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A Simulation Study of the Response of Plant-type and Nitrogen Fertilization on the Grain Yield of Pearl Millet

G.J. O'Leary[1*], N.L. Joshi[2] and E.J. van Oosterom[1**]

[1] *International Crops Research Institute for the Semi-arid Tropics, Patancheru 502324, India*

[2] *Central Arid Zone Research Institute, Jodhpur 342003, India*

Abstract: A simulation study was made on the response of plant-type and nitrogen fertilization on the yield of pearl millet in Rajasthan, India. A model of the pearl millet crop (APSIM-Millet) was tested against experimental and district data and was shown to be responsive to applied nitrogen (Root Mean Square Error=230 kg ha^{-1}, 13%) and to varied weather conditions with and without applied nitrogen in the region. The simulation study employed both observed (14-34 years between 1963 and 1997) and synthetic (50 years) daily weather data in a comparative analysis that showed little difference in conclusions if either data sequence were used. The probability analyses showed a strong plant-type, nitrogen and site effect in response to variation in weather (observed or synthetic). At Pali and Jodhpur choice of cultivar made a large yield difference with a strong interaction with nitrogen. In terms of median response, highest yield was achieved with cultivar RCB-IC911 (median 800 kg ha^{-1}) followed by cultivar HHB67 (median 613 kg ha^{-1}) with the lowest consistent yield from cultivar WRajPop (median 500 kg ha^{-1}). At Bikaner and Jaisalmer cultivar response was much smaller than at the wetter sites but generally the same order of response was seen. Similarly, the response to nitrogen was greatest at Pali and Jodhpur; moreover, the nitrogen response was generally larger than the cultivar response, despite the negative effect in dry conditions at Pali. Thus, at these wetter sites significant yield increases (e.g. 700-900 kg ha^{-1}) above what is currently achieved with unfertilized landraces are likely with the combination of an improved cultivar and application of N fertilizer. Even at the drier site at Bikaner, yields could be more than doubled (from 250 to 550 kg ha^{-1}) with improved cultivars and N-fertilization. However, at Jaisalmer, improved cultivars and N-fertilization could not be economically justified. Significant benefits are likely from an integrated approach to plant breeding and agronomy in these semi-arid regions of India and Africa where N deficiency is endemic.

Key words: Arid region, grain yield, nitrogen, pearl millet, plant-type, simulation.

Pearl millet is the main food grain crop grown in more arid parts of the semi-arid tropics of Africa and India. Significant variation in weather and soils are well known in that region, with the management of crops by farmers being largely conservative to minimize risk of crop failure. In these areas, soils are typically poor in nutrients, particularly, nitrogen in Rajasthan, India (Aggarwal *et al.*, 1990) and phosphorus in Sahel, West-Africa (Bationo *et al.*, 1990) and have low water holding capacity representing largely the sandier arid-zone soils (Dregne, 1976).

Present address:

* Department of Primary Industries, PB 260, Horsham, Victoria 3400, Australia.

** School of Land, Crop and Food Sciences, The University of Queensland, Brisbane QLD 4072, Australia.

Pearl millet has a capacity to offset the effects of severe water and nutrient stresses firstly by being able to withstand high temperatures (Ong, 1983) and by having a sensitive and adaptive tillering capability (Ong and Monteith, 1985; Singh *et al.*, 1998). This tillering ability can effectively restart the crop after long periods of drought by producing new tillers that can at least mature into harvestable grain. Consequently, it is the preferred crop by farmers in much of the marginal semi-arid to arid tropics.

There is significant genetic variation in pearl millet from the local (desi) landraces to hybrids that offer a wide range in plant-type from low- to high-tillering habit to early- and medium-duration cultivars (Bidinger *et al.*, 1994). Farmers in some areas of Rajasthan have used many of the hybrids, but in other regions have maintained largely the desi types. The reasons are complex, but in addition to social needs and risk reduction, there is a strong relation to the variation in weather conditions (van Oosterom *et al.*, 1996). Further, the use of N fertilizer is expected to compound the risk if drought conditions occur and water conservation methods are not employed (Cantero-Martinez *et al.*, 1999). Additionally, hybrids are often believed to require more fertilizer and water than the desi types because of their generally higher yields (Joshi and Kalla, 1986). The overriding problem, however, is that in any year the response of different-plant types to N-fertilization may be quite varied such that grain yield may increase or decrease. Therefore, short-term classical agronomic field experiments may not provide an economic way to untangle the interaction of plant-type, N-fertilization and weather conditions.

This paper reports a simulation analysis of the effects of weather variation on the response of plant-type and N-fertilization of pearl millet at four locations in Rajasthan, India. Previous studies in this region have examined the effect of weather (Gupta *et al.*, 1994), plant traits (van Oosterom *et al.*, 1996) and farmers preferences (Weltzien *et al.*, 1996). This study examines the importance of nitrogen fertility as an additional factor in respect to the relative benefits of breeding and agronomic objectives in a representative area of the semi-arid tropics. A simulation model of pearl millet (APSIM-Millet) was used, which was designed to simulate the development, growth and yield of pearl millet crop with the capacity to simulate the appearance, production and senescence of tillers in response to weather, soil water and nitrogen conditions, and agronomic management. The model has gone extensive development (van Oosterom *et al.*, 2001a, 2001b, 2002) and as such, it represents a new model for tillering crops and offers realistic behavior of pearl millet that should be instructive for plant breeders, agronomists and physiologists to help farmers obtain more profit from their crop.

Materials and Methods

Simulations

Grain yield of three cultivars of pearl millet were simulated under two nitrogen fertility regimes for four representative sites in Rajasthan. Two series of simulations were made. The first (Series A) utilized the observed continuous set of daily weather data from each site, which varied from 14 to 34 years between 1963 and 1997. To examine the utility of generated weather data for this study region a second simulation series was conducted. The second series

(Series B) utilized a 50-year sequence of a synthetic set of daily weather data generated to mimic the statistical behavior reflected in the observed data set. Our assumption here is that the statistical analyses (mean and variance) of the observed weather data at each site is representative of a 50-year period. All crop, soil and management parameters were identical for each series. The simulations commenced on 1 January with the soil water and nitrogen balance proceeding until the first crop is sown (typically June), after which the simulation continues for the remainder of the weather sequence without re-setting soil water or nitrogen levels.

