Estimating loss in grain yield due to poor plant stand in sunflower

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Summary.

An ability to assess yield loss in a heterogeneous plant stand would be valuable, to assist definition of solutions to poor crop establishment, and to aid replanting decisions. Recently, a multiple regression technique was reported, which permitted estimation of the evenness of the plant stand, and of the percent reduction in grain yield due to suboptimal plant density (gaps) and non-uniformity in plant spacing (clumps). The objective of this paper was to independently validate the technique, using data for sorghum and sunflower from 4 sites in the Central Highlands of Queenland. The results demonstraded that the regression procedures were suitable for quantifying loss in grain yield due to a poor plant stand. Despite low R^2 values for the multiple regression equations at individual sites, the grain yields predicted from them were in close agreement with the observed values. For plot yields, the relationship between predicted and observed values was linear , had an intercept close to zero, a slope close to unity, and accounted for 92 % of the variation. Similarly, for potential yield and mean yield at the four sites, 85 % of the variation was accounted for by linear regression. Because plant density and stand uniformity were less than optimum in the farmers' fields, predicted values of potential yield exceded observed values, especially at sites 2 and 4. Predicted loss in grain yield ranged from 30 to 41 %.

Introduction

In farmers' fields, plant stands are commonly variable (radford *et al.* 1989). Poor plant stands reduce grain yield, with less yield being contributed by any section of the crop in which plant number is excessive (clumps) (Wade 1990). Thus there is both under-utilization of, and excessive competition for, resources in the one stand (Wade *et al.* 1991). Heterogeneity in plant stand reduces the capacity of the crop to compensate effectively for varying seasonal conditions.

An ability to assess yield loss in a heterogeneous plant stand would be valuable, to assist definition of solutions to poor crop establishment, and to aid replanting decisions. An effective method would enable both density and uniformity effects on grain yield to be quantified. Recently, a multiple regression technique was reported, which permitted estimation of the evenness of the plant stand, and of the percent reduction in grain yield due to suboptimal plant density (gaps) and non-uniformity in plant spacing (clumps) (Wase *et al.* 1988 ; Wade 1990). The technique has yet to be indendently validadet, to confirm its utility in quantifying losses in grain yield due to a poor plant stand.

This paper seeks to validate this procedure for estimating yield loss in a variable stand, using independent data for sorghum (*Sorghum bicolor* L. Moench) and sunflower (*Helanthus annuus)* from the Central highlands of Queenslands. The objective was to compare predicted values of grain yield determined from the pultiple regression procedures of Wade *et al.* (1988) and Wade (1990), with direct measurements of grain yield obtained from mechanical harvest. Predicted and observed values of potential yield, mean yield and yield loss were also compared for each site.

Materials and methods

Design of the validation experiments

Four validation experiments were conducted in 1991 in farmers' fields near Emerald, Queensland (latitude 23° 28' S, longitude 148° 11' E). Two crops of sorghum and two of sunflower were selected. All sites commenced with full profiles of soil water (100-130 mm plant available water ; Shaw and Yule 1978). Further details are presented in Table 1 . Following emergence of the farmer's scrop at each location, selective hand-thinning was used to vary plant stand heterogeneity. Pairs of rows at least 50 m in length were either hand-thinned to reduce clumping, hand thinned to enlarge gaps, or not disturbed. At harvest, the grain wieght contribution of each individual plant in the first 10 m of each row was recorded separately, for development of the regression equation for the site. The remainder of each pair of rows was then mechanically harvested, following measurement of inter-plant spacing. Predicted yield from the regression was compared with observed yield from mechanical harvest. Further details are presented below..

Data collected at each site

Distances between rows and between neighbouring plants within the row were recorded. At harvest, a detailed sample was obtained by cutting heads from the first 10 m of each row and weighing the heads individually. Each sorghum head was cut at the lowest node of the panicle, and each sunflower head was cut where it joined the stem. At each site, 50 heads selected at random from this detailed sample were threshed by hand, and the grain weight contribution of each head was recorded separately. Linear regression was used to quantify the relationship between grain weight and heat weight at each site. Grain weight for the remaining plants in the detailed sample was estimated from these individual site regressions. The remainder of each plot was mechanically harvested, in order to obtain a direct measurement of observed grain yield.

