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Selection of Superior Tillage and Fertilizer Practices Based on Rainfall and Soil Moisture Effects on Pearl Millet Yield under Semiarid Inceptisols

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Abstract: Based on seven field experiments of pearl millet with nine treatment combinations of tillage and fertilizer nutrients conducted during 2000–2006 in a semiarid inceptisol at Agra, an assessment is made in this paper about sustainability of treatments using rainfall received during the crop growing period and available soil moisture at sowing, 20, 40, and 60 days after sowing (DAS) and harvest. Three practices, each of tillage: conventional tillage+mechanical weed control, low tillage+mechanical weed control, and low tillage+mechanical weed control+herbicide; and fertilizer application of 60 kg N [farm yard manure (FYM)]+40 kg P/ha, 30 kg N (FYM)+30 kg N (urea)+40 kg P/ha and 60 kg N (urea)+40 kg P/ha were tested in the same site over seven years. The F-test indicated significant soil moisture differences on different DAS and also between different tillage treatments. Significant yield differences were found among treatments of tillage and fertilizer and their interaction in all seasons, except 2001 and 2002. Treatment-wise correlation of yield with monthly rainfall received in June–September and available soil moisture on different DAS indicated that September rainfall had a negative and significant correlation with yield attained by tillage and fertilizer treatments. The soil moisture at 20 DAS had a negative and significant correlation with yield under all treatments except conventional tillage+mechanical weed control. The soil moisture at 60 DAS and harvest had a positive and significant correlation with yield attained under different tillage and fertilizer treatments. Regression models of yield were calibrated for tillage and fertilizer treatments through monthly rainfall during July–September and soil moisture on different DAS. The predictability of yield improved significantly by inclusion of both rainfall and soil moisture variables in the models compared to either of the two groups of variables. Ranks were assigned to tillage and fertilizer treatments for yield attained in individual years and mean yield, prediction error, and sustainable yield index over years. The study indicated that conventional tillage+mechanical weed control among tillage together with 30 kg N (FYM)+30 kg N (urea)+40 kg P/ha was superior with a minimum rank sum compared to other treatments. The treatment gave a maximum sustainable yield of 1,683 kg/ha with a net return of Rs 5,670 ha, benefit–cost ratio of 1.16, and sustainable yield index of 47.2% under semiarid inceptisols of Agra.

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Introduction

Pearl millet (*Pennisetum americannum L.*) is an important cereal grown under rainfed conditions in different states of India. It is grown in monsoon season (June to September) in different states as a rainfed crop. During 2004–2005, it was grown in an area of 9.26 million hectares and attained a production of 8.11 million tons with a productivity of 876 kg/ha in the country. Pearl millet is grown both as a sole crop and also in combination with other rained crops as an intercrop. In drylands, apart from rainfall and available soil moisture, the grain yield of a crop is greatly influenced by tillage and fertilizer practices. The quantity of rainfall and its distribution would greatly influence the effects of tillage and fertilizer on crop yield. The farmers adopt conventional tillage together with a below optimum level of fertilizer for different crops grown under rainfed conditions. Maruthi Sankar et al., (2006) assessed the efficiency of tillage and fertilizer practices for different rainfed crops grown under varying soil and agroclimatic situations in India. Sharma et al., (2003) assessed the effects of tillage and fertilizer nutrients on rainfed sorghum under shallow alfisols. In a paper by Prihar and Gajri (1988), the authors examined the usefulness of fertilization of rainfed crops under dryland conditions. Venkateswarlu and Singh (1982) reviewed the soils researched in India and described responses of different rainfed crops to applied nutrients under limited water conditions.

There is a need to identify a superior tillage together with a fertilizer practice for attaining a sustainable productivity of pearl millet under semiarid inceptisols. Although pearl millet has a lower water requirement compared to other rainfed crops, there is a need to correctly identify a suitable tillage and fertilizer practice for attaining a stable and sustainable yield under rainfed conditions. The regression models discussed by Draper and Smith (1998) and Maruthi Sankar (1986, 1992) would be useful for

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Table 1. Distribution of Rainy Days and Rainfall Occurring in the Kharif Season at Agra

				June		July		August		September		Total	
Year	DOS	DOH	CGP	Rainfall (mm)	Rainy days	Rainfall (mm)	Rainy days	Rainfall (mm)	Rainy days	Rainfall (mm)	Rainy days	Rainfall (mm)	Rainy days
2000	July 6	September 28	85	150	6	93	15	141	10	54	5	439	36
2001	July 12	October 11	90	49	7	192	14	57	5	170	3	467	29
2002	August 18	October 25	60	13	1	43	5	224	11	198	4	478	21
2003	July 17	September 30	76	36	3	315	13	41	4	129	6	521	26
2004	July 12	October 10	91	24	5	120	7	310	14	28	3	481	29
2005	August 4	October 19	77	10	2	482	17	100	4	46	6	638	29
2006	July 17	September 30	76	12	1	306	8	34	3	0	0	352	12
Mean	—	—	81	42	4	222	11	130	7	89	4	482	26
CV	—	—	10	119	68	70	40	80	59	85	55	18	29

Note: DOS=date of sowing; DOH=date of harvest; CGP=crop growing period; and CV=coefficient of variation (%).

describing the effects of rainfall and soil moisture on crop yield and thereby assessing the superiority of tillage and fertilizer practices for pearl millet under rainfed conditions. The sustainability of tillage and fertilizer treatments could be assessed based on the procedure discussed by Vittal et al. (2002, 2003).

Materials and Methods

Seven field experiments on pearl millet (*Pennisetum americannum L.*) with variety "MBH-163" were conducted in the kharif season during 2000–2006 under a sandy loam inceptisol at Agra. The experiments were conducted with nine treatments based on combinations of three treatments each of tillage and fertilizer in the research farm at Raja Balwant Singh (RBS) College, Bichpuri, Agra under the All India Coordinated Research Project for Dryland Agriculture. Agra is situated at a latitude of 27.2° North, longitude of 77.9° East, and an altitude of 163.4 m above mean sea level. The crop was grown at a spacing of 45 cm in a net plot size of 4.5 m×5 m in each season. The experiments were conducted in a split-plot design with three replications. The field was divided into three main plots and each main plot was further divided into three subplots under each replication. The tillage treatments were superimposed to the main plots and fertilizer treatments were superimposed to the subplots. All agronomic practices recommended for the crop were adopted (Vittal et al., 2004). The tillage treatments comprised of (1) conventional tillage+mechanical weed control; (2) low tillage+mechanical weed control; and (3) low tillage+mechanical weed control +herbicide. The mechanical weed control was carried out by "hand hoe" to remove weeds. The conventional tillage comprised of a summer ploughing, three ploughings with a disk harrow after effective rainfall and mechanical weed control at 20 and 40 days after sowing. The "summer ploughing" is the ploughing operation carried out just before the onset of monsoon by primary tillage implement viz., disk plough. The depth of summer ploughing is about 20 cm and is carried out for aeration of soil, weed control and harvest of premonsoon showers. The low tillage+mechanical weed control treatment comprised of two ploughings with a disk harrow and mechanical weed control at 20 days after sowing. The low tillage+mechanical weed control +herbicide treatment comprised of two ploughings with a disk harrow, mechanical weed control at 20 days after sowing and application of herbicide.