Pearl millet cultivars

The cultivars that were simulated were designed to represent high- and low-tillering plant types. Three pearl millet cultivars that are currently under cultivation viz., WRajPop (high tillering and medium duration); RCB-IC911 (low tillering and medium duration), and HHB67 (high tillering and short duration) were used in the present study. Table 1 lists the APSIM-Millet model parameters used to define these cultivars. Sowing date was simulated to occur if the daily rainfall exceeds 20 mm during a sowing window from 10 June (DAY=161) until 31 July (DAY=212) each year. A plant population of 7.5 plants m^{-2} was set at sowing for all cultivars and sites.

Soil and site description

Sites representing a soil and rainfall gradient were selected: Pali (25°50′N 73° 15′E), Jodhpur (26° 18′N 73 01′E), Bikaner (28°00′N 73°18′E) and Jaisalmer (26°54′N 70° 55′E). Jaisalmer represents the extreme limit for crop production in the region, whereby farmers rely heavily upon livestock with millet being largely a fodder crop, but more opportunistic grain crop in higher rainfall seasons. Therefore, the more favourable cropping area is towards Pali with its more fertile soil and higher annual rainfall. The soil types varied from a loam (Lithic Haplocambids) at Pali, sandy loam (Typic Haplocambids) at Jodhpur, loamy sand (Typic Torripsamments) at Bikaner and fine sand (Typic Torripsamments) at Jaisalmer. Table 2a and b lists the key physical and chemical differences used to simulate crop growth in the soil water (SOILWAT2) and nitrogen (SOILN2) APSIM modules (Probert *et al.*, 1997). In summary, the maximum available water holding capacity was 45 mm at Pali, 71 mm at Jodhpur, 70 mm at Bikaner and 37 mm at Jaisalmer. One important feature of our simulation was the allowance of nitrification of ammonium-N up to pH 8.5 that is known to occur in these soils.

Soil fertility levels were set to (1) no applied nitrogen fertilizer and (2) 20 kg N ha^{-1} applied at sowing 5 cm deep for each annual crop. Initial soil water and mineral nitrogen levels were set at 25% available water content and 25 kg NO_3-N ha^{-1} and 10 kg NH_4-N ha^{-1} in the root zone for each site to reflect, but not deficient, typical levels seen in the region in winter (Table 3).

Weather data

Monthly summaries of daily rainfall (probability of rain and quantity of rain, mm), maximum and minimum screen air temperature (°C), solar radiation (MJ m^{-2}) and wind speed (m s^{-1}) were collated from long-term records from each site (Table 4). At each site solar radiation was calculated

Table 1. APSIM-Millet parameters defining each cultivar of pearl millet. Separate parameters are used for the main stem (MS) and up to 5 tillers (T1-T5) where, the thermal time (tt) and photoperiod (pp) specify phenophases. Appendix 1 defines each of the APSIM variables

Parameter	MS	T1	T2	T3	T4	T5
			WRajPop			
head_grain_no_max	2600	2200	2200	2200	2200	2200
grain_gth_rate	0.46	0.46	0.46	0.46	0.46	0.46
tt_emerg_to_endjuv	225	128.5	118.5	108.5	98.5	88.5
est_days_emerg_to_init	17	17	17	17	17	17
pp_endjuv_to_init	164	164	164	164	164	164
tt_flower_to_maturity	457	457	457	457	457	457
tt_flag_to_flower	61	61	61	61	61	61
tt_flower_to_start_grain	80	80	80	80	80	80
tt_maturity_to_ripe	1	1	1	1	1	1
y0_const	8350	2100	2100	2100	2100	2100
y0_slope	1430	1150	1150	1150	1150	1150
			HHB67			
head_grain_no_max	2600	2200	2200	2200	2200	2200
grain_gth_rate	0.61	0.61	0.61	0.61	0.61	0.61
tt_emerg_to_endjuv	185	88.5	78.5	68.5	58.5	48.5
est_days_emerg_to_init	17	17	17	17	17	17
pp_endjuv_to_init	164	164	164	164	164	164
tt_flower_to_maturity	457	457	457	457	457	457
tt_flag_to_flower	77.8	77.8	77.8	77.8	77.8	77.8
tt_flower_to_start_grain	80	80	80	80	80	80
tt_maturity_to_ripe	1	1	1	1	1	1
y0_const	7280	3480	3480	3480	3480	3480
y0_slope	330	740	740	740	740	740
			RCB-IC911			
grain_gth_rate	3300	2900	2900	2900	2900	2900
tt_emerg_to_endjuv	0.61	0.61	0.61	0.61	0.61	0.61
est_days_emerg_to_init	225	128.5	118.5	108.5	98.5	88.5
pp_endjuv_to_init	17	17	17	17	17	17
tt_flower_to_maturity	164	164	164	164	164	164
tt_flag_to_flower	457	457	457	457	457	457
tt_flower_to_start_grain	47.4	47.4	47.4	47.4	47.4	47.4
tt_maturity_to_ripe	80	80	80	80	80	80
y0_const	1	1	1	1	1	1
y0_slope	3200	1810	1810	1810	1810	1810
	1270	1820	1820	1820	1820	1820

Table 2a. Surface soil variable used by APSIM SOILWAT2 and SOILN2 modules [Based on soil descriptions in the CAZRI-INDO-US Project (1997); Saxena et al. (1994) and other unpublished data (Joshi, 1998)]. Appendix 1 defines each of the parameters

