Statistical models for assessing sustainability of rainfed practices of crops from long term experiments

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In All India Coordinated Research Project for Dryland Agriculture (AICRPDA), field experiments are conducted on different research themes like rain water management, integrated nutrient management, energy management, cropping systems, crop improvement, alternate land use and integrated farming systems. Statistical models are developed for assessing the effects of soil, weather, crop and socio-economic parameters on yield of rainfed crops at different locations. Based on long term experiments conducted in the project, efficient statistical models are described in this paper for rainfed crops in different soil and agro-climatic conditions. The models were developed for the crop yield data over years with the objective of (i) efficient prediction of crop yield; (ii) assessing effects of crop seasonal rainfall on yield; (iii) assessing effects of soil fertility of nutrients on yield; (iv) combined model to assess the interactive effects of soil x rainfall x fertilizer variables on yield; (v) assessment of efficiency of treatments based on a sustainability yield index (SYI); and (vi) calibrating optimum fertilizer doses at varying soil fertility and crop seasonal rainfall situations. The modeling, treatment evaluation based on SYI procedure are described in this paper using permanent manorial trials conducted on finger millet at Bangalore in semi-arid alfisols.

Details of statistical modeling

The data of long–term experiments conducted for more than 15 years in permanent sites at different AICRPDA centers from 1984 onwards have been examined in the study. Multivariate statistical models have been explored for the data recorded on variables of different factors over years viz., (i) weather; (ii) soil; (iii) crop; and (iv) controllable variables like organic and inorganic fertilizer nutrients through different sources. The weather factor included variables like (i) daily, weekly, monthly, crop growing stages, seasonal (*kharif* and *rabi*) and annual rainfall; (ii) number of rainy days; (iii) minimum and maximum temperature; (iv) relative humidity; (v) evaporation; (vi) length and duration of dry spells (occurred from sowing to harvest). The soil factor comprised of variables like (i) soil moisture available at sowing, different crop growing stages and harvest; (ii) soil fertility of N, P, K and sulphur nutrients. The crop factor included variables like (i) date of sowing and harvest; (ii) crop growing period; (iii) plant uptake of N, P, K and sulphur nutrients; (iv) grain yield at harvest. The controllable factor included variables like (i) organic and inorganic fertilizer treatments; and (ii) variety. In order to homogenize the data, a classification has been made based on rainfall groups viz., < 500 mm (arid); 500 – 750 mm (dry semi-arid); 750 – 1000 mm (wet semi-arid); and 1000 – 1250 mm (dry sub-humid); 1250 – 1500 mm (moist sub-humid); and > 1500 mm (per humid) observed at each location in different years. The study has been explored with the objective of assessing the efficiency of input fertilizer treatments over years for (i) attaining sustainable crop yield and monetary returns; (ii) minimizing cost of cultivation of crops; and (iii) maintenance of maximum soil fertility of nutrients after harvest of crops.

Multivariate statistical assessment has been made based on input–output correlations of variables within a factor and also between factors. The sustainability of treatments was examined by de-trending the crop yields with efficient estimates of 'prediction error' measured based on statistical models of yield calibrated through variables of each of the four factors examined. The yield models were also calibrated with variables of different factors under each rainfall group and also over rainfall groups for different crops tested at different locations. The treatments were evaluated based on a 'Sustainability yield index' (SYI) as described by Vittal *et al.,* (2003) and modified by Behera *et al.,* (2007) and Nema *et al.,* (2008). An assessment of convergence of the mean yield attained by a treatment over years to the potential or maximum yield attained in the study period has been made for different crops. Based on the ranks assigned to mean, coefficient of variation, coefficient of determination, prediction error, SYI, apart from yield attained and soil fertility maintained in individual years, efficient fertilizer practices were identified for different crops at different locations. Optimum fertilizer doses at varying soil fertility and crop seasonal rainfall situations were derived using the models.

Statistical assessment of treatment effect on soil fertility and crop yield

The differences among treatments for their effect on soil fertility and yield in different crop seasonal rainfall situations could be tested based on the standard ANOVA procedure. Using Least Significant Difference criteria, the treatments which have a significantly higher influence on yield and soil fertility in each rainfall situation could be identified. Estimates of correlation of yield with crop duration, crop seasonal rainfall, soil and fertilizer nutrients could be derived for exploring multivariate models for testing influence of variables on yield in different rainfall situations. The effects of monthly rainfall (June to October) and crop growing period (CGP) on yield could be assessed by a regression model of each treatment as

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

Similarly, the effects of soil N (SN), soil P (SP) and soil K (SK) on yield could be assessed based on a curvi-linear model as described below :

$$Y = \pm \alpha \pm \beta 1 \text{ (SN)} \pm \beta 2 \text{ (SP)} \pm \beta 3 \text{ (SK)} \pm \beta 4 \text{ (SN}^2) \pm \beta 5 \text{ (SP}^2) \pm \beta 6 \text{ (SK}^2) \quad \ldots\ldots\ldots (2)$$

