Uneven Variation in Plant-to-Plant Spacing in Pearl Millet[1]

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ABSTRACT

Plant-to-plant spacing in farmers' fields of pearl millet [*Pennisetum americanum* (L.) Leeke] is often highly variable. The effect of typical variation in spacing on grain yield was determined in a range of cropping situations. Twenty within-row plant spacing patterns were designed so that the variance of spacing (Vs) between plants would range from 0 to 2.3 m^2, which represented the range measured from farmers' fields in India. These spacing patterns were tested in three trials conducted on an alfisol (Udic Rhodustalf, Patancheru series) in which plant population, fertility, and season varied. In all the trials, seeds were sown in predetermined positions in each row and later thinned to a single plant per position. As Vs increased from 0.01 to 0.05, 0.10, and 0.70 m^2, yields declined 21, 29, and 47%, respectively. This reduction in yield did not depend on fertility level, season, or plant population. Most of the yield reduction could be attributed to reduction in panicle number per plant, the major yield determinant in the cultivar studied. The results suggest that the tillering capacity of pearl millet, although it provides the capacity to adjust to a wide range of plant populations per se, does not provide adjustment to major changes in Vs. Emphasis in the design of new seeding technology should therefore be on even distribution of seed, rather than on control of seeding rate.

***Additional index words:* *Pennisetum americanum* (L.) Leeke, Plant stand, Variance of plant spacing, Plant population.**

POOR crop emergence in pearl millet [*Pennisetum americanum* (L.) Leeke] often results in suboptimal plant populations in farmers' fields (Soman et al., 1984). Suboptimal crop stands are characterized by both low mean plant populations and an uneven distribution of plants. Both situations can reduce yields, as the area of the polygonal space occupied by a plant in a crop influences yield of an individual plant in a nonlinear fashion (Willey and Heath, 1969). This effect is the result of both excess competition for resources as well as under-utilization of resources.

With Indian cultivars of pearl millet, plant populations less than 100 000 plants ha^{-1}, or one plant per 0.1 m^2, have resulted in reduced yields (Gautam, 1970; Pal and Kaushik, 1972; and Srivastava et al., 1977). Therefore, open spaces greater than 0.1 m^2 in size could affect crop yields. However, the magnitude of such effects is not known, and there are no known reports on the influence of within-row variability in plant spacing on yield in pearl millet.

Both Krall et al. (1977) and Erbach et al. (1972) reported yield reductions due to increases in the standard deviation of spacing between plants in maize (*Zea mays* L.). However, Ramanatha Chetty and Reddy (1979) reported that as long as the optimum plant population (150 000 plants ha^{-1}) and row width (0.45 m) of sorghum [*Sorghum bicolor* (L.) Moench] were maintained, the pattern of distribution of plants within the row (range of plant-to-plant spacing of 0.1–0.5 m) did not influence yield. Their data showed that there was a loss in yield per unit area due to missing plants. Uniformity of plant distribution, therefore, seems to be an important consideration for optimizing yield in these cereals.

Pearl Millet produces many productive tillers and may, therefore, be less sensitive to uneven stands than maize or sorghum. Given the frequent poor stands of