APSIM variables	Pali	Jodhpur	Bikaner	Jaisalmer
U (mm)	8.00	6.00	5.00	4.00
Cona	3.50	3.50	3.50	3.50
Soilalb	0.18	0.20	0.22	0.22
Diff_const	88.00	88.00	88.00	88.00
Diff_slope	35.40	35.40	35.40	35.40
Cn_bare	77.00	77.00	72.00	72.00
Cn_red	15.00	15.00	10.00	10.00
Cn_cov	0.80	0.80	0.80	0.80
Cn_canopy-fact	1.00	1.00	1.00	1.00
Soil_cn	14.00	13.00	12.00	12.00
Root_cn	45.00	45.00	45.00	45.00
Root_wt (kg ha^{-1})	300.00	300.00	200.00	200.00
Mean T (°C)	26.50	26.70	25.90	26.50
Amp (°C)	17.60	13.80	21.20	19.40

from measurements of sunshine hours by the method of Doorenbos and Pruitt (1984) using a locally calibrated function for the region. Such that: $R = [0.26 + 0.44\ nN]\ R_{max}$; n = 515; $R^2 = 0.72$; where, R is the daily radiation, nN is the daily proportion of bright sunshine hours with maximum sunshine hours based upon day length with no twilight and R_{max} is the radiation without atmospheric absorption, calculated as a function of latitude and day of year (Penning de Vries *et al.*, 1989). The maximum number of years of continuous daily weather data varied from 14 years (Bikaner) to 34 years (Jodhpur) (Table 4). The APSIM-Millet model does not utilize wind speed, but was included here in this summary to assist interpretation of crop growth response at these sites.

These data provide the input parameters for generating synthetic weather data using the SIMMETEO weather generator (Geng *et al.*, 1988). This weather generator has been modified by O'Leary and Connor (1998) to account for differences in solar radiation between wet and dry days by a sinusoidal factor during the year (Table 4), such that wet days have the least effect in reducing solar radiation in Jaisalmer (3 MJ m^{-2} day^{-1}) compared to Pali (4 MJ m^{-2} day^{-1}) because of the lower amount and frequency of rain in Jaisalmer. This generator has given a high degree of accuracy (R^2>0.97) in mediterranean (O'Leary and Connor, 1998), temperate (Bannayan and Crout, 1999) and tropical regions (Bheenick, 1994). No major differences between the observed and synthetic sequences were observed. Fig. 1 shows a good comparison of mean monthly observed and generated radiation (R^2 = 0.78-0.90) and rainfall (R^2 = 0.96-0.99) for each site. The weather generator provides a sequence of daily weather data that is

Table 2b. Sub-surface soil parameters used by APSIM SOILWAT2 and SOILN2 modules [Based on soil descriptions in the CAZRI-INDO-US Project (1997); Saxena et al. (1994) and other unpublished data (N.L. Joshi, 1998)]. Appendix 1 defines each of the parameters

Depth (cm)	Airdry	Ll15	Dul	Sat	Bd	Swcon	Oc	Fbiom	Finert	pH
Pali										
0-10	0.081	0.071	0.172	0.32	1.49	0.70	0.37	0.02	0.40	8.1
10-22.5	0.082	0.073	0.172	0.32	1.39	0.70	0.37	0.02	0.45	7.9
22.5-35	0.105	0.101	0.206	0.35	1.36	0.70	0.42	0.01	0.50	7.8
35-45	0.092	0.091	0.187	0.35	1.39	0.70	0.42	0.01	0.65	7.8
Jodhpur										
0-10	0.053	0.028	0.102	0.26	1.50	0.75	0.16	0.02	0.40	8.3
10-30	0.056	0.031	0.112	0.26	1.50	0.75	0.09	0.02	0.45	8.4
30-50	0.048	0.031	0.101	0.26	1.50	0.75	0.20	0.01	0.50	8.2
50-80	0.048	0.030	0.094	0.26	1.50	0.75	0.12	0.01	0.65	8.4
80-100	0.040	0.040	0.110	0.26	1.50	0.75	0.12	0.01	0.75	8.4
Bikaner										
0-10	0.046	0.02	0.09	0.35	1.50	0.80	0.06	0.02	0.40	7.8
10-30	0.054	0.031	0.112	0.36	1.40	0.80	0.06	0.02	0.45	7.8
30-50	0.051	0.031	0.101	0.36	1.40	0.80	0.08	0.01	0.50	8.1
50-80	0.047	0.030	0.094	0.34	1.40	0.80	0.09	0.01	0.65	8.2
80-100	0.049	0.033	0.10	0.34	1.40	0.80	0.09	0.01	0.75	8.2
Jaisalmer										
0-10	0.031	0.017	0.063	0.30	1.60	0.80	0.07	0.02	0.40	9.0
10-20	0.031	0.017	0.063	0.31	1.60	0.80	0.07	0.02	0.40	9.0
20-40	0.030	0.018	0.060	0.29	1.50	0.80	0.08	0.02	0.45	8.9
40-60	0.031	0.019	0.063	0.29	1.60	0.80	0.09	0.01	0.50	8.9
60-80	0.032	0.020	0.063	0.29	1.70	0.80	0.09	0.01	0.50	8.9

consistent with the historical daily data in terms of first order statistics (mean and variance). It then captures dry years and wet years, but does not forecast the future weather nor does it reflect autocorrelation between seasons and years that enter prolonged drought, wet periods or climate change. Nevertheless, this type of synthetic weather has been found useful in simulation studies where long-term observed data are unavailable.

Statistical analyses

Tabular comparisons of simulated and observed yields are made with the mean simulation error calculated as the Root Mean Square Error (RMSE) of the residuals. Graphical comparisons were also made as a time series and probability analyses where initial conditions were not known.

The effects of differing plant-type and applied nitrogen on crop yield from the multi-year simulations are presented as

Table 3. Initial soil water (SW, Mg m^{-3}) and nitrate (NO_3-N) and ammonium (NH_4-N) nitrogen (g Mg^{-1}) amounts set at the commencement of the simulation on January 1 for each site. The initial total profile available soil water (mm) and mineral nitrogen (kg N ha^{-1}) is also shown