The effects of soil N (SN), soil P (SP), soil K (SK), fertilizer N (FN), fertilizer P (FP), fertilizer K (FK) and their interactions on yield could be assessed by calibrating a regression model of yield for each crop seasonal rainfall situation viz., arid (< 500 mm), dry semi-arid (500–750 mm), wet semi-arid (750–1000), dry sub-humid (1000–1250 mm), moist sub-humid (1250–1500) and per humid (> 1500 mm) situations as :

$$Y = \pm \alpha \pm \beta 1 \text{ (SN)} \pm \beta 2 \text{ (SP)} \pm \beta 3 \text{ (SK)} \pm \beta 4 \text{ (FN)} \pm \beta 5 \text{ (FN}^2) \pm \beta 6 \text{ (FP)} \pm \beta 7 \text{ (FP}^2) \pm \beta 8 \text{ (FK)} \pm \beta 9 \text{ (FK}^2) \pm \beta 10 \text{ (FN)(SN)} \pm \beta 11 \text{ (FP) (SP)} \pm \beta 12 \text{ (FK) (SK)} \quad \ldots\ldots\ldots\ldots (3)$$

In (1), (2) and (3), α is intercept and β's are regression coefficients of variables included in the model. Using mean yield of a treatment 'i' ($\bar{A}_i$); prediction error (Φ_i); and maximum yield (Y_{max}) attained under each rainfall situation, sustainability yield index (SYI) 'η' of a treatment could be derived as

$$\eta_i = [(\bar{A}_i - \Phi_i) / (Y_{max})] * 100 \quad \ldots\ldots\ldots (4)$$

Based on estimates of SYI, an efficient treatment with a maximum value could be identified for attaining a significantly higher yield and maintaining maximum soil fertility of nutrients in different rainfall situations. Using model (2), we can derive soil test based optimum fertilizer doses for attaining sustainable maximum yield and profit and maintain maximum soil fertility in different soil and agro-climatic situations.

Long-term field experiments conducted at different locations

The long term trials on different crops were conducted in varying soil and climatic conditions at different locations as detailed in Table 1. The experiments involved treatments comprising of 100% recommended dose of fertilizer (RDF); 50% RDF; combinations of organic and inorganic sources of N fertilizer; 100% N through organic source; and control. The organic sources of N fertilizer included FYM, glyricidia, sunhemp, leucaena, cassia, wheat straw, maize residue, groundnut shells, soybean residue, apart from farm residue of different crops at different locations.

Table 1. Permanent manorial trials conducted at different AICRPDA locations

Center	Climate	Soil	Crops	Year of start	Treat-ments	Source of organic N
Phulbani	Moist sub-humid	Alfisols	Rice-horse gram	1994	9	FYM, Glyricidia, Casia
Ranchi	Moist sub-humid	Alfisols	Rice-linseed	1988	7	FYM, Crop residue (wheat straw)
Varanasi	Dry sub-humid	Inceptisols	Rice-lentil	1985	8	FYM
Bijapur	Semi-arid	Vertisols	Sorghum-safflower	1984	9	FYM, Sunhemp
Solapur	Semi-arid	Vertisols	Sorghum	1985	10	FYM, Leucaena, Crop residue
Rakh Dhiansar	Dry sub-humid	Inceptisols	Maize	1995	10	FYM, Crop residue
Agra	Semi-arid	Inceptisols	Pearl millet	1984	8	FYM, Farm residue
SK Nagar	Semi-arid	Vertisols	Castor/pearl millet/cluster bean	1989	6	FYM
Bangalore	Semi-arid	Alfisols	Finger millet	1982	5	FYM, Maize residue
Anantapur	Arid	Alfisols	Groundnut	1986	10	FYM, Groundnut shells
Indore	Semi-arid	Vertisols	Soybean	1992	9	FYM, Soybean residue
Akola	Semi-arid	Vertisols	Cotton+ green gram	1987	8	FYM, Leucaena
Kovilpatti	Semi-arid	Vertic Inceptisols	Sorghum/pearl millet	1982	9	FYM, Farm residue

Out of different long term experiments conducted at AICRPDA centers, the results based on finger millet trials conducted at Bangalore center under semi-arid alfisols during 1984 to 2006 are described in the following sections.

Rainfall and its distribution at Bangalore

The earliest date of sowing of finger millet was on 14th July in 2004, while the latest was on 30th September in 2002. The earliest date of harvest of the crop was on 25th October in 2004, while the latest was on 3rd January in 2003. The crop had a minimum duration of 96 days in 2002 and maximum of 155 days in 1994 with a mean of 126 days and variation of 9.6%. The rainfall received from June to November was in a range of 396.6 mm in 1990 to 1174.7 mm in 2005. Four crop seasonal rainfall situations of < 500, 500–750, 750–1000 and 1000–1250 mm were observed during 1984 to 2006. The rainfall was < 500 mm in 3 years, 500–750 mm in 10 years, 750–1000 mm in 7 years and 1000–1250 mm in 3 years. June received a mean rainfall of 103.7, 70.1, 92.4 and 95.0 mm; while July received 53.5, 89.7, 112.2 and 91.9 mm; and August received 57.2, 105.3, 151.1 and 251.2 mm under < 500, 500–750, 750–1000 and 1000–1250 mm situations respectively. Similarly, September received a mean rainfall of 65.8, 200.6, 282.0 and 170.3 mm; while October received 105.2, 133.0, 197.2 and 435.4 mm; and November received 64.9, 40.2, 56.9 and 76.9 mm under the 4 rainfall situations respectively. It is observed that September rainfall had the lowest variation of 49.7%, while November rainfall had the highest variation of 87.7% in the 23 year study.