A recommended fertilizer dose of 60 kg N (urea) +40 kg P/ha is normally applied for pearl millet at the time of sowing. In the present study, the fertilizer treatments comprised of application of (1) 60 kg N/ha through farm yard manure (FYM); (2) 30 kg N/ha (FYM)+30 kg N/ha (urea); and (3) 60 kg N/ha (urea) at the time of sowing. The study was conducted with the objective of assessing the effects of (1) monthly rainfall received during July to September and available soil moisture at sowing, and 20, 40, and 60 days after sowing and harvest on yield; and (2) selection of a superior tillage and fertilizer treatment for attaining a sustainable pearl millet yield under semiarid inceptisols.

Rainfall and Its Distribution in Different Years

The details of the dates of sowing and harvest of pearl millet, crop growing period, number of rainy days, and rainfall occurred during June to September in different years along with the mean and coefficient of variation of different variables are given in Table 1. During the last 40 years, Agra received a mean annual rainfall of 665 mm from 35 rainy days. Out of this rainfall, about 80% (538 mm) was normally received during July to September. Out of a rainfall of 538 mm, 28% (186 mm) was received in July, 39% (262 mm) in August, and 13% (90 mm) in September. In the present study, the rainfall occurred on a minimum of 12 days in 2006 to a maximum of 36 days in 2000. In July, a minimum rainfall of 43 mm was received in 2002 compared to a maximum of 482 mm in 2005. The August rainfall ranged from 34 mm in 2006 to 310 mm in 2004, while September had no rainfall in 2006 compared to a maximum of 198 mm in 2002. June received a rainfall of 10–49 mm during 2001–2006, while it had a high rainfall of 150 mm in 2000.

A minimum crop seasonal rainfall of 352 mm was received in 2006 compared with a maximum of 638 mm in 2005 in the study. Except for 2006, the cumulative rainfall of June–September received in different years was in convergence with the mean rainfall received in this period over seven years. However, a comparison of the actual monthly rainfall received in each of the seven years with the mean rainfall of the respective month indicated that an above mean rainfall was received in June of 2000 and 2001; July of 2003, 2005, and 2006; August of 2000, 2002, and 2004; and September of 2001, 2002, and 2003. Depending on the onset of monsoons, the earliest date of sowing was on July 6, 2000, while the latest was on August 18, 2002. Similarly, depending on the withdrawal of monsoons, the earliest date of harvest was on September 28, 2000, while the latest was on October 25, 2002. The crop had a minimum duration of 69 days in 2002 and a maximum of 91 days in 2004 in the seven year study.

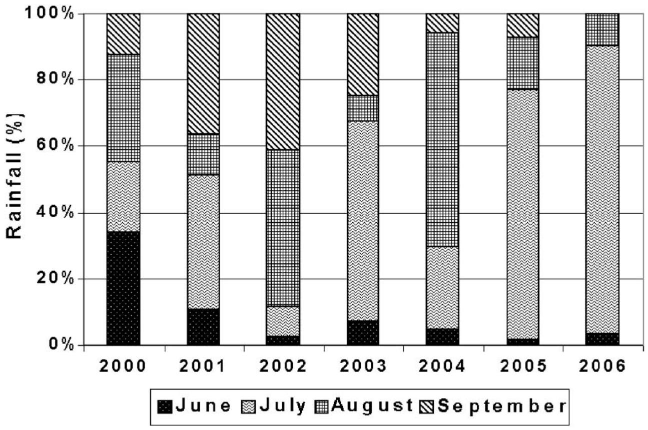

Fig. 1. Rainfall (%) of annual rainfall received during June to September at Agra

The erratic distribution of rainfall at Agra is depicted in Fig. 1 based on the cumulative percent of monthly rainfall received in different years. The monthly rainfall varied in different years and the cumulative rainfall of June–September was below normal in six out of seven years in the study. Out of seven years, June received 34% of crop seasonal rainfall in 2000, while it was less than 10% in the remaining six years. June and July put together received about 90% of crop seasonal rainfall in 2006, compared with 77% in 2005, 67% in 2003, 55% in 2000, 51% in 2001, 30% in 2004, and only 12% in 2002. June, July, and August put together received 100% of crop seasonal rainfall in 2006, compared with 94% in 2004 and 2005, 87% in 2000, 76% in 2003, 63% in 2001, and 59% in 2002. September received about 41% of crop seasonal rainfall in 2002, while there was 36% in 2001, 25% in 2003, 12% in 2000, and less than 10% in 2004, 2005, and 2006.

Selection of Superior Tillage and Fertilizer Treatments for Sustainable Crop Yield

The F-test based on analysis of variance (ANOVA) was used for testing the differences in soil moisture observed on different days after sowing (DAS) and yield attained under nine treatment combinations of tillage and fertilizer and their interaction (Kempthorne 1952; Gomez and Gomez 1985). Based on least-significant-difference (LSD) criteria, a superior tillage and fertilizer combination that provided a significantly higher soil moisture on different days after sowing and pearl millet yield could be identified. Regression models of yield could be calibrated as a function of monthly rainfall, available soil moisture on different days after sowing for tillage, and fertilizer treatments tested in the study (Draper and Smith 1998; Maruthi Sankar 1986). Since the earliest date of sowing of the crop was in July, inclusion of monthly rainfall received during July to September would provide meaningful models for predicting yield and assessing the sustainability of treatments. The regression models of yield could be postulated as a function of (a) monthly rainfall received during July to September; (b) soil moisture observed at sowing, 20, 40, and 60 DAS, and harvest; and (c) both monthly rainfall and soil moisture variables. The models are useful for prediction of yield; assessing the effects of monthly rainfall and available soil moisture on yield; and identifying a superior tillage and fertilizer treatment for attaining a sustainable pearl millet yield under semiarid inceptisols.

The regression models of yield postulated through variables of rainfall (RF) and soil moisture (SM) at sowing, 20, 40, and 60 days after sowing and harvest for tillage and fertilizer treatments are as follows:
Rainfall

$$Y = \pm\alpha \pm \beta1(\text{July}) \pm \beta2(\text{August}) \pm \beta3(\text{September}) \quad (1)$$

Soil moisture

$$Y = \pm\alpha \pm \beta1(\text{SMS}) \pm \beta2(\text{SM20}) \pm \beta3(\text{SM40}) \pm \beta4(\text{SM60}) \pm \beta5(\text{SMH}) \quad (2)$$

Rainfall and soil moisture

$$Y = \pm\alpha \pm \beta1(\text{July}) \pm \beta2(\text{August}) \pm \beta3(\text{September}) \pm \beta4(\text{SMS}) \pm \beta5(\text{SM20}) \pm \beta6(\text{SM40}) \pm \beta7(\text{SM60}) \pm \beta8(\text{SMH}) \quad (3)$$

In Models (1), (2), and (3), α=intercept; and β=regression coefficients of monthly rainfall and available soil moisture variables. The regression coefficients are tested based on a t-test by comparing with their standard errors in each model (Snedecor and Cochran 1967). We can assess the regression models based on the estimates of coefficients of determination (R^2) and prediction error (Φ) derived under each model. Using prediction errors of tillage and fertilizer treatments under each model, a combined prediction error of each of the nine treatment combinations of tillage and fertilizer could be derived as a mean of errors attained by the respective tillage and fertilizer components in the treatment. The combined prediction error would be useful for measuring the sustainable yield index of each treatment and selection of a superior treatment.

