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ESTIMATION OF OPTIMUM PLOT DIMENSIONS AND REPLICATION NUMBER FOR WHEAT EXPERIMENTATION IN ETHIOPIA

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ABSTRACT

Bread wheat was row and broadcast sown using uniform crop management practices on a research station soil classified as a haplic Nitisol, situated in a major wheat producing region of Ethiopia, during the 1996 and 1997 crop seasons. The harvested area was divided into basic units measuring 1 m by 1 m. Resultant basic unit grain yields were combined to simulate different plot sizes and shapes, and Smith's empirical model and subsequent derivations were used to estimate soil heterogeneity. The broadcast sown trials generally resulted in lower estimates of soil heterogeneity, higher coefficients of variation, and higher values for adjacent plot correlation due to both modified inter-plant competition, and a more variable distribution of wheat plants and basal fertiliser within plots. Parameter estimates from the broadcast sown trials were less consistent over the two year trial period relative to those from the row sown trials. The analyses suggested a marginal superiority for square plot shapes for broadcast sown trials, while for row sown trials rectangular and square plot shapes were equally precise in measuring soil heterogeneity. A comparison of the trial design parameters currently favoured by wheat researchers in Ethiopia with the optimal parameters estimated in the current study suggests that: (a) the design characteristics of broadcast sown wheat agronomic trials appear close to optimal, but (b) the net plot areas harvested from row sown wheat breeding trials are markedly suboptimal.

Key Words: Heterogeneity index, optimum plot size, plot shape, rectangularity, replication

RÉSUMÉ

Ce travail a été réalisé en 1996 et 1997, sur du blé tendre semé en rang ou à la volée, selon des méthodes culturales uniformes. L'essai était situé dans une station de recherche d'une importante région productrice de blé d'Ethiopie, dont le sol était qualifié de Nitisol haplique. La surface récoltée était divisée en unités de base mesurant 1 m par 1 m. Les rendements en grains obtenus par unité de base étaient combinés pour simuler différentes tailles et formes de parcelles. Le modèle empirique de Smith et les dérivations consécutives étaient utilisés pour estimer l'hétérogénéité du sol. Généralement, dans les essais avec semis à la volée, on notait une plus faible estimation de l'hétérogénéité du sol, des coefficients de variation plus grands et des valeurs plus élevées pour la corrélation entre parcelles adjacentes, causées par une modification de la compétition entre plantes et une distribution intraparcellaire des plants de blé et du fertilisant de base plus changeante. Les paramètres estimés à partir des essais semés à la volée étaient moins cohérents d'une année sur l'autre que ceux des essais semés en rangs. L'analyse des données suggère qu'il y a une supériorité marginale des parcelles de forme carrée dans les essais avec semis à la volée, alors que dans les semis en rangs, les parcelles de forme carrée ou rectangulaire donnaient une mesure aussi précise de l'hétérogénéité du sol. Une comparaison des paramètres des plans expérimentaux actuellement favorisés par les chercheurs Ethiopiens travaillant sur le blé et les paramètres optimaux estimés dans cette étude suggère que (a) les caractéristiques du plan expérimental des essais agronomiques de blé semés à la volée semblent proches de l'optimum, mais que (b) les surfaces nettes récoltées dans les essais de sélection du blé semés en rangs sont nettement sous-optimales.

Mots Clés: Forme de parcelles expérimentales, index d'hétérogénéité, parcelles rectangulaires, répétition, taille optimale de parcelles expérimentales

INTRODUCTION

Wheat (*Triticum* spp.) is one of the most important cereal crops grown under rainfed conditions in the highlands of Ethiopia (Hailu, 1991). The Ethiopian Agricultural Research Organisation (EARO) and collaborating institutions conduct a multi-disciplinary national wheat research programme directed towards improving the productivity, yield potential and quality of wheat in Ethiopia (Desalegn *et al*., 1996).