Prediction of plot yield for each site

The relationship between grain yield, plant density and stand uniformity was examined for the individual plant data for each site, using the method reported by Wade *et al.* (1988) and Wade (1990). The technique involved quantifying the relationship between grain weight per plant and area per plant, and adding a term for uniformity based on the proximity of neighbouring plants withing the row (equation 1). Multiplying through by density provided a direct relationship with grain yield (equation 2).

$$W = a + bA + cA^2 + dC$$

$$Y = aP + b + cA + dCP$$

where Y is grain yield (g/m^2) ; W is grain weight per plant (g) ; A is area per plant (m^2) ; P is plant density (plants/m^2) ; a,b,c and d are fitted regression coefficients ; and C is coefficient of variation
(%), which simplifies to the following for $X_1 > X_2$:

$$C = 100 \times 2 \times (X_1 - X_2)/(X_1 + X_2)$$

Where X_1 and X_2 are distances (cm) to the neighbouring plants within the row. The proximity of the two neighbours would be expected to dominate inter-plant competition in a wide-row summer crop of low yield expectation.

For each site, values of W, A and C were obtained for each plant in the detailed sample, and equation 1 was fitted by stepwise multiple regression. Predicted grain yield was obtained by substituting into equation 2 the mean values for A and C from the mechanically harvested plot area. The relationship between predicted and oberved plot yield was then graphed and analysed using linear regression.

The potential yield of a site was taken as Y_{opt}, the yield prediction from equation 2 for commercially recommended plant densities and levels of uniformity presumably attainable by skilful farmers (Wade 1990). This commercially achieveable yield potential was calculated by allocating each plant at a site tol of 9 groups, according to its density and uniformity (Table 2). Plant number (N) and mean value of area per plant (A) and uniformity (C) were obtained for each of the 9 groups. Mean grain yield of each group was calculated by substituting its A and C values into equation 2. Commercially achievable site yield potential (Y_{opt}) was taken as the value for the P_1 Co group, (plant density from 5 to 10/m^2 for sorghum and 4 to 6/m^2 for sunflower, coefficient of variation from O to 50 %.

The contribution of each group to the overall reduction in grain yield, relative to Yopt, was calculated according to equation 4 :

$L = 100 \times (Y_{opt} - Y) / Y_{opt} \times NA / \Sigma NA$

where L is percent reduction in grain yield for the group relative to Y_{opt} ; Y, A and N are mean yield (g/m^2), mean area per plant (m^2) and plant number for each group ; and ΣNA is the total area of crop sampled.

The sum of values of L for each group indicated below was then taken to indicate percent reduction in grain yield mainly due to suboptimal plant density (Lp) and non-uniformity in plant spacing (Lc). The equations are :

$L_p = P_oC_o + P_oC_1 + P_oC_2$
$L_c = P_1C_1 + P_1C_2 + P_2C_1 + P_2C_2$

Mean yield of each site was calculated by subtracting the yield losses from the potential yield. The equation is :

$Y_{mean} = (100 - L_P . L_c)\, Y_{opt}$

The relationship between predicted and observed values of potential yield and mean yield were then graphed and analysed using linear regression.

Results

All sites commenced with full profiles of soil water. The deeper scrub soils at sites 1 and 4 received follow-up rain before flowering, while the shallower downs soils at sites 2 and 3 did not. Consequently, the yield of sorghum was higher at site 1 than site 2, and the yield of sunflower was higher at site 4 than site 3 (Table 1). Site mean yield ranged from 0.78 T/ha at site 3 to 3.27 t/ha site 1.