Soil depth (cm)	SW	NO_3-N	NH_4-N
Pali			
0-10	0.0963	8.72	3.36
10-20	0.0978	3.74	1.73
20-35	0.1273	2.06	0.59
35-45	0.1150	1.44	0.72
Complete profile	11.4000	25.00	10.00
Jodhpur			
0-10	0.0465	8.67	3.33
10-30	0.0513	2.17	0.83
30-50	0.0485	1.00	0.33
50-80	0.0460	0.44	0.22
80-100	0.0575	0.17	0.17
Complete profile	17.7000	25.00	10.00
Bikaner			
0-10	0.0375	8.13	3.13
10-30	0.0513	2.03	0.78
30-50	0.0485	0.94	0.31
50-80	0.0460	0.42	0.21
80-100	0.0498	0.15	0.15
Complete profile	17.2000	25.00	10.00
Jaisalmer			
0-10	0.0285	8.13	3.13
10-20	0.0285	4.06	1.56
20-40	0.0285	1.00	0.33
40-60	0.0300	0.63	0.31
60-80	0.0333	0.15	0.15
Complete profile	10.4000	25.00	10.00

probability-of-exceedence curves (1-cumulative probability) for each treatment (crop-type x nitrogen x site). The probability-of-exceedence graphs show the probability of exceeding the nominated yield on the x-axis and are useful to compare the expected performance of crops over many years on a probabilistic basis. They overcome the problem of a different number of years between our sites, but we also address this with the Series B analyses where each site comprised 50 years of weather data. A graphical comparison of the effect of utilising synthetic weather data was also made comparing Series A and B probability graphs.

Results

Performance against observed data

A comparison of the model against observed data was made from a comprehensive nitrogen fertilization

Table 4. Observed average monthly weather variables used for generating daily weather data with SIMMETEO weather generator. Wet days are defined as days when the daily rainfall equals or exceeds 0.2 mm. The mean annual difference in average daily solar radiation between wet and dry days and its annual amplitude, respectively, is also shown in parentheses

Month	Proportion of wet days	Rain per wet day (mm)	Min temp. (°C)	Max temp. (°C)	Solar radiation (MJ m^{-2} day^{-1})	Wind speed (m s^{-1})
		Pali [27 years (1967-1996): 4.0 and 1.0 MJ m^{-2} day^{-1}]				
January	0.0215	4.36	7.6	25.6	15.01	1.72
February	0.0260	5.20	10.2	28.3	17.46	1.89
March	0.0161	5.87	15.9	34.0	19.77	2.08
April	0.0233	4.87	21.6	39.2	22.72	2.43
May	0.0387	8.44	26.3	41.9	23.33	3.46
June	0.1133	11.74	28.0	40.5	21.86	4.16
July	0.3000	17.23	26.5	35.8	18.57	3.70
August	0.3011	14.92	25.1	33.5	17.39	2.90
September	0.1233	14.96	23.6	35.2	19.13	2.07
October	0.0247	14.28	18.9	36.2	18.32	1.43
November	0.0167	5.67	12.8	31.8	15.75	1.33
December	0.0086	5.36	8.8	27.5	14.27	1.48
		Jodhpur [34 years (1963-1997): 4.0 and 1.0 MJ m^{-2} day^{-1}]				
January	0.0175	4.23	9.2	21.2	12.83	1.66
February	0.0365	3.30	11.0	23.5	14.77	1.71
March	0.0166	6.81	15.1	28.3	17.04	1.82
April	0.0181	11.52	19.5	32.8	19.30	2.07
May	0.0525	8.87	22.5	35.0	19.96	2.80
June	0.0733	9.66	23.8	34.3	19.25	3.36
July	0.2212	15.78	22.7	30.9	16.54	3.18
August	0.2581	13.16	21.5	29.1	15.96	2.42
September	0.1067	14.24	20.2	30.1	16.95	1.75
October	0.0203	5.89	17.0	30.6	15.93	1.14
November	0.0133	8.18	13.3	26.6	13.53	1.20
December	0.0074	3.68	10.1	22.5	12.12	1.45
		Bikaner [14 years (1977-1990): 3.2 and 1.0 MJ m^{-2} day^{-1}]				
January	0.0369	5.26	5.0	23.2	14.03	1.40
February	0.0559	6.53	8.5	25.9	16.33	1.74
March	0.0691	5.69	14.7	31.8	18.92	2.26
April	0.0405	6.04	21.0	38.3	22.15	2.57
May	0.0806	9.65	25.7	41.8	23.37	3.46
June	0.0857	14.38	28.6	42.0	22.39	4.44

Table 4 contd......

Table 4. contd......

Month	Proportion of wet days	Rain per wet day (mm)	Min temp. (°C)	Max temp. (°C)	Solar radiation (MJ m^{-2} day^{-1})	Wind speed (m s^{-1})
July	0.2350	14.17	27.7	37.9	20.75	4.05
August	0.1636	12.64	26.6	37.0	21.33	3.44
September	0.0929	13.82	24.3	37.0	20.16	2.65
October	0.0323	4.91	18.0	36.1	18.12	1.65
November	0.0238	5.45	11.7	30.5	15.07	1.29
December	0.0161	0.90	6.1	24.9	13.21	1.13
Jaisalmer [15 years: (1981-1995) 3.0 and 1.0 MJ m^{-2}]						
January	0.0172	4.88	6.3	24.1	14.16	1.32
February	0.0284	3.58	9.2	27.0	16.36	1.65
March	0.0215	3.03	14.8	32.5	18.13	2.03
April	0.0133	11.20	20.4	38.5	21.06	2.38
May	0.0172	11.24	24.3	42.6	22.84	3.59
June	0.0289	14.25	26.4	42.6	21.77	4.93
July	0.1333	14.98	25.5	38.4	19.48	4.61
August	0.1140	17.39	24.4	36.5	19.82	3.84
September	0.0467	17.86	22.8	37.1	19.25	2.97
October	0.0086	8.30	18.5	36.7	17.59	1.59
November	0.0044	24.50	12.0	31.5	15.18	1.17
December	0.0022	7.00	6.6	26.4	13.39	1.10

experiment at CAZRI, Jodhpur. In the experiment at Jodhpur the soil water and nitrogen and growth of pearl millet (cv. WRajPop) were measured throughout the season. Table 5 shows a good performance of the model in simulating absolute grain yield and its response to applied nitrogen at rates from 0 to 40 kg N ha^{-1}. The RMSE was 230 kg ha^{-1} providing a mean relative error of 13%. Whilst comparison of the model against three observed crops is not strong evidence of a robust model the error is typical of such models, despite small over simulation of yield in each case, but well within two times the RMSE.