The conduct of cost-effective agricultural research necessitates the efficient use of limited research resources; research trials should attain an acceptable level of experimental precision with minimal cost. The major factors that determine the cost of a field experiment are the size and shape of plots and blocks, and the number of replications used, since these factors are directly proportional to the area occupied by the field trial (Mohamed, 1987). The choice of plot size and shape is influenced by field management techniques, which are related to prevailing agricultural technologies, and the extent of within site variability, which is related to the degree of soil heterogeneity. Therefore, it is important to develop and utilise appropriate methodologies for field experimentation in order to optimise both experimental precision and the efficiency of research resource usage.

Research to determine optimum plot size and shape for specific field crops, based on uniformity trials, has been conducted for many years; considerable progress has been achieved, however, since Smith (1938) developed a method to estimate soil heterogeneity. Kock and Rigney (1951), Federer (1955), Hatheway and Williams (1958), and Narayana Reddy and Ramanatha Chetty (1983) modified Smith's methods.

The two most widely used methods for selecting optimum plot sizes are those suggested by Smith (1938) and Hatheway (1961). Utilising these techniques, crop scientists have recommended optimal plot sizes and shapes for specific crop-soil combinations. For example, Mohamed (1987) reported an optimum plot size and shape for Dura sorghum (*Sorghum bicolor*) in the Gezira irrigation scheme in Sudan, and Narayana Reddy and Ramanatha Chetty (1985) identified an efficient plot size for pigeonpea (*Cajanus cajan*) under dryland conditions in India.

The relationship between the coefficient of variability (*CV*) and plot size can be used for the optimisation of plot size. Subsequent to representing this relationship graphically, the optimum plot size has been obtained in one or two ways by different authors. Narayana Reddy and Ramanatha Chetty (1985) considered optimum plot size to be represented by the point on the curve at which the maximum rate of change in the estimate of *CV* per incremental unit of plot size occurs. However, this method may be affected by the scale of the co-ordinates used in plotting. The second method (Lessman and Atkins, 1963) is based on a derivation of the variance per basic unit area, or similar measures of variability, in relation to plot size. This method was further simplified by introducing the concept of critical plot size: the critical plot size corresponds to the point of maximum curvature on the graphical relationship between variance and plot size (Lessman and Atkins, 1963).

Another method previously considered in the determination of optimum plot size was based on cost factors associated with the number and size of plots within a trial (Smith, 1938). However, this method often identified an impracticably narrow plot dimension as optimal (Narayana Reddy and Ramanatha Chetty, 1985).

Wheat researchers in Ethiopia strive to improve the experimental precision of field trials in order to obtain unbiased and accurate estimates of treatment effects. However, information on the degree of soil heterogeneity and on optimum plot dimensions for wheat experimentation is lacking. By convention, wheat breeders in Ethiopia manually sow wheat in rows within long and narrow plots; gross plot areas are 3.0 m^2 and net plot areas (i.e., harvested areas) are 2.0 m^2 for variety trials, and four replications are normally used (Desalegn *et al*., 1996). By contrast, wheat agronomists conduct their research trials under small-holder conditions; the agronomists customarily establish trials by manually broadcasting wheat seed and basal fertiliser and subsequently incorporating the broadcast inputs with one pass of the local ox-plough (i.e., similar to the conventional practice of peasant farmers in Ethiopia). Agronomic trials, both on-farm and on-station, generally consist of individual plots characterised by gross and net plot areas of 25 and 9.0 m^2, respectively, with two or three replications being common (Tanner *et al*., 1992).

The objectives of this study were to estimate the degree of soil heterogeneity on a typical research station soil in the central highlands of Ethiopia, and to determine the associated optimum plot sizes and shapes for broadcast and row sown wheat experiments.

