kg N (urea) + 20 kg P ha^{-1}, 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. However, the effects of soil N and K on yield were significant only with application of 20 kg N (urea) + 20 kg N ha^{-1} (FYM), whereas the effect of soil P was significant on yield attained by 20 kg N ha^{-1} (urea), 20 kg N (urea) + 10 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N ha^{-1} (FYM). In the case of black gram, the effect of soil N was negative on yield attained by all treatments, and soil P had a negative effect on yield in all treatments except the control, 40 kg N ha^{-1} (urea), 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1}. Soil K had positive effect on the yield attained by all treatments except the control and 20 kg N ha^{-1} (FYM).

Sustainability of Treatments for Different Crops over Years

The estimates of sustainability yield index (SYI) of each nutrient management treatment were measured by considering the mean yield of treatments over years, maximum potential yield attained by any treatment in any year during the study period, and prediction error based on a regression model with available soil N, P, and K nutrient variables. The maximum attained yields in the study period or the yield potential of crops considered for measuring SYI were 3241 kg ha^{-1} for sorghum, 146 kg ha^{-1} for cowpea, 826 kg ha^{-1} for cotton, and 585 kg ha^{-1} for black gram. The estimates of SYI of treatments indicating their suitability and superiority for sorghum and cowpea under sorghum + cowpea system and cotton and black gram under a cotton + black gram system are given in Table 11. Based on the model fitted with soil OC, P, and K variables, the SYI were in the range of 19.9% to 63.4% for sorghum, 14.5% to 35.0% for cowpea, 37.8% to 58.7% for cotton, and –10.9% to 5.0% for black gram. However, in the case of a model fitted with available soil N, P, and K variables, these estimates ranged from 18.7% to 36.1% for sorghum, 20.0% to 43.9% for cowpea, 28.7% to 60.9% for cotton, and –10.2% to 5.4% for black gram. Among the four crops tested for crop rotation systems during 13 years, black gram was found to be unsustainable with a negative SYI observed in the case of eight treatments based on the model fitted with soil OC, P, and K variables, and nine treatments based on the model fitted with available soil N, P, and K variables.

The analysis indicated that under a sorghum + cowpea system, 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} was quite superior with a SYI of 63.4% for sorghum and 35.0%

Table 11
Sustainability yield index (SYI) of treatments for different crops over years

	SYI based on model with soil organic C, P, and K variables				SYI based on model with soil N, P, and K variables			
Treatment	Sorghum	Cowpea	Cotton	Black gram	Sorghum	Cowpea	Cotton	Black gram
T1	31.9	17.7	39.9	2.8	20.3	25.9	28.7	0.8
T2	19.9	22.4	46.5	0.2	19.3	22.4	49.0	−0.5
T3	21.7	21.8	53.9	5.0	18.7	24.5	37.1	5.1
T4	34.6	14.5	52.7	0.9	32.4	20.0	52.5	−1.4
T5	43.4	16.3	37.8	−0.4	22.3	27.3	45.3	5.4
T6	25.8	14.5	50.2	−10.2	22.0	20.0	39.9	−10.2
T7	35.1	21.0	44.0	−10.9	23.7	25.1	38.9	−8.2
T8	37.5	14.5	58.7	−4.6	25.6	24.7	49.6	−4.1
T9	37.1	28.9	45.2	−3.8	25.3	34.4	44.7	−3.5
T10	37.1	22.2	54.0	1.4	24.7	25.0	47.1	3.1
T11	38.7	23.9	50.6	−3.9	36.1	25.9	60.9	−1.6
T12	31.5	30.3	48.3	−5.3	26.2	33.0	46.9	−0.2
T13	63.4	35.0	50.6	−7.1	35.1	43.9	45.3	−4.9

for cowpea based on model fitted with soil OC, P, and K variables. This treatment was also superior for sorghum with the second best SYI of 35.1% and cowpea with greatest SYI of 43.9% based on the model fitted with available soil N, P, and K variables. However, 20 kg N (urea) + 20 kg N ha^{-1} (FYM) was superior for sorghum with the greatest SYI of 36.1% based on the model fitted with soil N, P, and K variables. In the case of the cotton + black gram system, 20 kg N (FYM) + 10 kg P ha^{-1} was superior with the greatest SYI of 58.7% for cotton, whereas 40 kg N ha^{-1} (urea) was superior with a SYI of 5.0% for black gram based on the model fitted with soil OC, P, and K variables. However, 20 kg N (urea) + 20 kg N ha^{-1} (FYM) was superior for cotton with the greatest SYI of 60.9%, whereas 40 kg N (urea) + 20 kg P ha^{-1} was superior for black gram with the greatest SYI of 5.4% based on the model with soil N, P, and K variables.