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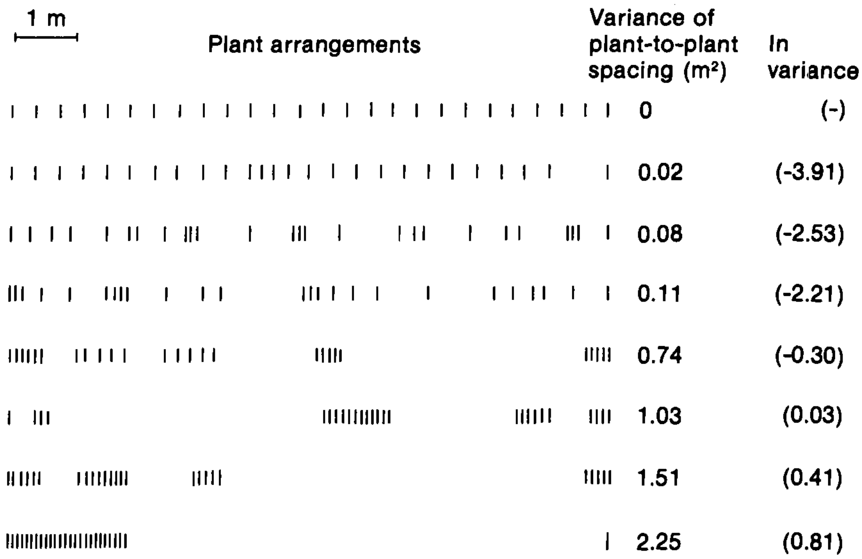

Fig. 1. Sample plant arrangements (50 000 plants ha^{-1}) with respective variances of plant-to-plant spacing.

pearl millet in farmers' fields, the degree of compensation possible may be of extreme importance. In our present study we surveyed village fields near the research station to assess the magnitude of variation in plant-to-plant spacing in farmers' fields. We then simulated this range of variation to assess the effect of uneven plant spacing on grain yield and components in pearl millet under two population densities, two fertilizer levels, and rainy and dry environments.

MATERIALS AND METHODS

Evaluation of Variance of Spacing (Vs) in Farmers' Fields

To assess the within-row variability of plant intervals in farmers' fields, we surveyed 39 fields at Aurepalle village, Andhra Pradesh, India, as part of a larger investigation of the relationship of cultural practices and poor millet and sorghum stands (Soman et al., 1984). Farmers sow the two cereals mixed within the row and we did not distinguish species in estimating the Vs. All plant-to-plant distances within each of 10 rows 10 m long were measured at three locations in each field at crop maturity in the 1981 rainy season. The Vs of each field was the average variance (standard deviation squared) of the mean plant-to-plant spacing of each location.

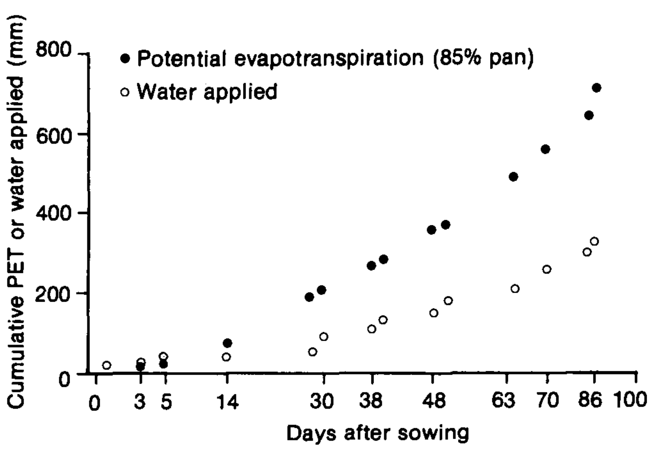

Fig. 2. Cumulative potential evapotranspiration (PET) and amount of water applied for the experiment period of the moisture stress trial (1983 dry season). Days on which sprinklers were run are indicated on the *x* axis.

Variance of Spacing and Grain Yield

Twenty within-row plant patterns were designed so that the Vs for the row would range from 0 (identical spacing between plants) to approximately 2.3 m^2. The distances between plant positions were pre-determined to achieve the desired Vs for each of the 20 treatment rows (Fig. 1). Plots were a 10-m length of row bordered on both sides by evenly spaced plants at the same population, with a row width of 0.5 m. Three seeds were sown by hand at each marked position in the field along the 10-m row. A week after emergence the seedlings were thinned to one per position. At harvest, plant-to-plant spacing was measured in each row and the actual Vs calculated from the standard deviation of the mean plant-to-plant spacing for each row.