MATERIALS AND METHODS

Two sets of soil uniformity trials, broadcast and row sown, were established on a soil classified as a haplic Nitisol at the Holetta Research Center (altitude 2400 m a.s.l., latitude 9°03' N, and longitude 38°30' E) which is located in a major wheat producing region of Ethiopia (Hailu, 1991). The trials were conducted during the 1996 and 1997 cropping seasons. Both sets of trials were hand sown using the popular local bread wheat (*T. aestivum*) cultivar "Qubsa" (=Attila, a CIMMYT-derived, semi-dwarf with high yield potential in the central highlands of Ethiopia). The trials were sown on June 20 in 1996 and June 18 in 1997 with uniform application of the inputs and cultural practices recommended for the area (Tanner *et al*., 1991). For row sown trials, fertiliser, in the form of urea and triple superphosphate at the rate of 60 kg N and 60 kg P_2O_5 ha^{-1}, was placed in rows spaced 20 cm apart and then seeds were sown in the rows at the rate of 150 kg ha^{-1}: rows were subsequently covered manually. For broadcast trials, 60 kg N, 60 kg P_2O_5 and 175 kg seed ha^{-1} were broadcast by hand and then were covered by one pass with the local ox-plough. Weeds were controlled by post-emergence spray application of fenoxaprop-p-ethyl at 69 g a.i. ha^{-1} and 2,4-D at a rate of 1.08 kg a.i. ha^{-1}.

At emergence, each trial was subdivided into basic unit plots measuring 1 m x 1 m by fixing sisal strings on permanent pegs spaced at 1 m intervals along all four sides of the trial. At maturity, border strips measuring 3 m for broadcast sown and 2 m for row sown trials were manually removed along each trial perimeter leaving a net area of 12 x 60 m for broadcast sown and 12 x 80 m for row sown trials in 1996, and 10 x 72 m for both trials in 1997. Thus, a total of 720 and 960 basic unit plot areas were harvested from broadcast and row sown trials, respectively, in 1996; in 1997, a total of 720 basic units were harvested from each trial. Each basic unit plot was hand harvested separately by sickle, placed in cloth sacks, tagged, sun-dried in the open air, and then threshed by manually beating the sacks. Grain yield was determined for each basic unit plot area and recorded on a g m^{-2} basis. The grain yields from adjacent basic unit plots were subsequently combined to derive values for different plot shapes and sizes. Plot sizes ranging from 1 to 240 m^2 with various shapes were considered in the study.

Statistical analysis. For grain yield (*GY*), variance among plots, $V_{(X)}$, was computed as the variance among plots for each specific plot area *X*. From this value, the variance per basic unit area, V_X, was determined by the formula:

$V_X = V_{(X)}/X^2$ . . . (Mohamed, 1987)

and comparable variance, *V*, was calculated as:

$V = V_{(X)}/X$ . . . (Keller, 1949)

Coefficient of variation, *CV*, was estimated using grain yield on a basic unit area:

$CV = 100 * {}^2Ö\ V_X/(Mean\ GY)$

The coefficient of soil heterogeneity, *b*, was estimated using Smith's heterogeneity index (Smith, 1938):

$V_X = V_1/X^b$

Using linear regression on the log scale and solving for *b* results in the following equation (Narayana Reddy and Ramanatha Chetty, 1983):

$b = [logV_1 * S \cdot logX – S \cdot logV_X * logX]/[S \cdot (logX)^2]$

where V_X is the variance of yield per unit area of *X* and V_1 is the variance per basic unit of 1 m^2 area.

The values of *b* were subsequently used in the computation of optimum plot sizes and shapes. For plot sizes having more than one shape, the homogeneity of comparable variance was tested to determine the significance of plot shape (i.e., plot orientation): for plot sizes having two shapes, the F-test was applied; for plot sizes having more than two shapes, the Bartlett's chi-square test was used (Narayana Reddy and Ramanatha Chetty, 1982) to test for homogeneity of multiple variances (Gomez and Gomez, 1984). The *b* coefficient was adjusted for infinite field size using the table of adjusted values of Smith's index of soil heterogeneity given by Gomez and Gomez (1984) and the ratio of the size of basic units, 1 m^2 in this case, to the total area. Interpolation was applied to tabular values in order to obtain adjusted values.