At each of the four sites, grain weight per plant was linearly related to head weight per plant (Table 3), with values of R^2 ranging from 0.81 to 0.99. No further improvement in accountability was obtained by adding a quadratic term to the regression. The proportion of head weight allocated to grain was consistent within species, being 36 % in sunflower and 79 % in sorghum at these locations.

In contrast, the regression equations for yield response to plant density and stand uniformity accounted for only a minor proportion of the total variation at each site (Table 4). Nevertheless, the fitted regression coefficients were often statistically signifiant. At site 2 for example, where the regression accounted for 10 % of the total variation in grain yield, all four regression coefficients were statistically significant.

The mean plant density and stand uniformity for each of the 18 two-row plots which were mechanically harvested are show in Table 5, together with their observed and predicted grain yields. The relationship between predicted and observed grain yield was linear, had an intercept close to zero, a slope close to unity, and accounted for 92 % of the total variation (Fig. 1). The equation is :

$$Y_p = 0.17 + 1.10\, Y_0 \qquad (R^2 = 0.92\,;\, N = 18)$$

Where Y_P and Y_0 are predicted and observed grain yield (t/ha).

The calculation of predicted grain yield for the 9 density and uniformity groups at sites 1 to 4 is shown in tables 6 to 9, respectively. At each site, Y_{opt} is taken as the P_1C_0 group. Yields greater than Y_{opt} were predicted for the P_2 groups at each of the 4 sites. Yield losses were examined only for the P_0 and P_1 groups.

Observed and predicted values of potential yield and mean yield for each of the 4 sites are shown in Table 10. For the observed values at each site, potential yield was taken as that of the highest yielding plot, and mean yield was taken as the average of the observed plot yields. Mean values of density and uniformity associated with those observed grain yields are also shown. Similarly, predicted values of Y_{opt} and Y_{mean} are shown for each site, together with the density (1/A) and uniformity (C) used in the calculation. The relationship between predicted and observed grain yield was linear, had an intercept close to zero, a slope close to unity, and accounted for 85 % of the total variation (Fig. 2). The equation is :

$$Y_P = 0.38 + 1.01\, Y_0 \qquad (R^2 = 0.85\,;\, N = 8)$$

where Y_p and Y_0 are predicted and observed grain yield (t/ha).

For site mean yield, predicted and observed values were almost identical. For potential yield, predicted values were similar to the observed values at sites 1 and 3, but exceeded the observed values at sites 2 and 4.

Losses in grain yield calculated from both the predicted and observed values of potential yield and mean yield at each site are schown in Table 11. Contributions to loss in predicted grain yield due to suboptimal plant density (P_0C_0, P_0C_1 and P_0C_2 groups) and non-uniformity in plant spacing (P_1C_1 and P_1C_2 groups) are also shown. Predicted loss in grain yield ranged from 30.5 to 41.3 % over the four sites, with almost all of the loss attributable to gaps in the stand (Table 11). Predicted loss in grain yield exceeded observed loss, particularly at sites 2 and 4.

Discussion

The cultural practices shown in Table 1 are typical of those used for rainfed summer crops in the Central Highlands of Queenland (Milne *et al.* 1988). Over the 18 mechanically harvested plots, observed grain yield ranged from 0.58 to 4.07 t/ha (Table 5). This range in grain yield is representative of that expected for rainfed summer crops of sorgum and sunflower in this region (Milne *et al.* 1988). Consequently, these data should be adequate for testing the utility of the regression method for quantifying loss in grain yield due to a poor plant stand.

At each site, the relationship between grain weight and head weight was linear, and accounted for more than 80 % of the variation (Table 3). Use of these regressions to predict grain weight for the other heads in the sample should not be a major source of error. This subsampling procedure provided considerable savings in the time and effort required to obtain the grain weight contributions by individual plants in these detailled samples.