Sustainable Yield Index of Tillage and Fertilizer Treatments

The sustainable yield index (η) of a tillage and fertilizer treatment combination "i" can be computed using the treatment mean yield "$\bar{A}_i$" over seven years; combined prediction error "Φ_i" of the treatment based on a regression model; and maximum yield "$Y_{\max}$" attained by any treatment in the study period (Vittal et al., 2002, 2003; Maruthi Sankar et al., 2006). The sustainable yield index of treatment i can be given as

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

A treatment that has a maximum η value could be selected for attaining a sustainable crop yield under a given soil and agroclimatic situation.

Ranks could be assigned to treatments for the yield attained in different years, mean yield, combined prediction error, and sustainable yield index based on regression models of yield postulated in Eqs. (1)–(3). Based on rank sum, a treatment combination of tillage and fertilizer with the lowest rank sum could be selected for attaining a sustainable pearl millet yield at Agra under semiarid inceptisols.

Distribution of Soil Moisture on Different Days after Sowing

The soil moisture (mm) was recorded from 0 to 20, 20 to 40 and 40 to 60 cm soil depth in different tillage and fertilizer treatments on different DAS based on a gravimetric method. The mean and

Table 2. Soil Moisture on Different Days after Sowing of Pearl Millet under Tillage and Fertilizer Treatments at Agra

	60 kg N (FYM)+40 kg P/ha		30 kg N (FYM)+30 kg N (urea)+40 kg P/ha		60 kg N (urea)+40 kg P/ha		Mean	
Treatment	Mean	CV	Mean	CV	Mean	CV	Mean	CV
(a) Soil moisture at sowing								
CT+MWC	232	3.3	231	3.4	230	3.2	231	3.3
LT+MWC	224	3.3	223	3.3	222	3.1	223	3.2
LT+MWC+HERB	223	5.2	222	5.4	221	5.2	222	5.3
Mean	226	3.9	225	4.0	224	3.8	225	3.9
(b) Soil moisture at 20 DAS								
CT+MWC	235	4.4	234	4.3	232	4.6	234	4.4
LT+MWC	229	5.0	227	4.8	225	5.3	227	5.0
LT+MWC+HERB	228	5.1	227	5.1	225	5.4	227	5.2
Mean	231	4.8	229	4.7	227	5.1	229	4.9
(c) Soil moisture at 40 DAS								
CT+MWC	223	7.5	222	7.4	220	7.4	222	7.4
LT+MWC	218	8.7	217	8.6	215	8.6	217	8.6
LT+MWC+HERB	218	7.1	216	7.1	215	7.0	216	7.1
Mean	220	7.8	218	7.7	217	7.7	218	7.7
(d) Soil moisture at 60 DAS								
CT+MWC	183	13.8	182	14.5	181	15.0	182	14.4
LT+MWC	178	14.5	177	15.2	176	15.7	177	15.1
LT+MWC+HERB	178	13.3	177	14.0	176	14.5	177	13.9
Mean	180	13.9	179	14.6	178	15.1	179	14.5
(e) Soil moisture at harvest								
CT+MWC	149	10.8	148	11.1	146	12.8	148	11.6
LT+MWC	145	11.8	144	12.1	142	13.9	144	12.6
LT+MWC+HERB	145	11.2	144	11.6	142	13.3	144	12.0
Mean	146	11.3	145	11.6	143	13.3	145	12.1
(f) Overall								
CT+MWC	204	8.0	203	8.1	202	8.6	203	8.2
LT+MWC	199	8.7	198	8.8	196	9.3	198	8.9
LT+MWC+HERB	198	8.4	197	8.6	196	9.1	197	8.7

Note: CT=conventional tillage; LT=low tillage; MWC=mechanical weed control; and HERB=herbicide. Soil moisture in tillage treatments: LSD ($p<0.05$)=4.3; LSD ($p<0.01$)=5.6. Soil moisture on different days after sowing: LSD ($p<0.05$)=5.5; LSD ($p<0.01$)=7.3.

coefficient of variation (%) of soil moisture in different treatments at sowing, 20, 40, and 60 DAS, and harvest during 2000–2006 along with the LSD values at $p<0.05$ and $p<0.01$ levels of significance are given in Table 2. The F-test indicated that there was a significant difference between soil moisture values observed under different tillage treatments and also on different days after sowing. However, there was no significant difference between the soil moisture values observed in different fertilizer treatments, and interaction of tillage and fertilizer on different days after sowing in the study.

Graphical plots of soil moisture at sowing, 20, 40, and 60 DAS, and harvest during 2000–2006 are given in Figs. 2(a–e), respectively. The soil moisture ranged from 204 to 243 mm at sowing, 208 to 240 mm at 20 DAS, 195 to 246 mm at 40 DAS, 144 to 212 mm at 60 DAS, and 102 to 166 mm at harvest in the study. The conventional tillage+mechanical weed control with either 60 kg N (FYM)+40 kg P/ha or 30 kg N (FYM)+30 kg N (urea)+40 kg P/ha provided a relatively higher soil moisture at sowing, 20, 40, and 60 DAS, and harvest in different years. The soil moisture at sowing was lower in all treatments in 2001, 2003, and 2006 compared to the immediate preceding year. The soil moisture at 20 DAS was uniform in 2000, 2001 and 2002, decreased in 2003 and increased from 2004 onwards. The soil moisture at 40 DAS was uniform in 2000 and 2001, decreased in 2003 and increased in the subsequent years with a marginal decrease in 2005 compared to 2004. The soil moisture at 60 DAS and harvest of pearl millet decreased in 2001 and 2002 compared to 2000, increased in 2003 and 2004, and decreased in the subsequent years in all treatments in the study.

Results and Discussion

Effect of Tillage and Fertilizer Treatments on Pearl Millet Yield in Different Years

The pearl millet yield varied from season to season due to an erratic distribution of rainfall during crop growing period, differences in soil moisture, tillage, and fertilizer treatments. A minimum yield of 575 kg/ha was attained with low tillage +mechanical weed control together with 30 kg N (FYM) +30 kg N (urea)+40 kg P/ha in 2001, while a maximum yield of 2,982 kg/ha was attained with conventional tillage+mechanical weed control together with 60 kg N (urea)+40 kg P/ha in 2000.