The mean crop seasonal rainfall in a month increased from < 500 mm group to 1000–1250 mm group. The variation of monthly rainfall was in a range of 37.6% for September to 62.9% for October under < 500 mm received in 3 years; while it ranged from 42.0% for July to 99.9% for June under 500–750 mm in 10 years. It ranged from 22.9% for September to 116.0% for November in 7 years under 750–1000 mm; and 38.6% for October to 107.5% for June under 1000–1250 mm received in 3 years. The mean crop growing period ranged from 121 days with variation of 17.9% under < 500 mm to 131 days with variation of 9.3% under 500–750 mm rainfall. The details of crop growing period, rainfall, date of sowing and harvest of finger millet under different crop seasonal rainfall situations are given in Table 2.

Table 2. Rainfall and sowing and harvest dates of finger millet during 1984 to 2006

Year	DOS	DOH	CGP	Jun	Jul	Aug	Sep	Oct	Nov	CRF
< 500 mm (3 years)										
1990	12-Aug	22-Dec	133	48.0	32.2	79.7	92.6	111.9	32.2	396.6
2002	30-Sep	3-Jan	96	150.4	44.0	31.8	43.8	167.8	52.2	490.0
2006	15-Jul	25-Nov	134	112.6	84.4	60.0	61.0	36.0	110.4	464.4
Mean			*121*	*103.7*	*53.5*	*57.2*	*65.8*	*105.2*	*64.9*	*450.3*
CV			*17.9*	*49.9*	*51.1*	*42.1*	*37.6*	*62.9*	*62.6*	*10.7*
500–750 mm (10 years)										
1984	23-Jul	27-Nov	128	70.4	103.7	131.2	200.0	148.1	57.9	711.3
1985	20-Jul	24-Nov	126	40.9	87.5	51.0	214.8	60.3	75.0	529.5
1986	21-Jul	21-Nov	124	153.0	74.1	70.0	333.6	28.0	59.6	718.3
1987	30-Jul	30-Nov	124	80.8	45.0	124.4	158.5	123.1	100.2	632.0
1989	18-Jul	12-Dec	148	9.3	154.4	48.2	283.0	193.4	22.6	710.9

1994	28-Jul	29-Dec	155	30.8	92.3	94.8	115.3	212.1	21.0	566.3
1995	4-Aug	4-Dec	123	36.4	86.6	189.4	75.9	126.4	26.6	541.3
1996	14-Aug	28-Dec	137	230.6	26.7	158.2	211.2	84.4	2.0	713.1
2001	31-Jul	5-Dec	128	18.8	136.0	78.1	347.6	121.8	32.6	734.9
2003	18-Jul	20-Nov	116	30.2	90.4	107.6	65.8	231.9	4.8	530.7
Mean			*131*	*70.1*	*89.7*	*105.3*	*200.6*	*133.0*	*40.2*	*638.8*
CV			*9.3*	*99.9*	*42.0*	*43.9*	*49.6*	*49.4*	*79.2*	*13.8*
750–1000 mm (7 years)										
1988	19-Jul	18-Nov	123	7.7	272.0	167.7	388.1	123.9	18.9	978.3
1992	6-Aug	30-Nov	117	167.6	135.8	98.6	194.2	107.6	70.8	774.6
1993	4-Aug	14-Dec	133	145.2	58.5	150.6	328.1	273.4	21.6	977.4
1997	27-Aug	28-Dec	124	53.0	30.4	67.8	294.9	316.8	193.8	956.7
1999	14-Aug	17-Dec	126	95.2	49.4	205.3	238.7	196.8	71.2	856.6
2000	4-Aug	7-Dec	126	104.8	97.3	312.4	239.8	168.4	5.8	928.5
2004	14-Jul	25-Oct	104	73.2	142.2	55.4	290.4	193.2	16.0	770.4
Mean			*122*	*92.4*	*112.2*	*151.1*	*282.0*	*197.2*	*56.9*	*891.8*
CV			*7.5*	*58.8*	*73.4*	*59.2*	*22.9*	*38.4*	*116.0*	*10.2*
1000–1250 mm (3 years)										
1991	6-Aug	12-Dec	129	212.9	21.1	152.2	66.9	540.9	152.2	1146.2
1998	29-Jul	29-Nov	124	32.0	132.2	352.2	245.7	241.7	37.5	1041.3
2005	23-Jul	21-Nov	122	40.2	122.4	249.2	198.2	523.6	41.1	1174.7
Mean			*125*	*95.0*	*91.9*	*251.2*	*170.3*	*435.4*	*76.9*	*1120.7*
CV			*2.9*	*107.5*	*66.9*	*39.8*	*54.4*	*38.6*	*84.8*	*6.3*