The regression equations for yield response to plant density and stand uniformity only accounted for up to 21 % of the variation (Table 4). Nevertheless, the fitted regression coefficients were often statistically significant. This result is interpreted as evidence that the from of the equation is robust, but there is considerable variation in individual plant grain weight for each combination of density and uniformity. Such variation in grain weight contribution would be associated with factors not considered in the regression, which dealt only with spatial relationship. As Wade *et al.* (1988) discussed, variation in seed size, depth of seed placement, time of emergence, the quality of the microenvironment for seedling emergence and subsequent growth, and the proximity of neighbouring plants in adjacent rows and at distances greater than X_1 and X_2 within the row could all contribute to variation in individual plant grain weight. These other factors contribute to individual plant vigour, and may become more important than spacing in a highly variable stand (Tekrony and Egli 1991).

The observed decline in R^2 values from 0.50 in carefully conducted experiments (Wade *et al.* 1989) supports the contention that vigour becomes increasingly important in variable stands. The early-emerging plant would presumably have the opportunity to utilise resources deemed otherwise to be available to its late-emerging neighbours, therby permitting the early-emerger to contribute a larger amount of grain than would have been expected. The data set would thus contain plants which contributed a large W from a small A. Variation in individual plant vigour would result in reduced precision in the relationship between grain weight, plant density and stand uniformity, and in a positive value for the ''a'' coefficient in equations 1 and 2.

Despite the low R^2 values for the regressions between grain weight, plant density and stand uniformaity, the grain yields predicted form them for each of the 18 plots are in close agreement with the observed values (Table 5). This close agreement provides further support for the contention that the form of the equation is robust, withing the limitations imposed by its accounting solely for spatial contributions to variation in grain yield. The strong linear relationship between predicted and observed grain yield, with an intercept close to zero and a slope close to unity, suggests the regressionreported by Wade *et al.* (1988) is suitable for estimating plot yield. The relationship could be further improved, however, by adding a term for individual plant vigour.

Estimates of potential yield, mean yield and yield loss (Wade 1990) are dependent uponthe accuracy of the regression equation for the site (Wade *et al.* 1988) The positive ''a'' values in equations 1 and 2 resulted in overprediction of yield at high density (Tables 6 to 9). This arose from imprecision in predicting the grain yield contribution of a plant from spatial relationships alone, and from the limited number of plants available at high density (P_2), particularly at site 4. Consequently, yield loss is examined for the range of plant densities in which adequate data were sampled, and in which the regressions should be sufficiently accurate. For each of the four sites, only the P_0 and P_1 groups are considered below. Deletion of the P_2 groups from the yield loss calculation should not be a major source of error, since there were few plants in the high density category at these sites.

Despite the limitations discussed above, predicted and observed values of potential yield and mean yield were similar (Table 10). The relationship between the predicted and observed values was linear, had a slope close to unity, an intercept close to zero, and accounted for 85 % of the total variation (Fig. 2). Indeed, values for mean yield fell extremely close to the dashed line with a slope of unity. For potential yield, however, predicted values did exceed observed values, especially at sites 2 and 4 (Table 10). The reason for this is provided by the density and uniformity data reported in Table 10. For each site, the observed yield potential was taken as that recorded from the highest yielding plot. Only at site 1 did the observed density of the highest yielding plot fall within the range specified for potential yield to be attained (P_1). None of the observed levels of uniformity were within the most favoured class (C_0). Consequently, the value taken as potential yield at each site is likely to underestimate the true site yield potential, which would presumably be attained by a plot within the P_1C_0 group (Wade and Foreman 1988 ; Wade and Douglas 1990). The predicted value of potential yield, which exceeded the observed value, may thus be closer to the true site yield potential.

Because predicted values of potential yield exceeded observed values, predicted losses exceeded observed losses (Table 11). Predicted losses ranged from 30 to 41 %, a result similar to that reported in a survey of crop establishment in sorghum and sunflower on the Central Highlands of Queensland in 1987/88 (Radford *et al.* 1989). The comparability in percent yield loss is not surprising, since both sources report stands characterised by inadequate plant number and poor plant distribution. Gaps in the stand were again the major contributor to yield loss in this analysis (Table 11). Higher yields should result from the attainment of better plant stands.