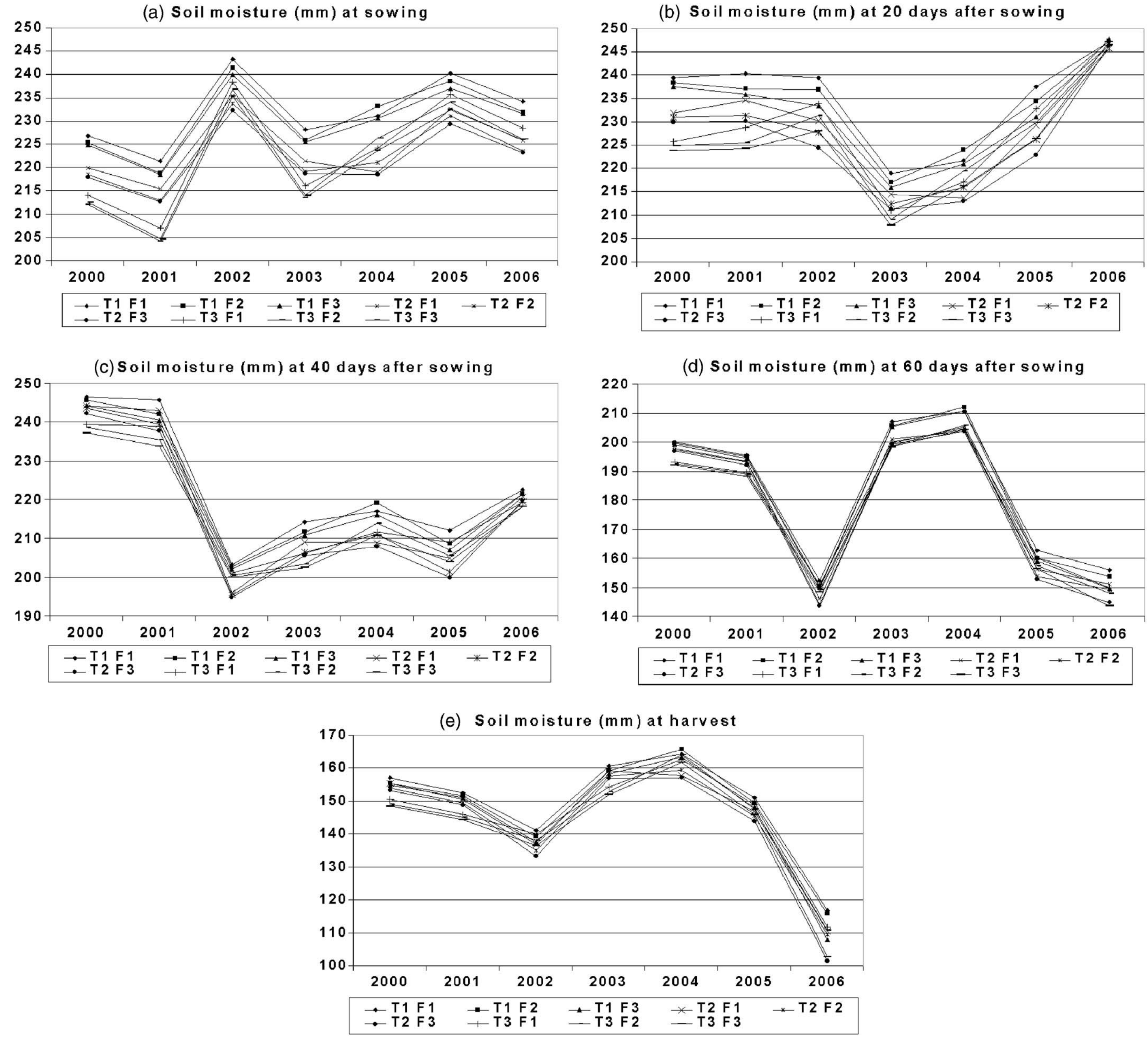

Fig. 2. Soil moisture of pearl millet at Agra at: (a) sowing; (b) 20 DAS; (c) 40 DAS; (d) 60 DAS; and (e) harvest

However, conventional tillage+mechanical weed control together with 30 kg N (FYM)+30 kg N (urea)+40 kg P/ha gave a maximum mean yield of 1,683 kg/ha with a coefficient of variation of 47.7%, while low tillage+mechanical weed control+herbicide together with 60 kg N (FYM)+40 kg P/ha gave a minimum mean yield of 1,452 kg/ha with a variation of 43.2% over seven years. A maximum mean cost of cultivation of Rs. 9,359 ha was incurred under conventional tillage+mechanical weed control together with 60 kg N (FYM)+40 kg P/ha treatment. However, the treatment gave a maximum net return of Rs. 6,480 ha and benefit–cost ratio of 1.18 compared to other treatments. Conventional tillage+mechanical weed control together with 30 kg N (FYM)+30 kg N (urea)+40 kg P/ha was the second best with a mean net returns of Rs. 5,670 ha and a benefit–cost ratio of 1.16 in the seven year study. The pearl millet yield attained with different treatments of tillage and fertilizer along with LSD values at $p<0.05$ level of significance and number of comparisons in which a treatment was superior based on ANOVA are given in Table 3.

The ANOVA indicated that there was a significant difference in yields attained by different treatments of tillage, fertilizer, and their interaction in all seasons except 2001 and 2002. The yield ranged from 575 to 819 kg/ha in 2001 and 698 to 788 kg/ha in 2002. Among tillage treatments, conventional tillage+mechanical weed control was superior with a significantly higher yield compared to low tillage+mechanical weed control in 2000, 2005, and 2006 and low tillage+mechanical weed control +herbicide in 2000, 2004, 2005, and 2006. Low tillage +mechanical weed control was superior to conventional tillage +mechanical weed control in 2003 and low tillage+mechanical

Table 3. Effect of Tillage and Fertilizer Treatments on Pearl Millet Yield at Agra

Treatment	2000	2001	2002	2003	2004	2005	2006	Mean	CV	CC	NR	BCR
T1 F1	2,494 (5)	819	698	1,918 (1)	2,335 (3)	2,028 (2)	1,249 (4)	1,649	44.0	9,359	6,480	1.18
T1 F2	2,612 (6)	793	727	1,758 (1)	2,563 (6)	2,175 (5)	1,154 (2)	1,683	47.7	8,777	5,670	1.16
T1 F3	2,982 (7)	739	748	1,468	2,287 (3)	2,252 (6)	1,105	1,654	52.4	8,531	5,223	1.14
T2 F1	1,720	637	715	2,210 (3)	2,234 (3)	1,601	1,112	1,461	45.1	8,965	5,595	1.09
T2 F2	1,868	575	743	2,055 (2)	2,400 (3)	1,744	1,017	1,564	47.1	8,383	4,785	1.07
T2 F3	2,053	622	764	2,094 (2)	2,163 (2)	1,835	968	1,500	45.6	8,137	4,337	1.05
T3 F1	1,716	676	739	2,360 (6)	1,904	1,655	1,117	1,452	43.2	9,040	5,624	1.09
T3 F2	2,094	689	767	2,244 (3)	1,929	1,746	1,021	1,499	43.7	8,458	4,814	1.07
T3 F3	2,216 (2)	600	788	2,103 (2)	1,847	1,912 (1)	973	1,578	44.3	8,212	4,367	1.05
Mean	2,195	683	743	2,023	2,185	1,883	1,080	1,560	44.1	8,651	5,210	1.10
CV	19.6	12.5	3.7	13.5	11.3	12.1	8.6	5.6		4.7	13.5	4.5
LSD (T)	580	NS	NS	184	356	258	123	145				
LSD (F)	231	NS	NS	123	150	176	87	NS				
LSD (T×F)	396	NS	NS	212	259	304	151	NS				