These Vs patterns were evaluated in three trials designed to simulate the range of environments that occur in millet-growing areas. A population trial (1981 rainy season) tested 20 Vs patterns at a high plant population of 100 000 plant ha^{-1} and a low population of 50 000 plant ha^{-1}. The trial was a split plot, with populations as main plots in three replicates. A population × fertility trial (1982 rainy season) compared the Vs pattern in the same two populations, but across a high fertility treatment of 100 kg N ha^{-1} and a low fertility treatment of 0 kg N ha^{-1}. The trial was grown as a split-split plot, with the fertility levels as main plots in three replicates. A moisture stress trial (1983 dry season) compared the 20 Vs patterns in the same two populations under deficit irrigation (moisture stress) conditions. The design was the same as in the population trial.

A high tillering pearl millet hybrid, BJ 104, was used in all trials, which were conducted in an alfisol field (Udic Rhodustalf, Patancheru series). Trials were hand-weeded to eliminate non-crop competition. There was no significant disease or pest incidence. In the population and moisture stress trials a total of 100 kg N ha^{-1} was banded in two equal amounts 18 and 30 days after sowing. In all trials a uniform application of 22 kg P ha^{-1} was broadcast before sowing. In the moisture stress trial, irrigation matched potential evapotranspiration (PET) until 14 days after sowing to establish the required stand. Subsequent water applications were approximately 50% of the estimated potential crop evaporation

(85% of USWB class A pan evaporation) to create a moisture stress environment (Fig. 2).

Data on grain yield per plot (5 m^2), number of panicles per plot, grain number per panicle, and 1000-grain mass were transformed to natural logrithms (ln) and analyzed as linear functions of ln Vs. The regressions were compared to test the effects of management (population and fertility levels) and environment (year and season) on yield-Vs relationships.

RESULTS AND DISCUSSION

Variance of Spacing in Farmers' Fields

In farmers' fields the range of within-row Vs was high, ranging from 0.01 to > 2.50 m^2 (Fig. 3). However, in 48% of the fields the Vs was less than 0.1 m^2, and 90% of the fields had a Vs less than 0.7 m^2. The fields we surveyed were plowed with a bullock-drawn plow, and seed was sown by hand. These factors, combined with the poor emergence ability of pearl millet (Lawan et al., 1985) accounted for the wide range in Vs. In a similar study of maize fields at three locations in Kansas, the Vs varied from 0.004 to 0.35 m^2 (Krall et al., 1977). Those maize fields were sown with precision planters and no problems with seedling emergence were noted.

Yield Reduction with Increasing Variance

In all treatments, yield was negatively correlated with Vs although there was considerable scatter in the relationships, possibly because of the small plot size (Fig. 4a–d). The effects of Vs on yield were illustrated for the various experiments by comparing yields (estimated by regression) at selected levels of Vs (Table 1). Since the linear relationships of yield on Vs tended to overestimate the yield of the zero Vs, a Vs of 0.01 m^2 (ln Vs = −4.61) was used for estimation of yield in uniform stands. For the most variable state, we used 0.7 m^2 since this range represents more than 90% of the range in Vs in farmers' fields.

Grain yields in uniform stands (Vs = 0.01 m^2) in the population trial (rainy season 1981) were excellent for both the high (4.74 Mg ha^{-1}) and the low (6.09 Mg ha^{-1}) populations but were reduced at a Vs of 0.7 m^2 by 28% in the high population and by 45% in the low population (Table 1).

Yields in uniform stands in the population × fertility trial were lower and more variable than in the population trial in 1981 (2.96 Mg ha^{-1} in the high population, and 2.81 Mg ha^{-1} in the low population, both in high fertility), but the effects of Vs were similar to those in the first trial. In the low fertility treatment (Fig. 4c), which approximated farmers' fields, yields decreased by 46% at the low population when Vs increased from 0.01 to 0.70 m^2 but only by 34% at the higher population (Table 1). With high fertility, yields in both populations decreased to the same extent (37 and 34%) at a Vs of 0.70 m^2.