We conclude that the techniques reported by Wade *et al.* (1988) and Wade (1990) are suitalbe for quantifying loss in grain yield due to a poor plant stand. Predicted yield losses appear to provide reasonable estimates of actual yield loss, despite the inability of the current methodology to account for all factors influencing the final outcome, and despite the difficulty in obtaining robust measurements of site yield potential. Work should continue to improve the methology by adding a term for individual plant vigour, and in particular, by developing a method whereby yield loss may be estimated at establishment. This would permit replanting decisions to be made early in the life cycle, and would entail less work than recording individual plant grain weight at harvest. These issues are examined in subsequent papers.

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Table 1. Details of the four locations used in the validation experiments, including soil type (McDonald and Baker 1986), soil classification (Northcote 1979), site agronomic management, crop phenology and site mean yield.

	Site 1	Site 2	Site 3	Site 4
Location	"Bettafield"	"The Glen"	"The Glen"	"Mt.Lowe"
Soil type	Scrub TbUg	Downs BUg	Downs BUg	Scrub TbUg
Soil classification	Ug. 5.25	Ug. 5.12	Ug. 5.12	Ug. 5.25
Crop	Sorghum	Sorghum	Sunflower	Sunflower
Cultivar	Pride	Gunsynd	Advance	Advance
Row spacing (m)	0.70	0.60	0.60	0.75
Plot length (m)	80.0	70.0	51.0	73.0
Planting date	22 January	20 January	24 January	25 January
Flowering date	21 March	26 March	25 March	26 March
Harvest date	14 May	29 May	29 May	15 June
Rainfall (mm)	103	235	235	291
Site mean yield (t/ha)	3.27	1.99	0.78	0.99
Number of plots	6	3	3	6

Table 2. The density and uniformity ranges corresponding to each of the nine groups to which plants were allocated in the detailed sample at each site, for sorghum and sunflower.

Group	Sorghum		Sunflower	
	Density (plants/m^2)	Uniformity (%)	Density (plants/m^2)	Uniformity (%)
P_0C_0	0 - 5	0- 50	0 - 4	0- 50
P_0C_1		50-100		50-100
P_0C_2		100-140		100-140
P_1C_0	5 - 10	0- 50	4 - 6	0- 50
P_1C_1		50-100		50-100
P_1C_2		100-140		100-140
P_2C_0	> 10	0- 50	> 6	0- 50
P_2C_1		50-100		50-100
P_2C_2		100-140		100-140

Table 3. Regression equations for the relationship between grain dry weight and head fresh weight at each of four locations.

W, grain weight/plant (g); H, head weight/plant (g).

Site	Regression Equation	R^2	N
1	W= -2.94(±0.76) + 0.803(±0.009).H	0.99	50
2	W= -0.88(±0.63) + 0.777(±0.009).H	0.99	50
3	W= +5.46(±0.38) + 0.377(±0.026).H	0.81	50
4	W= +7.98(±2.62) + 0.348(±0.016).H	0.88	64

Table 4. Regression equations for yield response to plant density and stand uniformity at four locations.

W, grain weight/plant (g); A, area/plant (m^2); C, coefficient of variation (%).

Site	Regression Equation	R^2	N
1	$W = 51.8(\pm 5.4) + 129.4(\pm 29.1).A - 17.4(\pm 30.8).A^2 - 0.077(\pm 0.059).C$	0.15	418
2	$W = 27.5(\pm 6.1) + 126.0(\pm 38.5).A - 130.7(\pm 53.3).A^2 - 0.012(\pm 0.005).C$	0.10	134
3	$W = 9.1(\pm 5.4) + 73.5(\pm 26.1).A - 45.8(\pm 26.4).A^2 - 0.020(\pm 0.041).C$	0.21	88
4	$W = 42.5(\pm 6.8) + 65.4(\pm 25.3).A - 53.4(\pm 21.7).A^2 - 0.045(\pm 0.049).C$	0.03	229

Table 5. The plant density, stand uniformity and observed grain yield for each of 18 plots of sorghum and sunflower grown in the Central Highlands of Queensland in 1991. The grain yield predicted for each of the 18 plots, by substituting the observed values of density and uniformity into the appropriate site regression (Table 4) are also shown.