The model showed a comparable performance to the expected yield without applying fertilizer. The model captured well the range of yields observed from near zero to over 2 t ha^{-1} in response to the variable weather conditions. This is illustrated in Fig. 2 that show the 30-year district yield probability compared to the non-fertilized response of cv. WRajPop at the four sites. The response at Pali and Bikaner was almost the same and closely matched the observed response, with Jodhpur producing higher median yields. The high level of crop failure and low median yield at Jaisalmer reflect the extremely marginal nature of this site for reliable cropping returns. We attribute this to the higher frequency of drought at Jaisalmer occurring throughout the growing season.

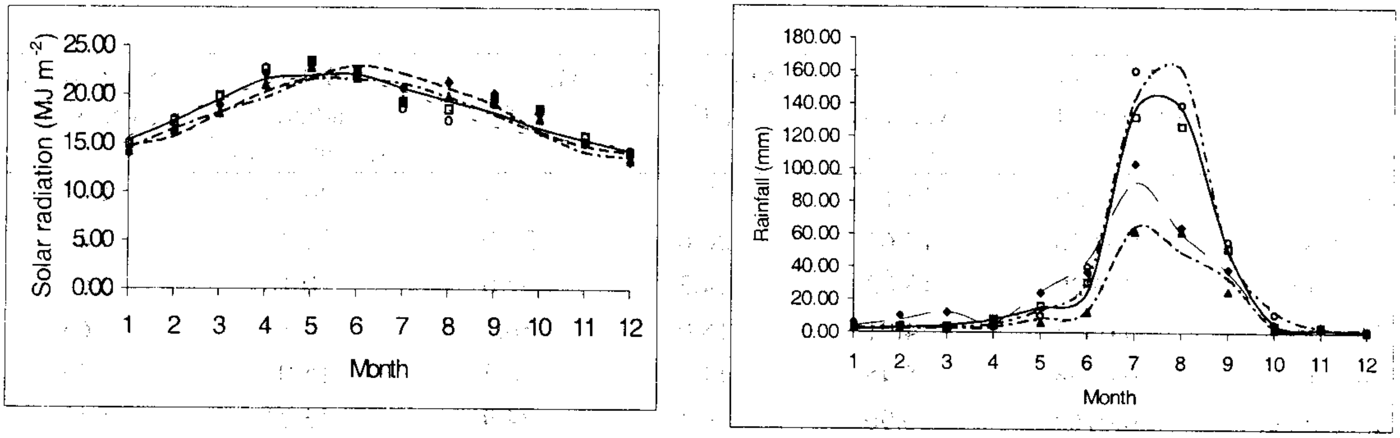

Fig. 1. Observed (symbols) and generated (lines) mean daily radiation (a) and mean monthly rainfall (b) for Pali (○, -----), Jodhpur (□,—), Bikaner (◆,---) and Jaisalmer (▲, -- -- --).

Overall, despite limitations in the possible validation combinations at all the sites, the model shows a behavior of simulating pearl millet grain yield consistent with observed data and as such is suitable for subsequent analyses of yield response to crop type and nitrogenous fertilizers in this region.

Comparison of synthetic and observed weather data

There were important, though small, differences in yield response between the sites due to choice of weather sequence. The observed sequence (Series A) provided a comparable response to the synthetic sequence (Series B) at Pali and Jodhpur (Figs. 3 and 4). At Pali a "cross-over" of the lines for the applied N treatments occurred at low yield under both weather sequences (Fig. 3). This pattern of response concurs that the 34-year sequence largely reflects that generated in the 50-year Series B sequence. However, shorter 14- and 15-year observed sequence from the drier sites of Bikaner and Jaisalmer reflected a more favourable environment than the 50-year Series B sequence (Figs. 5 and 6). Hence, the synthetic sequence (Series B) is probably more realistic of the long-term response at these sites.

Response to plant-type, nitrogen and site

The probability analyses (Figs. 3 to 6) show a strong plant-type (cultivar), nitrogen and site effect in response to variation in weather (observed or synthetic). At Pali and Jodhpur choice of cultivar made a large yield difference with a strong interaction with nitrogen. This is probably because of

Table 5. Comparison of observed and simulated grain yields (kg ha^{-1}) from cv. WRajPop grown under three nitrogen fertilization regimes at Jodhpur. Root Mean Square Error (RMSE) is 230 kg ha^{-1} (13%).

Rate of applied N (kg N ha^{-1})	Observed	Simulated	Square error
0	1264	1440	30976
20	1395	1746	123201
40	1879	1942	3969
Mean	1513	1709	52715

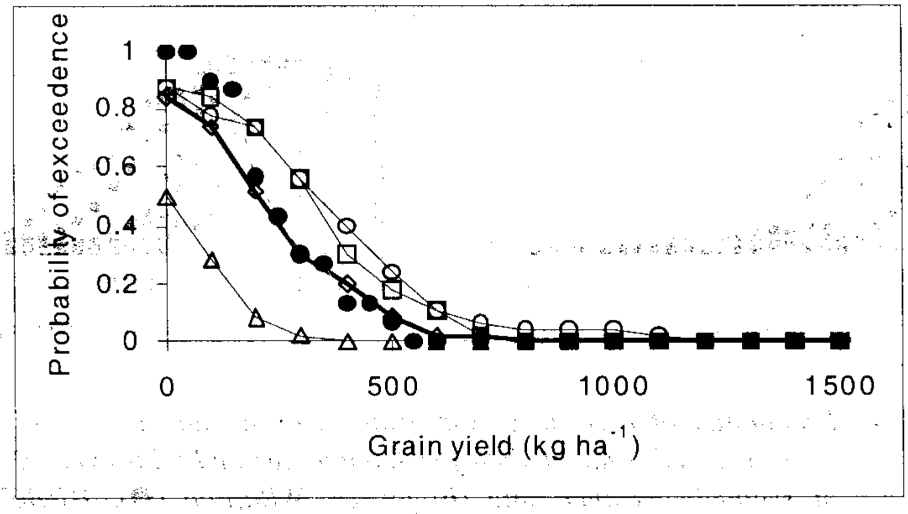

Fig. 2. Probability of exceedence for district grain yield measured over 30 years for Rajasthan (●) compared with the simulated probability for cv. WRajPop without applied nitrogen from Pali (O), Jodhpur (□), Bikaner (△) and Jaisalmer

the restricted maximum rooting depth to 45 cm at this site causing significant post-flowering water stress under N fertilization when it is dry. In terms of median response, highest yield was achieved equally with cv. RCB-IC911 (median 800 kg ha^{-1}) followed by cv. HHB67 (median 613 kg ha^{-1}) with the lowest consistent yield from cv. WRajPop (median 500 kg ha^{-1}) (Table 6). At Bikaner and Jaisalmer cultivar response was much smaller than at the wetter sites, but generally the same order of response was seen.