Discussion

Under both sorghum + cowpea and cotton + black gram systems, the analysis of variance (ANOVA) indicated the superiority of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} for attaining a significantly greater sorghum yield of 2146 kg ha^{-1} (variation 46.8%), cotton yield of 546 kg ha^{-1} (variation 25.4%), and black gram yield of 236 kg ha^{-1} (variation 85.0%), and the fourth greatest cowpea yield of 76 kg ha^{-1} (variation 47.8%), compared to the control, giving a yield of 1211 kg ha^{-1} of sorghum (variation 49.3%), 51 kg/ha of cowpea (variation 48.9%), 391 kg ha^{-1} of cotton (variation 30.5%), and 115 kg ha^{-1} of black gram (variation 63.9%) over the years. Application of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} was superior with a yield greater than mean sorghum yield of 1681 kg ha^{-1} (variation 12.3%), cowpea yield of 74 kg ha^{-1} (variation 15.9%), cotton yield of 486 kg ha^{-1} (variation 9.6%), and black gram yield of 180 kg ha^{-1} (variation of 25.2%) over years. A comparison of mean yield of treatments based on LSD criteria indicated that 40 kg N (FYM) + 20 kg P ha^{-1} and 20 kg N (urea) + 20 kg N ha^{-1} (FYM) were at par with 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} for sorghum, whereas 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} was at par with 40 kg N (FYM) + 20 kg P ha^{-1} for cowpea. Treatments of 40 kg N (urea) + 20 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1} were at par with 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} for cotton, and 40 kg N (urea) + 20 kg P ha^{-1}, 40 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1} were at par with 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} for black gram.

Relationship of Yield with Soil Nutrients and Rainfall

The sorghum grain yield had a significant negative correlation with OC (r = –0.77* to –0.88*) in the case of all the treatments except 20 kg N ha^{-1} (urea), 40 kg N ha^{-1} (urea), 20 kg N ha (FYM), and 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1} (r = –0.68 to –0.75). It had positive but nonsignificant correlation with soil N (r = 0.14 to 0.43) and negative correlation with soil P (r = –0.02 to –0.72) in all treatments. Further, the grain yield had a nonsignificant negative correlation with soil K (r = –0.11 to –0.61) in treatments of control, 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1}, whereas it had a positive correlation (r = 0.01 to 0.34) in 40 kg N (FYM) + 20 kg P ha^{-1}, 10 kg N (urea) + 10 kg N ha^{-1} (FYM), 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. The rainfall received in September, October, January, and February had positive correlations with "r" values varying from 0.05 to 0.32, 0.64 to 0.82**, 0.11 to 0.35, and 0.75 to 0.87*, whereas rainfall of November and December had negative correlations ranging from –0.03 to –0.19 and –0.01 to –0.19 respectively with sorghum grain yield. It was interesting to note that the yield–rainfall relations were significant for all the nutrient-management treatments except in the case of 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1} for February rainfall and 20 kg N ha^{-1} (urea), 40 kg N ha^{-1} (urea), 40 kg N (urea) + 20 kg P ha^{-1}, 20 kg N ha^{-1} (FYM), 40 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, and 40 kg N (FYM) + 20 kg P ha^{-1} for October rainfall.

The cotton yield attained by 20 kg N ha (urea) and 20 kg N (urea) + 10 kg P ha^{-1} had significant positive correlations of 0.94 and 0.96 with soil P respectively. Similarly, the control yield had a significant negative correlation of –0.87* with rainfall received in February. The yield–rainfall relationships were positive for September (0.02 to 0.48), October (0.06 to 0.58), November (0.01 to 0.49), and December (0.01 to 0.39), whereas these were negative with the rainfall of January (–0.46 to –0.68) and February (–0.52 to –0.87*). The OC and soil N had a positive relationship with yield of all treatments, whereas soil P also had a positive relationship with yield of all treatments except 40 kg N (urea) + 20 kg P ha^{-1} and 20 kg N (urea) + 20 kg N ha^{-1} (FYM). Soil K had a positive relation with yield of all treatments except 20 kg N (urea) + 20 kg N ha^{-1} (FYM) and 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1}. The positive correlation among crop yields, rainfall, and some of the nutrients are indicative of the positive performance of these variables over a long-term basis. In rain-fed agriculture, amount and distribution of rainfall plays an important role. Similarly, increase in organic matter and consequent increase in available soil N helps increase the crop yields significantly. The SOM, beside being the storehouse for many essential plant nutrients, has been positively associated with available water-holding capacity, total porosity, and mean weight diameter and negatively related with bulk density, pH, and soil erosion; thus it influences the crop yields positively (Evrendilek, Celik, and Kilic 2006).