Site and plot	Mean density (plants/m^2)	Mean coefficient of variation (%)	Observed grain yield (t/ha)	Predicted grain yield (t/ha)
Site 1				
1	8.11	58.4	4.07	5.11
2	4.43	55.5	2.35	3.36
3	5.28	57.1	3.58	3.76
4	4.23	59.5	3.05	3.25
5	4.45	58.8	3.03	3.36
6	5.48	57.4	3.52	3.86
Site 2				
7	7.37	64.8	2.10	3.06
8	4.10	63.3	1.70	2.04
9	3.85	64.9	2.18	1.95
Site 3				
10	3.65	68.6	0.58	0.89
11	2.75	64.5	0.75	0.78
12	1.90	74.0	1.01	0.64
Site 4				
13	2.90	54.9	1.13	1.63
14	2.47	58.8	0.87	1.42
15	2.46	58.0	0.99	1.42

Table 6. Plant number per group, mean plant density area per block, coefficient of variation, mean grain yield and percent yield reduction relative to the commercially achievable yield potential, for each of nine groups based on plant density and uniformity in plant spacing at site 1.

Group	Number of plants	Plant density (m^{-2})	Area per block (m^2)	Coefficient of variation (%)	Grain yield (t/ha)	Yield reduction (%)
P_0C_0	33	2.4	14.0	28.5	2.39	8.9
P_0C_1	51	3.0	17.2	76.1	2.59	10.0
P_0C_2	43	2.6	16.5	121.0	2.34	10.8
P_1C_0	54	6.9	7.8	29.6	4.69	Ref.
P_1C_1	51	7.2	7.1	73.5	4.58	0.2
P_1C_2	23	6.8	3.4	119.0	4.18	0.5
P_2C_0	71	14.7	4.8	23.3	8.65	0.0
P_2C_1	52	14.5	3.6	72.4	7.98	0.0
P_2C_2	40	16.6	2.4	116.0	8.38	0.0
	418	5.4	77.0	67.4	3.26	30.4

Table 7. Plant number per group, mean plant density area per block, coefficient of variation, mean grain yield and percent yield reduction relative to the commercially achievable yield potential, for each of nine groups based on plant density and uniformity in plant spacing at site 2.

Group	Number of plants	Plant density (m^{-2})	Area per block (m^2)	Coefficient of variation (%)	Grain yield (t/ha)	Yield reduction (%)
P_0C_0	30	3.1	9.7	20.4	1.68	14.0
P_0C_1	18	2.8	6.4	70.9	1.55	10.0
P_0C_2	19	2.6	7.3	117.8	1.43	12.5
P_1C_0	16	7.2	2.2	17.4	3.04	Ref.
P_1C_1	12	7.0	1.7	70.4	2.95	0.2
P_1C_2	15	6.9	2.2	113.1	2.86	0.4
P_2C_0	16	16.4	1.0	27.1	5.65	0.0
P_2C_1	7	13.3	0.5	83.5	4.70	0.0
P_2C_2	1	11.5	0.1	102.4	4.17	0.0
	134	4.3	31.1	60.2	1.91	37.1

Table 8. Plant number per group, mean plant density area per block, coefficient of variation, mean grain yield and percent yield reduction relative to the commercially achievable yield potential, for each of nine groups based on plant density and uniformity in plant spacing at site 3.