CGP: Crop growing period (days) CRF: Cumulative rainfall (mm)
CV: Coefficient of variation (%) DOS: Date of sowing DOH: Date of harvest

Effect of fertilizer treatments on soil nutrients and yield

Based on the ANOVA, fertilizer treatments differed significantly in influencing soil fertility of N, P and K and finger millet yield under all the 4 crop seasonal rainfall situations occurred during 1984 to 2006. The mean and variation of soil N, P and K nutrients and yield attained under different rainfall situations along with LSD at $p < 0.05$ level are given in Table 3.

Among 5 treatments tested in FYM block, FYM @ 10 t/ha + 100% NPK gave significantly higher yield and maintained maximum soil N, P and K nutrients under all the 4 rainfall situations. Maximum mean yield of 3545 kg/ha (variation of 20.8%) was attained under a crop seasonal rainfall of 500–750 mm (10 years), followed by 3183 kg/ha (11.9%) under 1000–1250 mm (3 years), 3145 kg/ha (16.5%) under 750–1000 mm (7 years), while significantly lower yield of 2239 kg/ha (16.7%) under < 500 mm (3 years). Maximum mean soil N of 210 kg/ha (14.9%) was maintained under 1000–1250 mm rainfall compared to 209 kg/ha (6.7%) under 500–750 mm, 206 kg/ha (5.2%) under < 500 mm and 200 kg/ha (3.5%) under 750–1000 mm rainfall. Maximum mean soil P of 168.0 kg/ha (15.6%) was maintained under 1000–1250 mm, followed by 157.6 kg/ha (20.7%) under 500–750 mm, 153.6 kg/ha (24.7%) under 750–1000 mm and 149.4 kg/ha (8.4%) under < 500 mm rainfall. Similarly, maximum mean soil K of 148 kg/ha (19.5%)

was maintained in < 500 mm, followed by 134 kg/ha (23.0%) in 500–750 mm, 131 kg/ha (11.8%) in 1000–1250 mm and 120 kg/ha (19.9%) in 750–1000 mm rainfall.

In MR block, MR @ 5 t/ha + 100% NPK was superior with a significantly higher yield, soil P and K nutrients under all rainfall situations. This treatment was also superior for soil N under < 500, 500–750 and 750–1000 mm, while MR @ 5 t/ha + 50% NPK was superior under 1000–1250 mm. The superior treatment gave highest mean yield of 3165 kg/ha (variation of 29.3%) under 500–750 mm, followed by 2453 kg/ha (26.5%) 750–1000 mm, 2086 kg/ha (11.9%) under 1000–1250 mm, while lowest yield of 1566 kg/ha (61.6%) was attained under < 500 mm rainfall. MR @ 5 t/ha + 50% NPK gave maximum mean soil N of 208 kg/ha (12.9%) under 1000–1250 mm; while MR @ 5 t/ha + 100% NPK gave 193 kg/ha (6.8%) under 500–750 mm, 190 kg/ha (6.1%) under < 500 mm and 179 kg/ha (9.6%) under 750–1000 mm rainfall. MR @ 5 t/ha + 100% NPK was superior for soil P with a maximum mean of 126.7 kg/ha (30.6%) under 1000–1250 mm, followed by 104.2 kg/ha (32.9%) under 750–1000 mm, 99.6 kg/ha (27.0%) under 500–750 mm and 95.5 kg/ha (15.5%) under < 500 mm rainfall. Similarly, maximum mean soil K of 110 kg/ha (10.3%) was maintained under < 500 mm, followed by 105 kg/ha (8.8%) under 1000–1250 mm, 102 kg/ha (16.9%) under 750–1000 mm and 102 kg/ha (25.3%) under 500–750 mm rainfall.