Note: CV=coefficient of variation (%); LSD=least significant difference at $p<0.05$; T1=conventional tillage+mechanical weed control; T2=low tillage+mechanical weed control; T3=low tillage+mechanical weed control+herbicide; F1=60 kg N (FYM)+40 kg P/ha; F2=30 kg N (FYM) +30 kg N (urea)+40 kg P/ha; F3=60 kg N (urea)+40 kg P/ha; CC=cost of cultivation (Rs/ha); NR=net returns (Rs/ha); and BCR=benefit–cost ratio. Values in parentheses indicate number of comparisons in which treatment was superior.

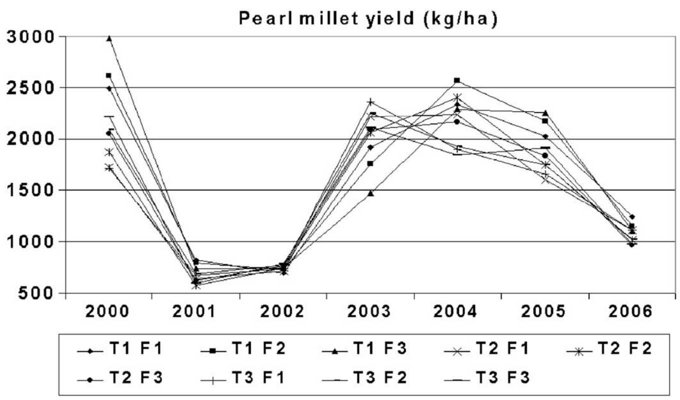

Fig. 3. Pearl millet yield attained by tillage and fertilizer treatments in different years at Agra

weed control+herbicide in 2004. Low tillage+mechanical weed control+herbicide was superior to conventional tillage+mechanical weed control in 2003.

Among fertilizer treatments, application of 60 kg N (FYM) +40 kg P/ha was superior to 30 kg N (FYM)+30 kg N (urea) +40 kg P/ha and 60 kg N (urea)+40 kg P/ha in 2003 and 2006. Application of 30 kg N (FYM)+30 kg (urea)+40 kg P/ha was superior to 60 kg N (urea)+40 kg P/ha in 2003 and 2004, while 60 kg N (urea)+40 kg P/ha was superior to 60 kg N (FYM) +40 kg P/ha in 2000 and 2005 with a significantly higher yield in the study. The significance of the interaction of tillage and fertilizer treatments indicated that conventional tillage+mechanical weed control together with 30 kg N (FYM)+30 kg N (urea) +40 kg P/ha was superior with a significantly higher yield in a maximum of 20 comparisons of treatment pairs, followed by conventional tillage+mechanical weed control together with 60 kg N (urea)+40 kg P/ha in 16 comparisons in different years. Conventional tillage+mechanical weed control together with 60 kg N

Table 4. Correlation between Pearl Millet Yield, Rainfall, and Soil Moisture at Agra

Variable	T1	T2	T3	F1	F2	F3	Pooled
(a) Soil moisture							
Sowing	−0.08	−0.08	−0.10	−0.09	−0.06	−0.05	−0.04
20 DAS	−0.33	−0.58[a]	−0.54[a]	−0.55[a]	−0.51[a]	−0.43[b]	−0.47[a]
40 DAS	0.14	−0.15	−0.09	−0.06	−0.01	−0.05	−0.01
60 DAS	0.47[b]	0.57[a]	0.53[a]	0.57[a]	0.56[a]	0.49[b]	0.54[a]
Harvest	0.48[b]	0.55[a]	0.53[a]	0.55[a]	0.59[a]	0.55[a]	0.55[a]
(b) Rainfall received							
July	0.19	0.27	0.35	0.30	0.25	0.25	0.26[b]
August	0.30	0.28	0.11	0.18	0.28	0.24	0.23
September	−0.63[a]	−0.51[a]	−0.44[a]	−0.52[a]	−0.54[a]	−0.52[a]	−0.53[a]

Note: T1=conventional tillage+mechanical weed control; T2=low tillage+mechanical weed control; T3=low tillage+mechanical weed control +herbicide; F1=60 kg N (FYM)+40 kg P/ha; F2=30 kg N (FYM)+30 kg N (urea)+40 kg P/ha; and F3=60 kg N+40 kg P/ha.

[a]Significance at $p<0.01$.

[b]Significance at $p<0.05$.

Table 5. Effect of Rainfall and Soil Moisture on Pearl Millet Yield Attained by Different Tillage Treatments at Agra

Treatment	Regression model	R^2	Φ
(a) Rainfall			
CT+MWC	$Y=1{,}463^a+1.48$ (July RF) $+3.33^b$ (August RF) -5.96^a (September RF)	0.54^a	560
LT+MWC	$Y=1{,}014^b+1.92$ (July RF) $+3.19^b$ (August RF) -3.72^b (September RF)	0.46^a	514
LT+MWC+HERB	$Y=1{,}114^a+1.86$ (July RF) $+1.97$ (August RF) -2.97^b (September RF)	0.33	550
(b) Soil moisture			
CT+MWC	$Y=872+76.19$ (SMS) -111.81 (SM20) $+61.76$ (SM40) $+4.37$ (SM60) -23.97 (SMH)	0.39	688
LT+MWC	$Y=2{,}738+56.18$ (SMS) -75.39 (SM20) $+21.56$ (SM40) $+16.12$ (SM60) -29.23 (SMH)	0.62^a	460
LT+MWC+HERB	$Y=3{,}027+67.85^b$ (SMS) -96.84^b (SM20) $+39.11$ (SM40) $+7.38$ (SM60) -31.16 (SMH)	0.57^a	470
(c) Rainfall and soil moisture			
CT+MWC	$Y=4{,}497^b+17.20$ (SMS) -52.94 (SM20) $+22.55$ (SM40) -32.01^a (SM60) $+57.41$ (SMH) -2.85 (July RF) -3.85^b (August RF) -11.88^a (September RF)	0.93^a	257
LT+MWC	$Y=5{,}196^b+17.01$ (SMS) -35.26 (SM20) -7.63 (SM40) -3.73 (SM60) $+31.32$ (SMH) -2.20^b (July RF) -3.85^b (August RF) -8.32^a (September RF)	0.96^a	175
LT+MWC+HERB	$Y=5{,}807^a+25.99$ (SMS) -50.86^b (SM20) $+0.26$ (SM40) -16.09^b (SM60) $+45.92^b$ (SMH) -3.41^a (July RF) -6.81^a (August RF) -9.08^a (September RF)	0.93^a	209

Note: R^2=coefficient of determination; Φ=prediction error (kg/ha); CT=conventional tillage; LT=low tillage; MWC=mechanical weed control; and HERB=herbicide.