In the moisture stress trial, yields were intermediate between the other two trials. Yield reduction in the low population treatment was similar (42%) to that in the two rainy season trials (Table 1). However, in the high population treatment, the reduction was only 15% when Vs was 0.70 m^2 compared to 28 and 34% in the two rainy season trials (Table 1).

Year, Season, and Management Effects

As expected, year effects (rainy season) were significant for yield at uniform stand (Vs = 0.01 m^2) for both the 50 000 and 100 000 plants ha^{-1} populations (Table 1). In neither case, however, were the slopes significantly different, showing that the effects of Vs on grain yields were constant across years (Table 2). The comparison among seasons generally gave the same result, with the single exception of the high population, moisture stress treatment, which, as noted above, had a much lower reduction in yield with increasing Vs, and as a consequence differed significantly from the 1981 and 1982 rainy season trials (Table 2). Why the high population, dry season treatment responded differently to a change in Vs is not known.

Comparisons of the effects of plant population and fertility level on the response to Vs gave similar results. Generally, there were no differences among yields at uniform stands (Table 1) or slopes (Table 2). This is evident in the estimate of yield loss on a percentage basis (Table 1); the percent yield reductions were similar for all conditions, with the exception of the high population treatment in the moisture stress trial. Thus, the effects of Vs were similar across the majority of environments, both natural environments (season and year) and managed environments (plant population

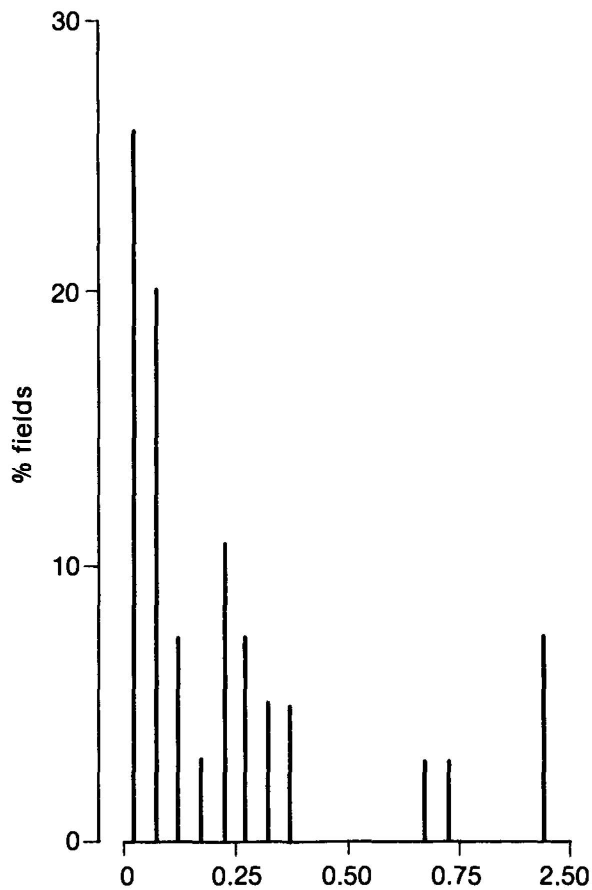

Fig. 3. The distribution of variance of plant-to-plant spacing measured from farmers' fields; the numbers on the x axis represent the class intervals.