Similarly, the response to nitrogen was greatest at Pali and Jodhpur, moreover, the nitrogen response was generally larger than the cultivar response, despite the negative effect in dry conditions at Pali. Thus, at these wetter sites significant yield increases (e.g. 700-900 kg ha^{-1}) above what is currently achieved with unfertilized landraces are likely with the combination of an improved cultivar and application of N fertilizer. Even at the drier site at Bikaner, yields could be more than doubled (from 250-550 kg ha^{-1}) with improved

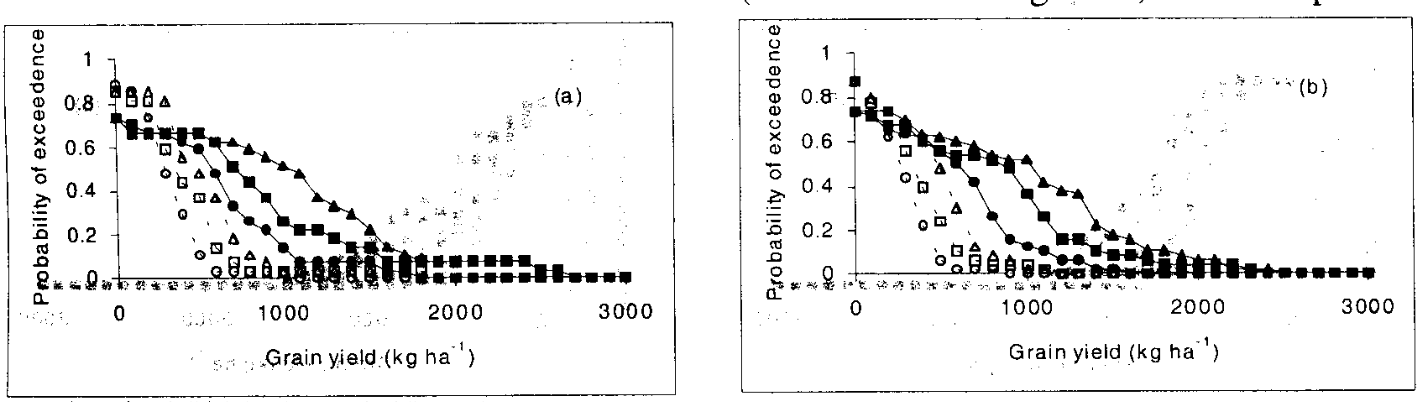

Fig. 3. Probability of exceedence for grain yield simulated over 27 years with observed weather data for Pali (a) and with over 50 years of synthetic weather data (b) for cv. WRajPop (●), HHB67 (■) and RCB-IC911 (▲) without (open symbols) and with (closed symbols) applied nitrogen at 20 kg N ha^{-1}.

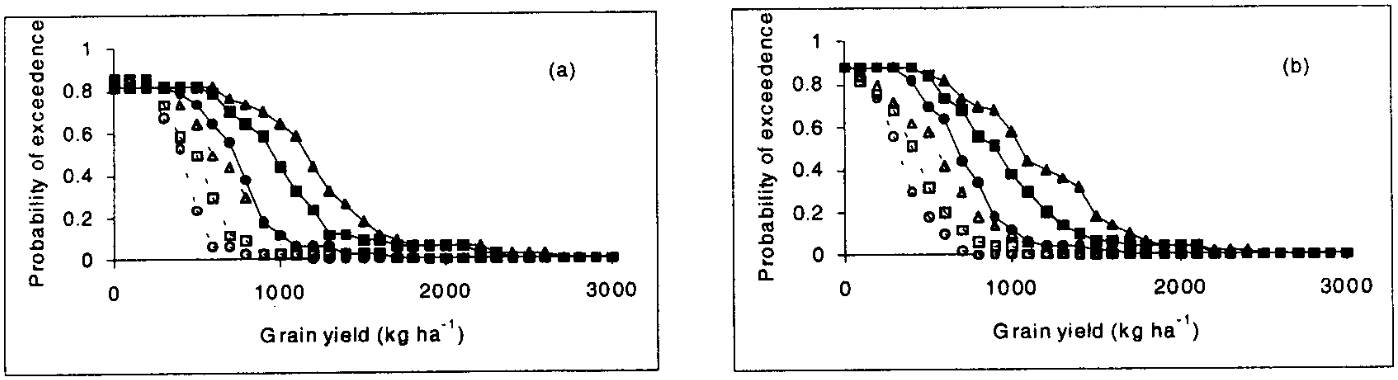

Fig. 4. Probability of exceedence for grain yield simulated over 34 years with observed weather data for Jodhpur (a) and with over 50 years of synthetic weather data (b) for cv. WRajPop (●), HHB67 (■) and RCB-IC911 (▲) without (open symbols) and with (closed symbols) applied nitrogen at 20 kg N ha^{-1}.

cultivars and application of N fertilizer (Table 6). However, at Jaisalmer, improved cultivars and N fertilization could not be economically justified for pearl millet cropping. This is because of low rainfall, low water holding capacity of the soil and high evaporative demand. Indeed, wind speed is highest at Jaisalmer during the cropping season (Table 4) that will cause higher evaporation.