Table 3. Mean and variation of yield and soil nutrients

Treatment	Mean (Variation) yield and soil nutrients under different crop seasonal rainfall (mm)							
	< 500	500–750	750–1000	1000–1250	< 500	500–750	750–1000	1000–1250
	FYM block				MR block			
Yield (kg/ha)								
T1	532 (120.1)	767 (57.3)	424 (73.6)	172 (90.1)	497 (126.7)	1360 (91.0)	372 (99.3)	118 (73.1)
T2	1883 (34.0)	2690 (18.9)	2567 (14.9)	2283 (29.4)	935 (83.4)	1696 (74.0)	866 (70.9)	595 (72.6)
T3	2206 (7.3)	3092 (21.8)	3023 (8.2)	2880 (20.4)	1360 (70.6)	2402 (43.2)	1961 (19.6)	1630 (12.0)
T4	2239 (16.7)	3545 (20.8)	3145 (16.5)	3183 (11.9)	1566 (61.6)	3165 (29.3)	2453 (26.5)	2086 (11.9)
T5	1415 (63.1)	2290 (40.6)	1669 (39.3)	1315 (39.7)	1272 (83.5)	2631 (36.1)	1820 (46.2)	1408 (21.0)
LSD (5%)	768	363	448	962	439	348	393	392
Soil N (kg/ha)								
T1	166 (2.5)	170 (8.4)	164 (5.0)	160 (13.9)	154 (9.5)	154 (14.6)	150 (13.6)	166 (19.5)
T2	196 (4.7)	196 (9.4)	195 (3.8)	202 (2.4)	181 (7.1)	181 (5.7)	176 (8.8)	190 (13.8)
T3	196 (3.6)	197 (4.8)	195 (2.1)	196 (11.9)	185 (5.2)	186 (6.5)	173 (12.3)	208 (12.9)
T4	206 (5.2)	209 (6.7)	200 (3.5)	210 (14.9)	190 (6.1)	193 (6.8)	179 (9.6)	207 (16.6)

T5	194 (6.9)	198 (9.1)	190 (5.8)	187 (15.6)	182 (5.8)	184 (6.4)	173 (11.9)	196 (11.7)
LSD (5%)	2.8	5.2	8.3	25.4	3.5	11.2	8.3	25.2
Soil P (kg/ha)								
T1	23.2 (18.9)	19.6 (25.6)	20.8 (26.6)	21.1 (45.1)	30.5 (7.3)	32.4 (41.4)	27.4 (24.2)	22.1 (52.9)
T2	86.1 (24.5)	93.8 (33.2)	101.6 (32.4)	117.7 (17.5)	54.7 (20.1)	64.6 (25.2)	54.6 (29.9)	70.3 (9.5)
T3	124.1 (11.3)	125.4 (34.5)	137.1 (24.3)	151.9 (16.3)	73.7 (17.9)	78.3 (25.2)	84.0 (31.3)	92.6 (10.5)
T4	149.4 (8.4)	157.6 (20.7)	153.6 (24.7)	168.0 (15.6)	95.5 (15.5)	99.6 (27.0)	104.2 (32.9)	126.7 (30.6)
T5	100.0 (22.1)	112.0 (31.5)	113.0 (26.7)	127.4 (15.3)	89.6 (1.0)	85.7 (25.2)	91.4 (25.9)	94.8 (31.3)
LSD (5%)	20.0	17.0	18.3	23.8	15.2	13.2	15.6	35.0
Soil K (kg/ha)								
T1	79 (19.8)	69 (24.1)	65 (18.3)	75 (6.6)	72 (19.9)	60 (12.4)	68 (20.0)	60 (13.8)
T2	116 (15.1)	108 (15.6)	101 (21.6)	99 (16.5)	87 (6.3)	85 (14.3)	83 (12.1)	81 (17.4)
T3	124 (12.7)	119 (23.0)	106 (17.3)	112 (9.1)	98 (14.0)	88 (18.7)	87 (15.7)	93 (15.8)
T4	148 (19.5)	134 (23.0)	120 (19.9)	131 (11.8)	110 (10.3)	102 (25.3)	102 (16.9)	105 (8.8)
T5	103 (12.6)	97 (20.2)	91 (12.9)	89 (12.6)	95 (17.7)	82 (12.4)	85 (13.0)	90 (30.3)
LSD (5%)	11.6	15.3	12.6	16.7	8.2	10.3	11.2	18.2

FYM block: T1: Control T2: FYM @ 10 t/ha T3: FYM @ 10 t/ha + 50% NPK
T4 : FYM @ 10 t/ha + 100% NPK T5 : 100% NPK
MR block : T1 : Control T2 : MR @ 5 t/ha T3 : MR @ 5 t/ha + 50% NPK
T4 : MR @ 5 t/ha + 100% NPK T5 : 100% NPK

Regression model of yield with soil nutrients, crop growing period and rainfall

The estimates of the regression coefficients (β), the coefficient of determination (R^2), the prediction error (Φ) and the sustainable yield index (η) based on regression models calibrated for each fertilizer treatment in the FYM and MR blocks are given in Table 4. In the FYM block, the yield attained by 100% NPK had a maximum predictability of 0.83 with a prediction error of 492 kg/ha whereas FYM @ 5 t/ha had a minimum predictability of 0.36 and a prediction error of 475 kg/ha. July rainfall had a positive influence on yield of all treatments except in FYM @ 10 t/ha. August rainfall had a positive effect on yield attained by treatments FYM @ 10 t/ha + 50% NPK and FYM @ 10 t/ha + 100% NPK. September rainfall influenced the yield attained by treatment FYM @ 10 t/ha + 100% NPK, while October rainfall influenced the yield of treatment FYM @ 10 t/ha positively based on the regression model. November rainfall and crop growing period had a positive effect on yield attained by treatment 100% NPK, while crop growing period had a positive effect on the yield for the control treatment. Soil N had a positive effect on yield attained by treatments FYM @ 10 t/ha, FYM @ 10 t/ha + 50% NPK and FYM @ 10 t/ha + 100% NPK. Soil P had a positive effect on yield attained by treatments FYM @ 10 t/ha + 50% NPK and FYM @ 10 t/ha + 100% NPK. Soil K had a positive effect on yield attained by all treatments.