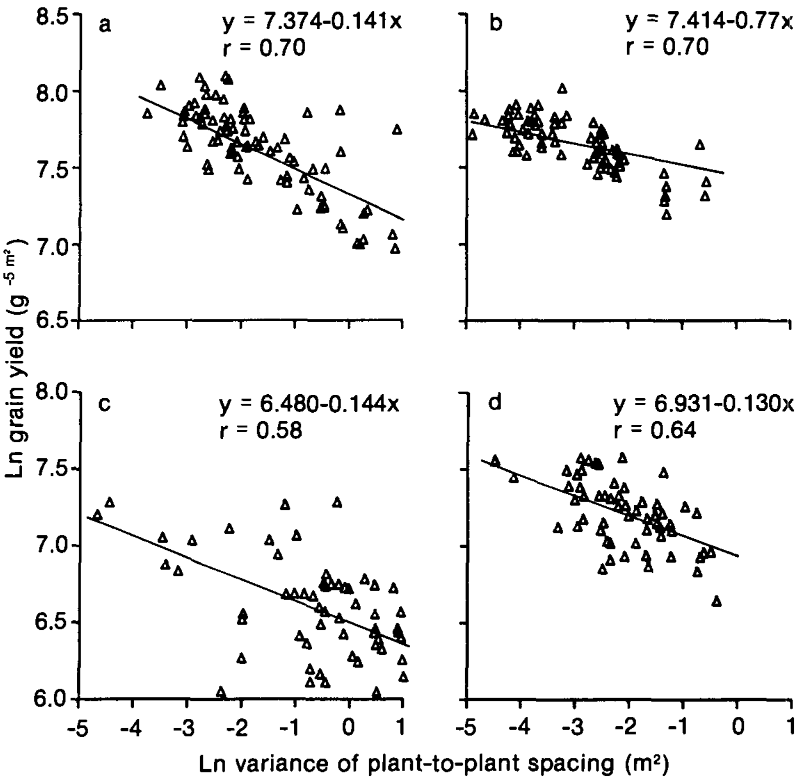

Fig. 4. Grain yield per plot (ln) as a function of the variance of plant-to-plant spacing (ln) for the different trials: (a) population trial, 1981 rainy season, 50 000 plants ha^{-1}; (b) population trial, 1981 rainy season, 100 000 plants ha^{-1}; (c) population × fertility trial, 1982 rainy season, 50 000 plants ha^{-1}, low fertility; and (d) moisture stress trial, 1983 dry season, 50 000 plants ha^{-1}.

and fertility). On average, yield was reduced 21, 29, and 47%, when compared to the yield at a Vs of 0.01 m^2, by an increase in Vs to 0.05, 0.10, and 0.70 m^2, respectively (values derived from the pooled regression of data from all three trials).

Yield Component Changes

Variance of spacing had a significant negative effect on numbers of panicles produced per unit area in all trials (Table 3), but did not affect either the number of grains per panicle, or the individual grain mass (data not presented). Therefore, variation in grain yield in

Table 1. Percent yield loss with an increase in the variance of plant-to-plant spacing from 0.01 m² (even stand) to 0.05, 0.10, and 0.70 m² in populations of 100 000 and 50 000 plants ha⁻¹ with high and low fertility for the three trials. Data are predicted values from fitted functions.

Trial	Managment: Population	Managment: Fertility	Yield at 0.01 m² Vs	Yield loss for increase in variance to 0.05 m²	0.10 m²	0.70 m²
			Mg ha^{-1}		%	
Population trial (1981)	High	High	4.74	12	16	28
	Low	High	6.09	20	27	45
Population × fertility trial (1982)	High	High	2.96	14	20	34
	Low	high	2.81	16	22	37
	High	Low	2.58	14	20	33
	Low	Low	2.54	21	28	46
Moisture stress trial (1983)	High	High	3.03	6	8	15
	Low	High	3.73	19	26	42

Table 2. Comparisons of the effects of year, season, plant population, and fertility on the relationship of grain yield and variance of plant-to-plant spacing. All comparisons are of the slope of ln yield = *a* + *b* ln Vs.