Changes in Soil Fertility Over Years

The critical analysis of the data indicated that with the application of all soil nutrient-management treatments, the soil N increased, whereas OC, soil P (except with application of 20 kg N (FYM) + 10 kg P ha^{-1} and 40 kg N (FYM) + 20 kg P ha^{-1}), and soil K have decreased over the years. The increases over the years in absolute terms were a maximum of 0.019% in soil OC with application of 10 kg N (urea) + 10 kg N ha^{-1} (FYM) + 10 kg P ha^{-1}; 8.46 kg ha^{-1} in soil N with application of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}; 0.27 kg ha^{-1} in soil P with application of 20 kg N ha^{-1} (urea); and 7.92 kg ha^{-1} in soil K with application of 20 kg N ha^{-1} (urea) + 10 kg P ha^{-1}. The increase in OC was significant in the case of all the treatments except in 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}, whereas the increase in soil N was significant with 20 kg N ha^{-1} (urea), 20 kg N ha^{-1} (urea) + 10 kg P ha^{-1}, 20 kg N (FYM) + 10 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}, and the control. The treatments did not influence the soil P and K status significantly over the years. While predicting the changes in fertility with time over years, the maximum magnitude of coefficient of determination for N ($R^2 = 0.54$) was attained with 20 kg N (urea) + 20 kg N ha^{-1} (FYM); it was 0.59 with 20 kg N ha^{-1} (urea) + 10 kg P ha^{-1} for soil N; 0.29 with 20 kg N ha^{-1} (urea) for soil P; and 0.25 with 20 kg N ha^{-1} (urea) + 10 kg P ha^{-1} for soil K prediction. The least prediction errors (0.05%) were attained with the model developed with 40 kg N (urea) + 20 kg P ha^{-1} for OC, 18.2 kg ha^{-1} for soil N, and 44.0 kg ha^{-1} for soil K with the model developed with unamended control; and 1.29 kg ha^{-1} with the model of 40 kg N ha^{-1} (urea) for soil P. Greater magnitude of R^2 and lower prediction error of some of the treatments indicate their better predictability in terms of soil fertility.

Effects of Soil Temperature, Crop Seasonal Rainfall, and Evaporation on Soil Nutrients

In the case of the models developed for predicting the influence of soil temperature, rainfall, and evaporation on soil nutrients, the predictability of OC was significant for all the treatments (0.91* to 0.97**) except the control, 40 kg N ha^{-1} (urea), 40 kg N (urea) + 20 kg P ha^{-1}, 20 kg N (FYM) + 10 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N ha^{-1} (FYM). The soil temperature measured at 5–7.5 cm deep at 07:20 h had a significant negative effect on OC with application of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}, whereas soil temperature measured at 10–15 cm deep at 07:20 h had a significant positive effect on OC with application of 40 kg N (urea) + 20 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, 10 kg N (urea) + 10 kg N ha^{-1} (FYM), 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. The evaporation had a significant negative effect on OC observed with application of 20 kg N ha^{-1} (FYM) and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. The soil temperature, rainfall, and evaporation had no significant effect on soil N under any treatment. The soil P was significantly decreased with application of 40 kg N ha^{-1} (FYM), 10 kg N (urea) + 10 kg N ha^{-1} (FYM), and 10 kg N (urea) + 10 kg N ha^{-1} (FYM) with an increase in soil temperature at 5–7.5 cm deep measured at 07:20 h, compared to application of 20 kg N ha^{-1} (FYM) and 40 kg N ha^{-1} (FYM) with an increase in soil temperature at 5–7.5 cm deep measured at 14:20 h. The soil P significantly increased with application of 20 kg N (urea) + 10 kg P ha^{-1} when the soil temperature at 10–15 cm deep measured at 07:20 hours increased and also with application of 40 kg N ha^{-1} (FYM) with an increase in soil temperature at 20–30 cm deep at 07:20 h. The soil K significantly increased with application of 20 kg N (FYM) + 10 kg

P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM) with an increased crop seasonal rainfall. Surprisingly, increased evaporation over the years exhibited a significant increase in available soil K in the case of 20 kg N (FYM) + 10 kg P ha^{-1} 40 kg N (FYM) + 20 kg P ha^{-1}, 20 kg N (urea) + 20 kg N ha^{-1} (FYM), 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}.