[a]Significance at $p<0.01$.

[b]Significance at $p<0.05$.

(FYM)+40 kg P/ha was the third best treatment with a significantly higher yield in 15 comparisons of treatment pairs in different years.

Based on the graphical plot given in Fig. 3, the pearl millet yield had a decreasing trend in 2001 and 2002, followed by an increasing trend in 2003 and 2004 and decreasing trend in 2005 and 2006 in the study. The decreasing trend in 2001 was due to a low rainfall of 57 mm and long dry spells in the flowering stage in August and a high rainfall of 170 mm in the grain filling stage in September. In 2002, the crop was severely affected in the flowering stage with a high rainfall of 198 mm received in September. In 2006, a high rainfall of 306 mm in July in the vegetative stage, low rainfall of 34 mm in August in the flowering stage and "no rainfall" in September in the grain filling stage severely affected the crop yield compared to 2005.

Correlation of Pearl Millet Yield with Rainfall and Soil Moisture

Estimates of correlation of yield with monthly rainfall received in July, August, and September and soil moisture observed at sowing, 20, 40, and 60 DAS, and harvest are given in Table 4. The correlation coefficients indicated that September rainfall had a negative and significant correlation with yield, while rainfall received in July and August had a positive and nonsignificant correlation with yield attained by different tillage and fertilizer treatments during 2000–2006. The soil moisture at 60 DAS and harvest had a positive and significant correlation, while soil moisture at sowing and 40 DAS had a negative and nonsignificant correlation with yield. The soil moisture at 20 DAS had a negative and significant correlation with yield under both low tillage+mechanical weed control and low tillage +mechanical weed control+herbicide and all fertilizer combinations, while it was negative and nonsignificant under conventional tillage+mechanical weed control treatment in the study. The correlation of yield with rainfall and soil moisture variables indicated that although sufficient soil moisture existed in the soil at different stages of crop growth, an excess rainfall at either flowering or grain filling stage has a significant negative influence on yield.

Regression Models of Yield Attained by Tillage Treatments through Rainfall and Soil Moisture

Regression models of yield as postulated in Eqs. (1)–(3) were calibrated through monthly rainfall and soil moisture at different DAS and are given in Table 5 for tillage treatments and Table 6 for fertilizer treatments, along with estimates of the coefficient of determination (R^2) and prediction error (Φ). The regression models of tillage calibrated through rainfall received in July, August, and September indicated that conventional tillage +mechanical weed control was superior with a maximum and significant coefficient of determination of 0.54, while the models of tillage calibrated through soil moisture at sowing, 20, 40, and

Table 6. Effect of Rainfall and Soil Moisture on Pearl Millet Yield Attained by Different Fertilizer Treatments at Agra

Treatment	Regression model	R^2	Φ
(a) Rainfall			
60 kg N (FYM)+40 kg P/ha	$Y=1{,}216^{a}+1.71$ (July RF)$+2.36$ (August RF) -3.88^{b} (September RF)	0.40^{b}	540
30 kg N (FYM)+30 kg N (urea)+40 kg P/ha	$Y=1{,}164^{b}+1.81$ (July RF)$+3.20^{b}$ (August RF) -4.35^{b} (September RF)	0.46^{a}	551
60 kg N (urea)+40 kg P/ha	$Y=1{,}209^{b}+1.75$ (July RF)$+2.93$ (August RF) -4.42^{b} (September RF)	0.42^{b}	592
(b) Soil moisture			
60 kg N (FYM)+40 kg P/ha	$Y=13{,}234+94.91^{a}$ (SMS)-60.67 (SM20) $+30.10$ (SM40)$+29.82^{b}$ (SM60)-32.02 (SMH)	0.59^{a}	475
30 kg N (FYM)+30 kg N (urea)+40 kg P/ha	$Y=17{,}089^{b}+116.67$ (SMS)-77.84 (SM20) $+46.0$ (SM40)$+26.32$ (SM60)-31.50 (SMH)	0.60^{a}	506
60 kg N (urea)+40 kg P/ha	$Y=17{,}332+128.74^{b}$ (SMS)-99.41 (SM20) $+65.23$ (SM40)$+15.04$ (SM60)-29.59 (SMH)	0.52^{b}	571
(c) Rainfall and soil moisture			
60 kg N (FYM)+40 kg P/ha	$Y=-6{,}716+73.42$ (SMS)-59.90 (SM20)$+19.30$ (SM40) -8.31 (SM60)$+7.33$ (SMH)-1.32 (July RF) -4.05 (August RF)-6.33^{a} (September RF)	0.89^{a}	272
30 kg N (FYM)+30 kg N (urea)+40 kg P/ha	$Y=-5{,}846+70.47$ (SMS)-65.97 (SM20)$+26.51$ (SM40) -1.60 (SM60)$+17.33$ (SMH)-1.54 (July RF) -3.53 (August RF)-7.51^{b} (September RF)	0.89^{a}	296
60 kg N (urea)+40 kg P/ha	$Y=3{,}062+68.52$ (SMS)-80.50 (SM20)$+36.44$ (SM40) -21.08 (SM60)$+37.63^{b}$ (SMH)-2.68 (July RF) -5.10 (August RF)-9.29^{a} (September RF)	0.85^{a}	352

Note: R^2=coefficient of determination; and Φ=prediction error (kg/ha).
[a]Significance at $p<0.01$.
[b]Significance at $p<0.05$.

60 DAS, and harvest indicated that low tillage+mechanical weed control was superior with a maximum and significant coefficient of determination of 0.62. The combined regression model of yield calibrated through both rainfall and soil moisture variables indicated that low tillage+mechanical weed control had a maximum and significant coefficient of determination of 0.96, while both low tillage+mechanical weed control+herbicide and conventional tillage+mechanical weed control treatments had 0.93 in the study.