Group	Number of plants	Plant density (m^{-2})	Area per block (m^2)	Coefficient of variation (%)	Grain yield (t/ha)	Yield reduction (%)
P_0C_0	14	1.8	7.8	26.0	0.64	9.6
P_0C_1	21	2.1	9.8	74.4	0.68	10.8
P_0C_2	18	2.0	9.0	119.1	0.64	11.1
P_1C_0	7	4.9	1.4	19.0	1.06	Ref.
P_1C_1	9	4.6	1.9	81.0	0.98	0.5
P_1C_2	4	5.0	0.8	121.6	0.97	0.2
P_2C_0	8	8.2	1.0	31.4	1.37	0.0
P_2C_1	6	9.7	0.6	65.7	1.44	0.0
P_2C_2	2	10.8	0.2	110.9	1.43	0.0
	89	2.7	32.5	70.3	0.72	32.2

Table 9. Plant number per group, mean plant density area per block, coefficient of variation, mean grain yield and percent yield reduction relative to the commercially achievable yield potential, for each of nine groups based on plant density and uniformity in plant spacing at site 4.

Group	Number of plants	Plant density (m^{-2})	Area per block (m^2)	Coefficient of variation (%)	Grain yield (t/ha)	Yield reduction (%)
P_0C_0	71	2.3	31.4	24.8	1.35	17.2
P_0C_1	56	2.2	26.0	71.1	1.25	15.6
P_0C_2	29	2.2	13.4	116.7	1.22	8.2
P_1C_0	19	4.8	4.0	28.8	2.50	Ref.
P_1C_1	18	5.0	3.6	72.3	2.53	0.0
P_1C_2	10	4.9	2.0	119.8	2.36	0.1
P_2C_0	10	8.8	1.1	26.7	4.23	0.0
P_2C_1	12	7.9	1.5	78.8	3.68	0.0
P_2C_2	4	7.2	0.6	120.7	3.25	0.0
	229	2.7	83.6	60.7	1.47	41.1

Table 10. Observed and predicted values of potential yield and mean yield for each of four sites in the Central Highlands of Queensland in 1991. Values of plant density and stand uniformity associated with both the observed and predicted yields are also shown.

Site	Observed			Predicted		
	Density (m^{-2})	Uniformity (%)	Yield (t/ha)	Density (m^{-2})	Uniformity (%)	Yield (t/ha)
			Potential Yield			
1	8.11	58.4	4.07	6.92	29.6	4.69
2	3.85	64.9	2.18	7.18	17.4	3.04
3	1.90	74.0	1.01	4.87	19.0	1.07
4	2.33	58.8	1.17	4.76	28.8	2.50
			Mean Yield			
1	5.33	57.8	3.27	5.44	67.4	3.26
2	5.11	64.3	1.99	4.30	60.2	1.91
3	2.77	69.0	0.78	2.73	70.3	0.72
4	2.39	58.7	1.00	2.74	60.7	1.47

Table 11. Observed and predicted losses in grain yield at each of four sites in the Central Highlands of Queensland in 1991. Predicted yield loss is also expressed as a percentage, for reductions in grain yield due to suboptimal plant density, non-uniformity in plant spacing, and their combination.

Site	Observed yield loss (t/ha)	Predicted yield loss (t/ha)	Predicted loss		
			Density L_p (%)	Uniformity L_c (%)	Total L_{pc} (%)
1	0.80	1.43	29.8	0.7	30.5
2	0.19	1.13	36.5	0.6	37.1
3	0.23	0.34	31.5	0.7	32.2
4	0.17	1.03	41.0	0.3	41.3
Mean	0.35	0.98	34.7	0.6	35.3