Discussion

The results show two important benefits for farmers that is possible in Rajasthan, India and other arid zones of the world where pearl millet is a major crop. These are the wide-scale increased yield from improved hybrid cultivars and further increase in yield with N-fertilization. Whilst the benefits of improved cultivars are well known in favourable environments the benefits have been elusive in Rajasthan based upon field experiments (Bidinger and Parthasarathy Rao, 1990). Our study shows that only at the extremely marginal site of Jaisalmer the high tillering landrace-type cultivars are probably the best types. However, at Pali, Jodhpur and Bikaner, the

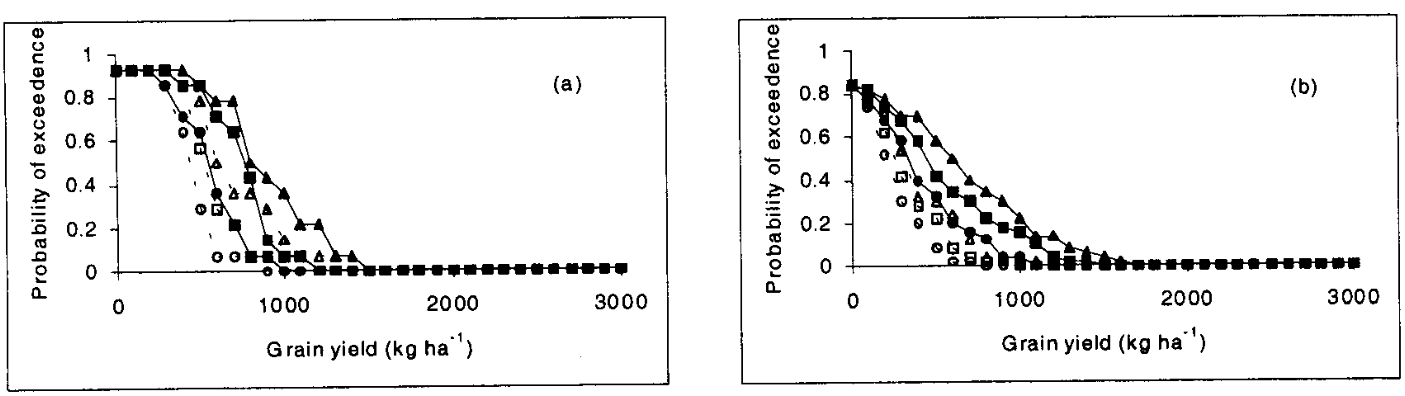

Fig. 5. Probability of exceedence for grain yield simulated over 14 years with observed weather data for Bikaner (a) and with over 50 years of synthetic weather data (b) for cv. WRajPop (●), HHB67 (■) and RCB-IC911 (▲) without (open symbols) and with (closed symbols) applied nitrogen at 20 kg N ha^{-1}.

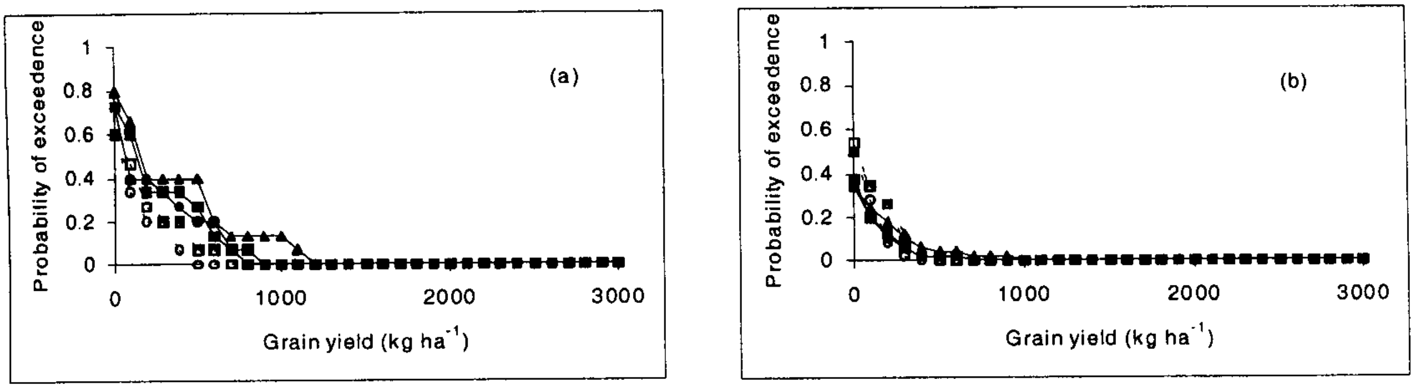

Fig. 6. Probability of exceedence for grain yield simulated over 15 years with observed weather data for Jaisalmer (a) and with over 50 years of synthetic weather data (b) for cv. WRajPop (●), HHB67 (■) and RCB-IC911 (▲) without (open symbols) and with (closed symbols) applied nitrogen at 20 kg N ha^{-1}.

more representative sites of Rajasthan's cropping zone, significant benefits could be provided with improved cultivars. At these three sites cv. RCB-IC911 had superior yield with or without N fertilizer. The hybrid HHB67 was nearly always better than the regional landrace, WRajPop, but not greater than cv. RCB-IC911.

This shows that the tillering and duration traits need to be combined in some optimal combination. The short duration cv. HHB67 despite high tillering capacity was an advantage over the comparable landrace, WRajPop that had larger leaves. However, low tillering was no disadvantage for cv. RCB-IC911 because of even larger leaves. The medium duration types, therefore, are more suited to the wetter regions. Clearly, pursuit of any single trait should be pursued with caution; rather a suite of traits may be the only practical way to proceed anyway.

The benefits of N fertilization shown in this study indicate that N-deficiency is endemic in Rajasthan and so also in other arid areas, but that amelioration with fertilization will benefit all but extreme arid situations as in Jaisalmer. What is surprising is the general additive effect of N fertilization to the cultivar effect except at Pali in very dry years. At Pali the reductive effect of N in the dry years is attributed to the shallow rooting depth restricting access to deeper stored soil water. This would, therefore, be a problem at other sites if rooting depth were shallow. Thus, any evaluation of the likely response of pearl millet at other sites needs an agronomic assessment (e.g. rooting depth) of likely crop response. This is the advantage of this modelling approach used here that was not possible in the earlier analyses of van Oosterom *et al.* (1996). The response at Jaisalmer highlights the differences between sites such that crops at Jaisalmer suffer more significant water stress early on in the season that results in lower yield potential and the lower risk of yield loss from water stress later in the season. The classic "hay-off" reaction as seen at Pali under nitrogen fertilization highlights the risk of over-fertilization (Fig. 3). This caused increased water use prior to flowering with subsequent water stress during grain filling and lower grain yield than would otherwise occur if the crop was unfertilized. Thus,

Table 6. Table of median yields (kg ha^{-1}) from each cultivar and nitrogen treatment at each site (Series B) except Jaisalmer, where significant crop failures placed the median close to zero (see Fig. 6 for more detail)

N Treatment (kg N ha^{-1})	WRajPop	HHB67	RCB-IC911
Pali			
0	250	300	450
20	600	750	950
Jodhpur			
0	400	500	600
20	750	900	1300
Bikaner			
0	250	300	400
20	350	450	550

at Jodhpur and Bikaner the risk of over-fertilization was lower than at Pali because of their respective deeper roots and lower rainfall with higher probability of water stress before flowering.