The regression models indicated that low tillage+mechanical weed control had a minimum prediction error of 514 kg/ha under the model with rainfall, 460 kg/ha under the model with soil moisture, and 175 kg/ha under the model with both rainfall and soil moisture variables. In Model (1), July and August rainfall had a positive effect, while September rainfall had a negative effect on yield. Both August and September rainfall had a significant influence on yield attained by conventional tillage +mechanical weed control and low tillage+mechanical weed control, while September rainfall had a significant influence on yield attained by low tillage+mechanical weed control+herbicide treatment. In Model (2), soil moisture at sowing, 40 and 60 DAS had a positive effect, while it had a negative effect at 20 DAS and harvest on yield. However, the soil moisture effect on yield was significant only at sowing and 20 DAS for low tillage +mechanical weed control+herbicide treatment. In Model (3), the effects of soil moisture at 60 DAS and September rainfall were negative and significant on yield attained by conventional tillage+mechanical weed control, while the effect of July, August, and September rainfall was negative and significant in the case of yield attained by low tillage+mechanical weed control. The effects of soil moisture at 20 and 60 DAS, rainfall of July, August, and September were negative and significant, while soil moisture at harvest had a positive and significant effect on yield attained by low tillage+mechanical weed control+herbicide treatment in the study.

Regression Models of Yield Attained by Fertilizer Treatments through Rainfall and Soil Moisture

Regression models of yield through rainfall and soil moisture variables, along with estimates of the coefficient of determination and prediction error calibrated for different fertilizer treatments are given in Table 6. The models indicated that application of 30 kg N (FYM)+30 kg N (urea)+40 kg P/ha was superior with a maximum and significant coefficient of determination of 0.46 when yield was regressed through monthly rainfall of July to September and 0.60 when regressed through soil moisture at sowing, 20, 40, and 60 DAS, and harvest. When both rainfall of July to September and soil moisture at sowing, 20, 40, and 60 DAS, and harvest were included in the model, the coefficient of determination significantly improved for all three fertilizer treatments. Application of either 30 kg N (FYM)+30 kg N (urea)

Table 7. Mean Pearl Millet Yield, Prediction Error and Sustainable Yield Index of Tillage and Fertilizer Treatments at Agra

Treatment	Mean yield (kg/ha)	Prediction error (kg/ha)			Sustainable yield index		
		Model (1)	Model (2)	Model (3)	Model (1)	Model (2)	Model (3)
T1 F1	1,649 (3)	550 (4)	582 (7)	265 (6)	36.8 (2)	35.8 (2)	46.4 (2)
T1 F2	1,683 (1)	556 (7)	597 (8)	277 (7)	37.8 (1)	36.4 (1)	47.2 (1)
T1 F3	1,654 (2)	576 (9)	630 (9)	305 (9)	36.2 (3)	34.4 (3)	45.3 (3)
T2 F1	1,461 (8)	527 (1)	468 (1)	224 (1)	31.3 (7)	33.3 (6)	41.5 (7)
T2 F2	1,486 (7)	533 (2)	483 (3)	236 (2)	32.0 (4)	33.6 (5)	41.9 (4)
T2 F3	1,500 (4)	553 (6)	516 (5)	264 (5)	31.8 (6)	33.0 (7)	41.5 (6)
T3 F1	1,452 (9)	545 (3)	473 (2)	241 (3)	30.4 (9)	32.9 (8)	40.6 (9)
T3 F2	1,499 (5)	551 (5)	488 (4)	253 (4)	31.8 (5)	33.9 (4)	41.8 (5)
T3 F3	1,491 (6)	571 (8)	521 (6)	281 (8)	30.9 (8)	32.6 (9)	40.6 (8)

Note: Model (1)=regression of yield as a function of rainfall received in July, August, and September; Model (2)=regression of yield as a function of soil moisture at sowing, 20, 40, and 60 DAS, and harvest; Model (3)=regression of yield as a function of both rainfall and soil moisture variables in Model (1) and (2); T1=conventional tillage+mechanical weed control; T2=low tillage+mechanical weed control; T3=low tillage+mechanical weed control+herbicide; F1=60 kg N (FYM)+40 kg P/ha; F2=30 kg N (FYM)+30 kg N (urea)+40 kg P/ha; and F3=60 kg N (urea)+40 kg P/ha. Values in parentheses are ranks of the treatments.

+40 kg P/ha or 60 kg N (FYM)+40 kg P/ha had a maximum coefficient of determination of 0.89 compared with 60 kg N (urea) +40 kg P/ha with 0.85 based on Model (3).

Application of 60 kg N (FYM)+40 kg P/ha had a minimum error of 540 kg/ha under Model (1), 475 kg/ha under Model (2) and 272 kg/ha under Model (3) for predicting yield compared to other fertilizer treatments. Based on Model (1), July and August rainfall had a positive effect, while September rainfall had a negative effect on pearl millet yield. August and September rainfall had a significant effect on the yield attained by 30 kg N (FYM) +30 kg N (urea)+40 kg P/ha, while September rainfall had a significant effect on the yield attained by 60 kg N (urea) +40 kg P/ha treatment. Based on Model (2), the soil moisture at sowing, and 40 and 60 DAS had a positive effect, while it had a negative effect at 20 DAS and harvest on yield. The soil moisture at sowing under all three fertilizer treatments and 60 DAS in the case of 60 kg N (FYM)+40 kg P/ha had a significant effect on yield based on Model (2). Model (3) indicated that soil moisture at sowing, 40 DAS, and harvest had a positive effect, while soil moisture at 20 and 60 DAS, rainfall of July, August, and September had a negative effect on pearl millet yield. However, only September rainfall had a significant influence on yield attained by all three fertilizer treatments under Model (3) in the study.

Selection of Superior Tillage and Fertilizer Treatments for Sustainable Pearl Millet Yield

Using prediction errors (Φ) of yield derived under Models (1), (2), and (3) and given in Table 5 for tillage and Table 6 for fertilizer treatments, a combined prediction error of each treatment combination of tillage and fertilizer was derived under each model. The combined prediction error was minimum under Model (3) compared with Models (1) and (2). It was lower for conventional tillage and higher for low tillage in combination with any of three fertilizer treatments under Model (1) compared with Model (2). The low tillage+mechanical weed control together with 60 kg N (FYM)+40 kg P/ha had a minimum, while conventional tillage+mechanical weed control together with 60 kg N (urea)+40 kg P/ha had a maximum combined prediction error under all three models.

Based on Eq. (4), the sustainable yield index of each treatment was derived as a ratio of the difference of mean yield and combined prediction error of the treatment and maximum pearl millet yield of 2,982 kg/ha attained by conventional tillage +mechanical weed control together with 60 kg N (urea) +40 kg P/ha in 2000. The estimates of combined prediction error and sustainable yield index of different treatments of tillage and fertilizer under Models (1), (2), and (3) are given in Table 7. The conventional tillage+mechanical weed control together with 30 kg N (FYM)+30 kg N (urea)+40 kg P/ha attained a maximum sustainable yield index of 37.8% under Model (1), 36.4% under Model (2), and 47.2% under Model (3) compared with other treatments based on the study.