Effect of Soil Nutrients on Yield of Crops

Under a sorghum + cowpea system, application of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} was superior in attaining a maximum sorghum yield predictability of 0.99 with an error of 91 kg ha^{-1} and cowpea yield predictability of 0.75 with an error of 25 kg ha^{-1} based on the model developed with OC and available soil P and K variables. However, in the model developed with soil N, P, and K variables, maximum sorghum yield predictability of 0.71 with an error of 770 kg ha^{-1} was attained with an application of 20 kg N (urea) + 20 kg N ha^{-1} (FYM), whereas the maximum cowpea yield predictability of 0.94 with an error of 12 kg ha^{-1} was attained with an application of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. Further, it was interesting to observe that based on the regression model with soil N, P, and K variables, the sorghum yield increased with an increase in soil N in all treatments except 10 kg N (urea) + 10 kg N ha^{-1} (FYM), whereas it decreased with an increase in soil P. Continuous application of P many times leads to P buildup, and greater P content creates imbalance of nutrients. The sorghum yield tended to decrease with an increase in soil K in the case of the control and 40 kg N ha^{-1} (urea), 20 kg N (urea) + 10 kg P ha^{-1}, 40 kg N (urea) + 20 kg P ha^{-1}, 40 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM). However, in the case of cowpea, the yield increased with an increase in soil N, whereas it decreased with an increase in soil P and K under all the treatments.

In the case of a cotton + black gram system, with OC, soil P, and soil K variables, maximum cotton yield predictability of 0.99* was attained with 20 kg N (FYM) + 10 kg P ha^{-1} and 10 kg N (urea) + 10 kg N ha^{-1} (FYM) with errors of 3 and 16 kg ha^{-1}, whereas maximum black gram yield predictability of 0.30 was attained by applying 20 kg N (urea) + 10 kg P ha^{-1} and 20 kg N (urea) + 20 kg N ha^{-1} (FYM) with errors of 174 and 212 kg ha^{-1} respectively. With soil N, P, and K variables, maximum yield predictabilities of 0.98* in cotton and 0.38 in black gram were attained with 20 kg N (urea) + 20 kg N ha^{-1} (FYM) with prediction errors of 40 and 199 kg ha^{-1} respectively.

The relationships predicted that the cotton yield increased with an increase in OC in all treatments except 40 kg N (urea) + 20 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, 10 kg N (urea) + 10 kg N ha^{-1} (FYM), 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}, whereas an increase in soil P increased the yield in all treatments except 40 kg N (urea) + 20 kg P ha^{-1}, 40 kg N ha^{-1} (FYM), and 20 kg N (urea) + 20 kg N ha^{-1} (FYM). An increase in soil K increased the yield in all treatments except 40 kg N ha^{-1} (urea), 20 kg N (urea) + 10 kg P ha^{-1}, 20 kg N (urea) + 20 kg N ha^{-1} (FYM), 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. However, the effect of OC was significant only on the yields attained by 40 kg N ha^{-1} (urea), 20 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM) . The influence of soil P was observed on yields attained by 40 kg N ha^{-1} (urea), 20 kg N (urea) + 10 kg P ha^{-1}, 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM) and that of soil K was noticed in the case of 20 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg

N (urea) + 10 kg N ha^{-1} (FYM). The yield of black gram decreased with an increase in OC under application of all treatments except 20 kg N (urea) + 10 kg P ha^{-1}, 40 kg N (urea) + 20 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N ha^{-1} (FYM), compared to a decrease in yields attained by 20 kg N ha^{-1} (urea), 20 kg N ha^{-1} (FYM), 40 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, 40 kg N (FYM) + 20 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM) with an increase in soil P and the control, 20 kg N ha^{-1} (urea), 40 kg N ha^{-1} (urea), 20 kg N ha^{-1} (FYM), 40 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM) with an increase in soil K.