Comparison		Relationship: *b*	SE	*P*
Year (rainy season)				
(50 000 plants ha^{-1})	1981 vs.	−0.14	(0.016)	NS
	1982	−0.11	(0.016)	
(100 000 plants ha^{-1})	1981 vs.	−0.08	(0.009)	NS
	1982	−0.10	(0.014)	
Season (high fertility)				
(50 000 plants ha^{-1})	Rainy (1981) vs.	−0.14	(0.016)	NS
	Dry (1983)	−0.13	(0.020)	
	Rainy (1982) vs.	−0.11	(0.016)	NS
	Dry (1983)	−0.13	(0.020)	
(100 000 plants ha^{-1})	Rainy (1981) vs.	−0.08	(0.009)	NS
	Dry (1983)	−0.04	(0.018)	
	Rainy (1982) vs.	−0.10	(0.014)	*
Populations (1982 & 1983)	Dry (1983)	−0.04	(0.018)	
(1982 high fertility)	50 000 vs.	−0.11	(0.016)	NS
	100 000 plants ha^{-1}	−0.10	(0.014)	
(1982 low fertility)	50 000 vs.	−0.14	(0.027)	NS
	100 000 plants ha^{-1}	−0.10	(0.023)	
(1983 dry season)	50 000 vs.	−0.13	(0.020)	**
	100 000 plants ha^{-1}	−0.04	(0.018)	
Fertility levels (1982)				
(50 000 plants ha^{-1})	Low vs.	−0.14	(0.027)	NS
	High	−0.11	(0.016)	
(100 000 plants ha^{-1})	Low vs.	−0.10	(0.023)	NS
	High	−0.10	(0.014)	

*,** Significant at the 0.05 and 0.01 probability levels, respectively. NS = not significant at P = 0.05. SE = standard error of the slope.

Table 3. The effect of variance in plant-to-plant spacing on panicle number of pearl millet for 50 000 plants ha^{-1} in the high fertility treatments in the three trials. The values are obtained from the relation ln panicle number = a + b ln Vs.

Trial	a	b	r†
Population trial (1981)	5.99	−0.11	0.65‡
Population × fertility trial (1982)	5.93	−0.13	0.65‡
Moisture stress trial (1983)	5.89	−0.10	0.62**

** Significant at the 0.01 probability level.
† r = correlation coefficient.
‡ Significant at the 0.001 probability level.

response to changes in Vs was primarily due to effects on the panicle number. Variation in panicle number explained 82% of the yield variation in the population trial (1981) and 73% in the population × fertility trial (1982). But in the moisture stress trial, panicle number per plot and grain number per panicle explained approximately equal portions of the variation in grain yield (54 and 46%, respectively). This occurred despite the lack of relationship between grain number per panicle and Vs.

Pearl millet is able to compensate for considerable variation in plant population (50 000–150 000 plants ha^{-1}, Anand Reddy and Rao, 1971; 150 000–400 000 plants ha^{-1}, Carberry et al., 1985). However, this ability may not be important in the farmers' fields because of the effects of Vs on this compensatory ability. When Vs increases, the plants within areas of high population decrease productive tiller numbers in response to competitive pressures. However, these effects are not fully compensated for by the increase in productive tiller numbers by the edge plants. For example, a row with a Vs of 0.014 m^2 resulted in an average of four panicles per plant as against only 2.4 panicles per plant in a row with a Vs of 0.54 m^2, the latter with severe clumping of individual plants, although both plots contained the same population density (100 000 plants ha^{-1}) distributed differently. Carberry et al. (1985) reported a similar observation for the same cultivar: panicle number per plant decreased from 4.0 to 1.7 when number of plants per square meter of area increased from five to 40. Since yields in this experiment depended largely on productive tiller numbers, clumping directly reduced yields.

Given the competitive forces, the failure to compensate for reduced panicle numbers by either greater grain numbers per panicle or grain mass under these conditions is not surprising. Pearl millet is thus well adapted to low plant populations per se but not necessarily to uneven plant spacing.

Large yield gains can be achieved by technologies that provide more even stands in the farmers' fields. The mean Vs observed in the farmers' fields suggests that a yield advantage of 35% could be achieved on average, and greater emphasis should be placed on research and extension efforts that will contribute to this goal.

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