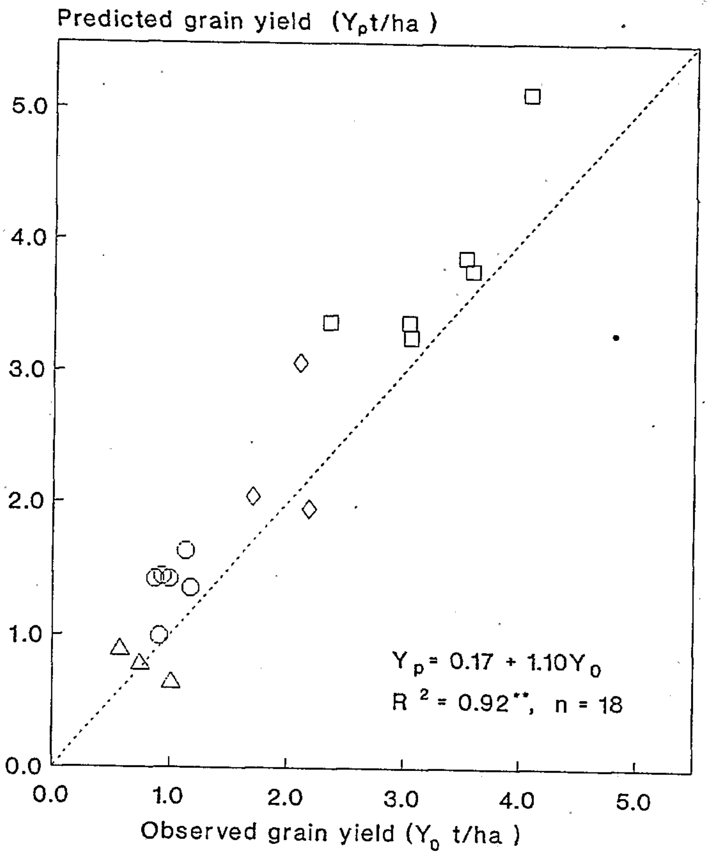

Fig. 1. The relationship between predicted and observed grain yield for each of the 18 plots of sorghum and sunflower grown in the Central Highlands of Queensland in 1991 (□ site 1, ○ site 2, △ site 3, ◇ site 4). The dashed line indicates a slope of unity.

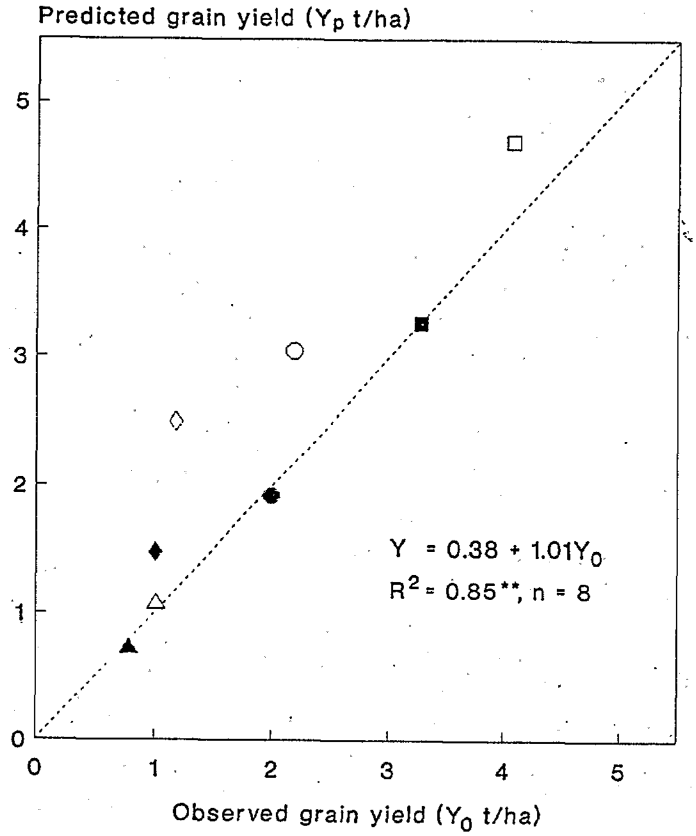

Fig. 2. The relationship between predicted and observed values of potential yield and mean yield at each of four locations in the Central Highlands of Queensland in 1991 (□ site 1, ⬡ site 2, △ site 3, ◇ site 4). Potential yield is shown as open symbols and mean yield as closed symbols. The dashed line indicates a slope of unity.