In the MR block, the grain yield attained by treatment MR @ 5 t/ha had a maximum and significant predictability of 0.87 with a prediction error of 565 kg/ha whereas treatment MR @ 5 t/ha + 50% NPK application had minimum of 0.33 with a prediction error of 991 kg/ha. July rainfall was beneficial to yield attained by treatments 100% NPK and MR @ 5 t/ha + 50% NPK, while August rainfall positively influenced yield of all treatments except the control. September rainfall increased grain yield of all treatments except treatment 100% NPK. Although the October rainfall had a negative effect, November rainfall and crop growing period had a positive effect on yield attained by all treatments. Soil N had a positive effect on yield attained by all treatments. Soil P had a positive effect on yield attained by treatment MR @ 5 t/ha and the control, while soil K had a positive effect on yield attained by treatment MR @ 5 t/ha + 100% NPK.

Table 4. Treatment-wise models of yield through rainfall and soil nutrients

Treatment	**Regression model**	**R^2**	**Φ**	**η**
FYM block				
Control	GY = –1480 + 3.1 (Jul RF) – 2.16 (Aug RF) – 1.27 (Sep RF) – 1.29 (Oct RF) + 5.16* (Nov RF) + 16.23* (CGP) – 3.38 (SN) – 2.39 (SP) + 12.91 (SK)	0.65*	371	4.0
FYM @ 10 t/ha	GY = 157 – 0.69 (Jul RF) – 0.47 (Aug RF) – 0.08 (Sep RF) + 1.49 (Oct RF) + 1.34 (Nov RF) + 7.69 (CGP) + 5.37 (SN) – 3.9 (SP) + 5.87 (SK)	0.36	475	44.4
FYM @ 10 t/ha + 50% NPK	GY = −4775 + 2.87 (Jul RF) + 2.07 (Aug RF) – 0.05 (Sep RF) – 0.15 (Oct RF) + 2.66 (Nov RF) + 10.27 (CGP) + 20.21 (SN) + 2.26 (SP) + 13.99 (SK)	0.41	501	53.3
FYM @ 10 t/ha + 100% NPK	GY = −3747 + 3.61 (Jul RF) + 1.32 (Aug RF) + 0.98 (Sep RF) – 0.87 (Oct RF) + 4.08* (Nov RF) + 14.95 (CGP) + 8.44 (SN) + 3.75 (SP) + 15.51* (SK)	0.56*	614	56.9
100% NPK	GY = −219 + 2.67 (Jul RF) – 0.77 (Aug RF) – 0.48 (Sep RF) – 2.18 (Oct RF) + 7.85* (Nov RF) + 30.43** (CGP) – 0.99 (SN) – 18.57** (SP) + 4.07 (SK)	0.83**	492	30.1
MR block				
Control	GY = –2414 – 0.01 (Jul RF) – 0.01 (Aug RF) + 0.69 (Sep RF) – 1.69 (Oct RF) + 1.41 (Nov RF) + 13.38 (CGP) + 5.57 (SN) + 58.98* (SP) – 13.35 (SK)	0.69*	825	−0.9
MR @ 5 t/ha	GY = 3324 – 3.71 (Jul RF) + 0.25 (Aug RF) + 0.16 (Sep RF) – 5.44** (Oct RF) + 5.71* (Nov RF) + 36.11** (CGP) + 0.01 (SN) + 15.57 (SP) – 78.59** (SK)	0.87**	565	13.8
MR @ 5 t/ha + 50% NPK	GY = −1666 + 0.63 (Jul RF) + 1.32 (Aug RF) + 0.81 (Sep RF) – 4.01 (Oct RF) + 6.79 (Nov RF) + 15.11 (CGP) + 13.68 (SN) – 2.81 (SP) – 4.7 (SK)	0.33	991	22.7

MR @ 5 t/ha + 100% NPK	GY = −3566 – 0.23 (Jul RF) + 1.49 (Aug RF) + 0.17 (Sep RF) – 2.32 (Oct RF) + 9.16 (Nov RF) + 32.85 (CGP) + 14.96 (SN) – 11.59 (SP) + 2.64 (SK)	0.51	893	37.2
100% NPK	GY = −681 + 1.45 (Jul RF) + 0.58 (Aug RF) – 1.12 (Sep RF) – 4.87* (Oct RF) + 7.49* (Nov RF) + 42.27* (CGP) + 0.95 (SN) – 10.65 (SP) – 14.12 (SK)	0.62*	864	25.8

RF: Rainfall (mm); CGP: Crop growing period; SN: Soil N (kg/ha); SP: Soil P (kg/ha); SK: Soil K (kg/ha)
R^2: Coefficient of determination; Φ: Prediction error (kg/ha); η: Sustainable yield index
* and ** indicate significance at 5 and 1% level, respectively

Prediction models of yield under different crop seasonal rainfall situations

The estimates of regression coefficients (β) of rainfall, soil and fertilizer nutrients, coefficient of determination (R^2) and prediction error (Φ) of yield were determined based on multivariate regression model of yield calibrated through different variables as postulated in (1) for different crop seasonal rainfall situations and are given in Table 5. Using regression models, fertilizer adjustment equations described in (2) to (4) have been derived for optimizing soil test based fertilizer doses for attaining sustainable finger millet yield under different rainfall situations.