Ranks were assigned to each treatment for (a) the yield attained in individual years and (b) mean yield attained over seven years, combined prediction error and sustainable yield index under Models (1), (2), and (3) and rank sum was derived. Based on the graphical plot given in Fig. 4, conventional tillage +mechanical weed control together with 30 kg N (FYM) +30 kg N (urea)+40 kg P/ha was found to be the most superior treatment with a minimum rank sum of 24 for the yield attained in individual years and 26 for the mean yield, combined prediction error, and sustainable yield index under Models (1), (2), and (3). The conventional tillage+mechanical weed control together with 60 kg N (FYM)+40 kg P/ha was the second best treatment with rank sums of 27 and 26, while low tillage+mechanical weed control+herbicide together with 30 kg N (FYM)+30 kg N (urea)+40 kg P/ha was the third best with a rank sum of 32 for the yield attained in individual years and an equal rank sum for mean yield, combined prediction error, and sustainable yield index over years. Based on the ranking of yield attained in individual years, conventional tillage+mechanical weed control together with 60 kg N (urea)+40 kg P/ha was superior with a rank sum of 27 compared to low tillage+mechanical weed control +herbicide together with 30 kg N (FYM)+30 kg N (urea) +40 kg P/ha with a rank sum of 32. However, the latter treatment had a better rank sum of 32 compared to the former with 38 based on the mean yield attained over seven years, combined prediction error, and sustainable yield index derived under the three models. Among different treatments, low tillage+mechanical weed control+herbicide together with 60 kg N (urea) +40 kg P/ha was most inferior with a maximum rank sum of 91 in the study.

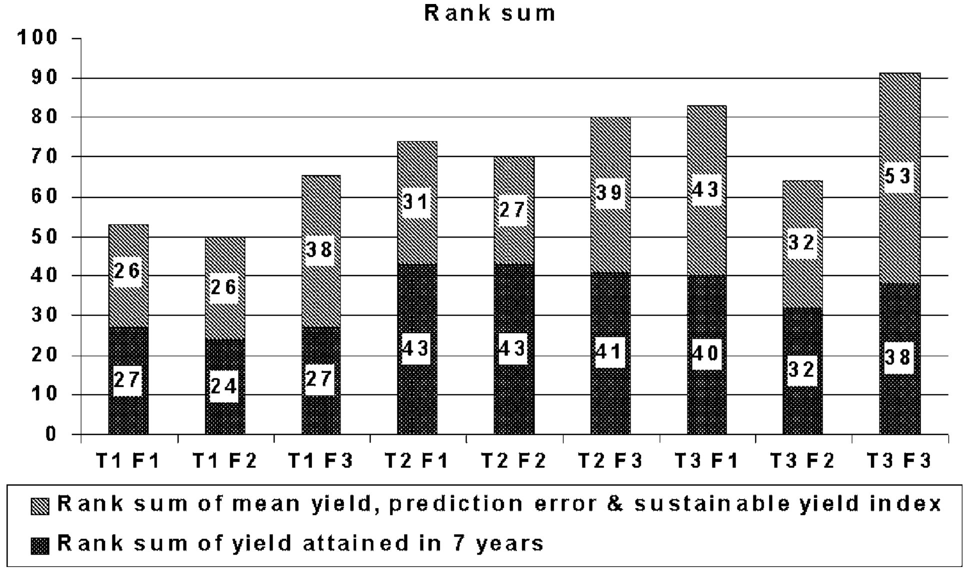

Fig. 4. Rank sum of yield, prediction error, and sustainable yield index of tillage and fertilizer treatments in pearl millet at Agra

Conclusion

A study was conducted to assess the performance of treatment combinations of tillage viz., conventional tillage+mechanical weed control, low tillage+mechanical weed control, and low tillage+mechanical weed control+herbicide and fertilizer treatments viz., 60 kg N (FYM)+40 kg P/ha, 30 kg N (FYM) +30 kg N (urea)+40 kg P/ha, and 60 kg N (urea)+40 kg P/ha and select a superior treatment for attaining a sustainable pearl millet yield under semiarid inceptisols at Agra. The treatments were assessed for yield attained during 2000–2006 based on rainfall received during crop growing period in July, August, and September and available soil moisture at sowing, 20, 40, and 60 DAS, and harvest. The ANOVA indicated a significant difference in soil moisture on different DAS and also under tillage treatments tested in the study. Similarly, there was a significant difference in the yield attained by tillage and fertilizer treatments and their interaction in all years except 2001 and 2002. July and August rainfall had a positive and nonsignificant correlation, while September rainfall had a significant negative correlation with yield in different years. Regression models of yield were calibrated through (1) rainfall of July, August, and September; (2) soil moisture at sowing, 20, 40, and 60 DAS, and harvest; and (3) both rainfall and soil moisture variables for each tillage and fertilizer treatment. Model (3) of low tillage+mechanical weed control gave a higher and significant coefficient of determination with a lower prediction error for all the treatments.

The regression models of tillage indicated that July and August rainfall had a positive effect and September rainfall had a negative effect on yield. Based on Model (2), soil moisture at sowing, and 40 and 60 DAS had a positive effect, while at 20 DAS and harvest had a negative effect on yield. However, the effect was significant only at sowing and 20 DAS under low tillage +mechanical weed control+herbicide treatment. In Model (3), soil moisture at 60 DAS and September rainfall had a significant negative effect on yield attained by conventional tillage +mechanical weed control, while July, August, and September rainfall had a significant negative effect on yield attained by low tillage+mechanical weed control treatment. Significant negative effect of soil moisture at 20 and 60 DAS, rainfall of July, August, and September and positive effect of soil moisture at harvest on yield were observed under low tillage+mechanical weed control +herbicide.

The regression models of fertilizer indicated that August rainfall had a significant positive and September rainfall had a significant negative effect on the yield attained by 30 kg N (FYM) +30 kg N (urea)+40 kg P/ha, while September rainfall had a significant negative effect on the yield attained by 60 kg N (urea) +40 kg P/ha. Model (2) indicated a significant effect of soil moisture at sowing on the yield attained by all three treatments and 60 DAS for 60 kg N (FYM)+40 kg P/ha, while Model (3) indicated a significant effect of September rainfall on yield.

Using prediction errors of yield derived under tillage and fertilizer models, a combined prediction error of each treatment was derived for assessing sustainability of treatments over years. The combined prediction error was minimum based on Model (3) compared with Models (1) and (2). Low tillage+mechanical weed control together with 60 kg N (FYM)+40 kg P/ha had a minimum, while conventional tillage+mechanical weed control together with 60 kg N (urea)+40 kg P/ha had a maximum prediction error under all models. Conventional tillage+mechanical weed control together with 30 kg N (FYM)+30 kg N (urea) +40 kg P/ha had a maximum sustainable yield index of 47.2% under Model (3) compared with other treatments. Ranks were assigned to treatments for yield attained in individual years and mean yield, combined prediction error, and sustainable yield index over the years and rank sum was derived. Conventional tillage+mechanical weed control together with 30 kg N (FYM) +30 kg N (urea)+40 kg P/ha was the most superior treatment with a minimum rank sum of 24 for yield attained in individual years and 26 for mean yield, combined prediction error, and sustainable yield index over the years.

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