From the perusal of the model of yield with soil N, P, and K variables, it can be seen that an increase in soil N increased the cotton yield attained by all the treatments except in the case of 20 kg N ha^{-1} (urea), 20 kg N ha^{-1} (FYM), 40 kg N ha^{-1} (FYM), 20 kg N (FYM) + 10 kg P ha^{-1}, and 10 kg N (urea) + 10 kg N ha^{-1} (FYM). An increase in soil P increased the yield attained by all treatments except in 20 kg N (urea) + 20 kg N ha^{-1} (FYM). The increase in available soil K also increased the yield attained by all treatments except the control, T3, 20 kg N (urea) + 10 kg P ha^{-1}, 40 kg N (urea) + 20 kg P ha^{-1}, 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1}. However, the significance of available soil N and K on yield was observed only in the case of 20 kg N (urea) + 20 kg N/ha (FYM), whereas the yield was significantly influenced by soil P under application of 20 kg N ha^{-1} (urea), 20 kg N (urea) + 10 kg P ha^{-1}, and 20 kg N (urea) + 20 kg N ha^{-1} (FYM). In the case of black gram, the yield attained by all treatments decreased with an increase in soil N, and the yield of all treatments except the control, 40 kg N ha^{-1} (urea), 20 kg N (urea) + 20 kg N ha^{-1} (FYM), and 10 kg N (urea) + 10 kg N (FYM) + 10 kg P ha^{-1} decreased with an increase in soil P. The yield of all the treatments except the control and 20 kg N ha^{-1} (FYM) increased with an increase in available soil K. These prediction models between crop yields and fertility status can help us to understand the quantitative relationships between crop yields and nutrient status in soil. One can compute the effects on crop yield with unit change in soil fertility parameters such as OC and soil available N, P, and K. The reliability of these small prediction models becomes great when long-term data are used to develop the prediction functions.

Identification of Best Nutrient-Management Treatments (BNMT) or Superior Treatments for Different Crops

The ultimate objectives of such studies employing the huge database are to identify the best nutrient-management practice from the viewpoints of greater sustainable yield and improved soil fertility and to understand the quantitative relationships between the dependent (yield) and independent variables (climatic and edaphic factors, per se; in this case, rainfall, soil temperature, evaporation rate, soil OC, and available soil N, P, and K). In this study, the estimates of SYI of each nutrient-management treatment measured using mean yield of treatments over years, maximum potential yield attained by any treatment in any year during the study period, and prediction error based on a regression model with soil nutrient variables clearly indicated that black gram yield was unsustainable with a negative SYI for eight treatments based on the model developed with soil OC, P, and K variables, and nine treatments based on soil N, P, and K variables. Application of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} gave the greatest mean yield of 2146 kg ha^{-1} of sorghum and fourth greatest mean yield of 76 kg ha^{-1} of cowpea under the sorghum + cowpea system. The greatest mean yields of 546 kg ha^{-1} of cotton and 236 kg ha^{-1} of black gram were under the cotton + cowpea system. This treatment maintained the greatest mean soil OC content of 0.44%, available soil P value of 10.9 kg ha^{-1}, and soil K value of 411 kg ha^{-1}

as well as the second greatest mean for available soil N content of 135 kg ha^{-1} during the 13-year study period. Further, the sustainability yield analysis based on regression models of yield through soil fertility measured by OC, N, P, and K indicated that application of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} was superior for sorghum and cowpea with the greatest SYIs of 63.4 and 35.0% respectively using prediction error based on the model developed with soil OC, P, and K variables. This treatment was also superior for sorghum with the second best SYI of 35.1% and for cowpea with the greatest SYI 43.9% using prediction error based on the model developed with soil N, P, and K variables. In the crop rotation system with cotton and black gram, application of 20 kg N (FYM) + 10 kg P ha^{-1} was superior with the greatest SYI of 58.7% for cotton, whereas 40 kg N ha^{-1} (urea) was superior with a SYI of 5.0% for black gram based on the model with soil OC, P, and K variables. However, 20 kg N (urea) + 20 kg N ha^{-1} (FYM) was superior for cotton with the greatest SYI of 60.9%, whereas 40 kg N (urea) + 20 kg P ha^{-1} was superior for black gram with the greatest SYI of 5.4% based on the model with soil N, P, and K variables. Thus, based on the study, 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} could be prescribed for sorghum + cowpea, whereas 20 kg N (urea) + 20 kg N (FYM) could be prescribed for cotton + black gram under rotation in alternate years. A range of assured yield and maintenance of soil fertility could be derived based on (i) the mean yield treatments over years and (ii) mean yield of the superior treatment over years. The study indicated that application of 20 kg N (urea) + 20 kg N (FYM) + 20 kg P ha^{-1} would provide sustainable yields in the range of 1681 to 2146 kg ha^{-1} of sorghum and 74 to 76 kg ha^{-1} of cowpea under sorghum + cowpea system and 486 to 546 kg ha^{-1} of cotton and 180 to 236 kg ha^{-1} of black gram under cotton + black gram over the years. These treatments would also maintain maximum soil fertility with 0.38 to 0.44% of OC, 126 to 135 kg ha^{-1} of available soil N, 8.9 to 10.9 kg ha^{-1} of available soil P, and 392 to 411 kg ha^{-1} of available soil K over the years. However, because black gram is unsustainable, sorghum + cowpea could be rotated with cotton, attaining maximum productivity, sustainability, and maintenance of soil fertility under semi-arid Vertisols.

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