In FYM block, the model gave a significant yield predictability of 0.96** under 1000–1250 mm rainfall, followed by 0.93** under < 500 mm, 0.91** under 750–1000 mm and 0.79** under 500–750 mm rainfall situations. A minimum prediction error of 356 kg/ha was observed under < 500 mm, followed by 403 kg/ha under 750–1000 mm, 434 kg/ha under 1000–1250 mm and 599 kg/ha under 500–750 mm rainfall. The crop seasonal rainfall and soil P had a positive effect on yield under < 500, 750–1000 and 1000–1250 mm, while they had a negative effect under 500–750 mm rainfall. However, crop seasonal rainfall was significant under 500–750 and 1000–1250 mm, while soil P was significant under 750–1000 and 1000–1250 mm rainfall. Soil N had a positive effect on yield under 500–750 and 750–1000 mm, while it had a negative effect under < 500 and 1000–1250 mm rainfall. Soil K had a positive effect on yield under < 500 and 500–750 mm and negative effect under 750–1000 and 1000–1250 mm rainfall. However, the effects of soil N and K on yield were significant only under < 500 mm rainfall situation. Application of FYM, fertilizer N and P had a significant positive effect on yield under all rainfall situations, except the FYM effect under 1000–1250 mm situation. Fertilizer K had a significant positive effect under < 500 and 500–750 mm and non-significant negative effect under 750–1000 and 1000–1250 mm rainfall situations.

In MR block, the model gave a significant yield predictability of 0.98** under < 500 mm rainfall, followed by 0.97** under 1000–1250 mm, 0.73** under 750–1000 mm and 0.61* under 500–750 mm rainfall. A minimum prediction error of 207 kg/ha was observed under < 500 mm, followed by 265 kg/ha under 1000–1250 mm, 590 kg/ha under 750–1000 mm and 862 kg/ha under 500–750 mm rainfall. The crop seasonal rainfall had a non-significant positive effect on yield under 500–750, 750–1000 and 1000–1250 mm, while it had a significant negative effect under < 500 mm rainfall. Soil N had a positive effect on yield under all the 4 situations, but was significant only under < 500 mm rainfall. Soil P had a positive effect and soil K had a negative effect on yield under all rainfall situations except < 500 mm. But the effect of soil P was significant only under 500–750 mm, while soil K was significant under 500–750 and 750–1000 mm rainfall. Fertilizer N and P had a positive effect on yield under all situations, but were significant only under 750–1000 and 1000–1250 mm situations. Application of MR had a significant positive effect on yield in all situations except < 500 mm. Fertilizer K had a positive effect on yield under 500–750 and 1000–1250 mm and negative effect under < 500 and 750–1000 mm rainfall, but was significant only under 500–750 mm situation.

Table 5. Regression models of yield through rainfall, soil and fertilizer nutrients