A question arises as to why this study showed consistent benefits with improved cultivars that have not been clear in farm experiments of Weltzien *et al.* (1996). The approach here allows the temporal variation of weather to be part of the analysis thus extending the analysis beyond the few years that were possible in the recent experiments. Generally, the fertilizer effect was greater than the cultivar effect, supporting the view that attention to the agronomy of pearl millet is more important than breeding *per se*. Of course, the institutional and household economics of both, breeding and agronomy strategies need to be evaluated. Future comprehensive field experiments are, however, needed to validate these results. This is particularly the case for the combined benefit of hybrids and N-fertilization.

We have concentrated only on the grain yield advantage of representative cultivars and N management of pearl millet. There are, of course, other traits and products that can be equally or more important than grain yield, but an analysis of these are beyond the scope of this study. Traits such as fodder value (van Oosterom *et al.*, 1996), grain size (Chintu *et al.*, 1996) and milling quality (Hadimani *et al.*, 1995) affect choice of cultivar and future research should investigate how these may be understood better and eventually modelled in a predictive way. With such models the value of research programs may be more accurately assessed over large geographical regions. The coupling of genetic, agronomic and social models in a Geographic Information Systems context, therefore, remains a worthwhile pursuit.

Conclusion

Our study showed that tangible benefits of increased pearl millet grain yield from improved cultivars with or without additional nitrogen fertilizer appears possible at all but our marginal study sites in Rajasthan. In terms of median response, highest yield was achieved with cultivar RCB-IC911 (median 800 kg ha^{-1}) followed by cultivar HHB67 (median 613 kg ha^{-1}) with the lowest consistent yield from cultivar WRajPop (median 500 kg ha^{-1}). At Bikaner and Jaisalmer cultivar response was much smaller than at the wetter sites but generally the same order of response was seen. Similarly, the response to nitrogen was greatest at Pali and Jodhpur; moreover, the nitrogen response was generally larger than the cultivar response, despite the negative effect in dry conditions at Pali. Thus, at these wetter sites significant yield increases (e.g. 700-900 kg ha^{-1}) above what is currently achieved with unfertilized landraces are likely with the combination of an improved cultivar and application of N fertilizer. Even at the drier site at Bikaner, yields could be more than doubled (from 250 to 550 kg ha^{-1}) with improved cultivars and N-fertilization. However, at Jaisalmer, improved cultivars and N-fertilization could not be economically justified. Significant benefits are likely from an integrated approach to plant breeding and agronomy in these semi-arid regions of India and Africa where N deficiency is endemic.

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Appendix 1. Definition of APSIM-Millet cultivar and soil water and nitrogen variables. Base, optimum and maximum temperature, 10, 33 and 46°C, respectively, are used for all thermal time calculations

Variable	Variable	Units
head_grain_no_max	Maximum number of gains per head	# $head^{-1}$
grain_gth_rate	Maximum grain growth rate	mg day^{-1}
tt_emerg_to_endjuv	Thermal time from emergence to end of juvenile stage	°C day
est_days_emerg_to_init	Estimated days between emergence and floral initiation	days
pp_endjuv_to_init	Photothermal sensitivity from end of juvenile to floral initiation	days
pp_endjuv_to_init	Photothermal sensitivity from end of juvenile to floral initiation	°C day hr^{-1}
tt_flower_to_maturity	Thermal time from flowering to maturity	°C day
tt_flag_to_flower	Thermal time from flag leaf to flowering	°C day
tt_flower_to_start_grain	Thermal time from flowering to start of grain filling	°C day
tt_maturity_to_ripe	Thermal time from maturity to harvest ripe	°C day
y0_const	Leaf area coefficient to determine the size of the largest leaf (from van Oosterom, 2001a; 2001b)	–
y0_slope	Leaf area coefficient to determine the size of the largest leaf (from van Oosterom, 2001a; 2001b)	–
U	Stage 1 evaporation coefficient	mm
Cona	Stage 2 evaporation coefficient	–
Soilalb	Soil albedo	–
Diff_const	Soil water diffusivity constant coefficient	–
Diff_slope	Soil water diffusivity slope coefficient	–
Cn_bare	Curve number for bare soil	–
Cn_red	Curve number reduction %	%
Cn_cov	Curve number with full surface cover	–
Cn_canopy-fact	Curve number canopy factor	–
Soil_cn	Soil carbon: nitrogen ratio	–
Root_cn	Root carbon: nitrogen ratio	–
Root_wt	Root biomass weight	kg ha^{-1}
Mean T	Annual mean temperature	°C
Amp	Amp . . . . Amplitude of monthly mean temperature	°C
Airdry(n)	Airdry soil water content in layer n	cm^3 cm^{-3}
Ll15(n)	Soil water content at 1.5 kPa in layer n	cm^3 cm^{-3}
Dul(n)	Drained upper limit soil water content in layer n	cm^3 cm^{-3}
Sat(n)	Saturated soil water content in layer n	cm^3 cm^{-3}
Bd(n)	Dry bulk density in layer n	g cm^{-3}
Swcon(n)	Initial soil water content in layer n	cm^3 cm^{-3}
Oc(n)	Initial organic carbon in layer n	%
Fbiom(n)	Initial fraction of mircobial biomass N in layer n	–
Finert(n)	Initial fraction of inert organic matter or N in layer n	–
pH(n)	Soil pH in water in layer n	–