Rain fall (mm)	Regression model	R^2	Φ	Fertilizer equations
FYM block				
< 500	Y = 50287 + 14.3 (CRF) – 377.9* (SN) + 20.3 (SP) + 76.6* (SK) + 67.5* (FN) – 1.1 (FN^2) + 67.5* (FP) – 1.1 (FP^2) + 457.9* (FK) + 20.8* (FK^2) + 857.5* (FYM) – 0.47 (FNSN) – 1.75* (FPSP) – 2.97* (FKSK)	0.93**	356	FN = 31 – 0.21 SN FP = 31 – 0.80 SP FK = #
500–750	Y = 1104 – 3.5** (CRF) + 9.9 (SN) – 5.02 (SP) + 5.1 (SK) + 85.3** (FN) – 1.23* (FN^2) + 85.3** (FP) – 1.23* (FP^2) + 136.5* (FK) + 1.1 (FK^2) + 183.2** (FYM) – 0.11 (FNSN) – 0.17* (FPSP) – 0.22 (FKSK)	0.79**	599	FN = 35 – 0.04 SN FP = 35 – 0.07 SP FK = #
750–1000	Y = –2222 + 1.5 (CRF) + 7.6 (SN) + 10.6* (SP) – 2.7 (SK) + 103.9** (FN) – 1.72** (FN^2) + 103.9** (FP) – 1.72** (FP^2) – 34.3 (FK) – 0.45 (FK^2) + 115.3** (FYM) + 0.18 (FNSN) – 0.28* (FPSP) + 0.51* (FKSK)	0.91**	403	FN = # FP = 30 – 0.08 SP FK = #
1000 – 1250	Y = –5541 + 1.5* (CRF) – 21.1 (SN) + 27.1* (SP) – 20.6 (SK) + 111.8* (FN) – 1.83* (FN^2) + 111.8* (FP) – 1.83* (FP^2) – 257.1 (FK) + 0.46 (FK^2) + 90.0 (FYM) + 0.36 (FNSN) + 0.12 (FPSP) + 0.52 (FKSK)	0.96**	434	FN = # FP = # FK = #
MR block				
< 500	Y = 171 – 12.4* (CRF) + 38.6* (SN) – 13.0 (SP) + 5.1 (SK) + 37.4 (FN) – 0.47 (FN^2) + 37.4 (FP) – 0.47 (FP^2) – 46.1 (FK) – 2.14 (FK^2) – 72.9 (MR) + 0.74 (FNSN) + 0.16 (FPSP) + 0.88* (FKSK)	0.98**	207	FN = # FP = # FK = #
500–750	Y = 2875 + 0.07 (CRF) + 6.3 (SN) + 28.4* (SP) – 60.2** (SK) + 42.6 (FN) – 0.30 (FN^2) + 42.6 (FP) – 0.30 (FP^2) + 243.5 (FK) + 3.65* (FK^2) + 213.3* (MR) – 0.70 (FNSN) – 1.02** (FPSP) + 1.78** (FKSK)	0.61*	862	FN = 71 – 1.17 SN FP = 71 – 1.70 SP FK = #
750–1000	Y = 232 + 1.07 (CRF) + 3.8 (SN) + 4.9 (SP) – 21.7* (SK) + 76.9** (FN) – 0.93* (FN^2) + 76.9** (FP) – 0.93* (FP^2) – 43.3 (FK) – 2.66 (FK^2) + 99.3* (MR) + 0.21 (FNSN) + 0.04 (FPSP) + 0.97 (FKSK)	0.73**	590	FN = # FP = # FK = #

1000-1250	Y = –662 + 0.81 (CRF) + 5.56 (SN) + 0.74 (SP) – 18.03 (SK) + 74.0** (FN) – 0.93* (FN^2) + 74.0** (FP) – 0.93* (FP^2) + 97.7 (FK) – 1.98 (FK^2) + 141.7* (MR) – 0.08 (FNSN) – 0.03 (FPSP) + 0.58 (FKSK)	0.97**	265	FN = 40 – 0.04 SN FP = 40 – 0.02 SP FK = #

* & ** indicate significance at 5 & 1% level R^2 : Coefficient of determination
Φ : Prediction error (kg/ha) # indicates calibration not possible due to non-diminishing response

Sustainability of treatments under different rainfall situations

Estimates of SYI were derived for assessing performance of treatments in each rainfall situation and are given in Table 6. FYM @ 10 t/ha + 100% NPK gave maximum potential yield of 4552 kg/ha in FYM block and MR @ 5 t/ha + 100% NPK gave 4591 kg/ha in MR block during 1984 under a crop seasonal rainfall of 711.3 mm. Based on SYI, FYM @ 10 t/ha + 100% NPK was superior in FYM block with maximum SYI of 64.7% in 500–750 mm, followed by 60.4% under 1000–1250 mm, 60.2% in 750–1000 mm and 41.4% in < 500 mm rainfall. FYM @ 10 t/ha + 50% NPK was 2nd best with SYI of 57.6% under 750–1000 mm, 54.8% under 500–750 mm, 53.7% under 1000–1250 mm and 40.6% under < 500 mm. Similarly, MR @ 5 t/ha + 100% NPK was superior in MR block with SYI of 50.2% under 500–750 mm, followed by 40.6% under 750–1000 mm, 39.7% under 1000–1250 mm and 29.6% under < 500 mm rainfall. MR @ 5 t/ha + 50% NPK was the 2nd best treatment with SYI of 29.9% under 750–1000 mm, 29.7% under 1000–1250 mm and 25.1% under < 500 mm, while 100% NPK was 2nd best with 38.5% under 500–750 mm rainfall. Application of inorganic fertilizer in combination with FYM was superior to MR in all rainfall situations occurred in the study.

Table 6. Sustainable yield index of treatments under different rainfall situations

Treatments	SYI under different crop seasonal rainfall (mm) situations			
	< 500	500–750	750–1000	1000–1250
FYM block				
Control	3.9	3.7	0.5	-5.8
FYM @ 10 t/ha	33.5	45.9	47.5	40.6
FYM @ 10 t/ha + 50% NPK	40.6	54.8	57.6	53.7
FYM @ 10 t/ha + 100% NPK	41.4	64.7	60.2	60.4
100% NPK	23.3	37.1	27.8	19.4
MR block				
Control	6.3	10.8	-4.7	-3.2
MR @ 5 t/ha	15.9	18.2	6.0	7.2
MR @ 5 t/ha + 50% NPK	25.1	33.5	29.9	29.7
MR @ 5 t/ha + 100% NPK	29.6	50.2	40.6	39.7
100% NPK	23.2	38.5	26.8	24.9

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