The coefficients of rectangular heterogeneity, which are indicative of the level of correlation between adjacent plots, were determined from the equation of Narayana Reddy and Ramanatha Chetty (1982):

$V_X = V_1/(W^{b1} * L^{b2})$

Depending on the magnitude of the coefficients (*b1* and *b2*), the rectangular heterogeneity equation can be rewritten as:

$V_X = V_1/[(L/W)^{B1} * (WL)^{B2}]$ . . if $b1 > b2$, or

$V_X = V_1/[(W/L)^{B1} * (WL)^{B2}]$ . . if $b2 > b1$

where

$B2 = (b1 + b2)/2$ and $B1 = ½b2 - b1½/2$

The shape of a plot was represented by the ratio of *L/W* or *W/L*. The coefficient *B2* represents heterogeneity due to square plot shape, whereas *B1* represents heterogeneity due to rectangular plot shape. A greater divergence between *b1* and *b2* values indicates enhanced efficiency due to rectangular plot shape.

For a given plot size and number of replications, the true treatment difference, *d* (i.e., the least significant difference at the 5% probability level for yield measured in g m^{-2}), was determined using the following equation (Hatheway, 1961):

$d^2 = [2 * (t_1 + t_2)^2 * C_1^2]/[r * X^b]$

This equation may be simplified to:

$d = (Ö\ 2/r) * (w/X^{b/2})$

where

t_1 = the tabulated value of the student-t test of significance

t_2 = the tabulated value of t corresponding to $2 * (1 - p)$ where p is the probability of obtaining a significant result (5% in this case)

C_1 = the coefficient of variation of basic unit size plots

r = the number of replications

$w = (t_1 + t_2) * C_1$

Using modifications suggested by Lessman and Atkins (1963) and Narayana Reddy and Ramanatha Chetty (1985), the optimum plot size, or *X critical* value, was determined at the point of maximum curvature on the graphical relationship between plot size and true treatment difference using the following formula:

$X\ critical = b + [4 * (C_1^2 * (b/2)^3)-]/[b + 2]$

where b is the soil heterogeneity index.

RESULTS AND DISCUSSION

The total number of plots for each plot size and shape considered for row and broadcast sown wheat trials in 1996 and 1997, and the associated measures of variability, are given in Tables 1 and 2. Small plots consistently exhibited higher degrees of variability than larger plots as indicated both by the variance per basic unit area and the *CV*. The coefficient of variation decreased markedly for both row and broadcast sown trials as plot size increased. However, the rate of change was more pronounced for row sown than for broadcast sown trials, especially for plot widths greater than 4 m. Variability was higher for broadcast sown than for row sown trials for the larger plot sizes in both years and for all plot sizes in 1996. The change in *CV* for a constant width (*W*) while varying length (*L*), or vice-versa, was small and similar for both row and broadcast sown trials, indicating a similar degree of soil heterogeneity along both sides of the trials. Plot lengths of 1 to 2 m exhibited the highest degree of variability, particularly as plot widths increased. Variance per basic unit area was consistent for row sown trials in both years, whereas for broadcast sown trials, the variance in the 1996 trial was markedly higher than in the 1997 trial.

TABLE 1. Number of plots, variance among plots ($V_{(X)}$), comparable variance (V), variance per basic unit area (V_X), and coefficient of variation (CV) for all plot areas and shapes for row and broadcast sown wheat in 1996

Shape			Row sown					Broadcast sown				
W[a] (m)	L[a] (m)	Area (m^2)	Plots (no.)	$V_{(X)}$ (x 10^5)	V (x 10^3)	V_X (x 10^3)	CV (%)	Plots (no.)	$V_{(X)}$ (x 10^5)	V (x 10^3)	V_X (x 10^3)	CV (%)
1	1	1	960	0.05	4.56	4.56	20.9	720	0.06	5.7	5.69	30.8
1	2	2	480	0.13	6.59	3.30	17.8	360	0.18	18.4	4.60	27.7
1	4	4	240	0.33	8.13	2.03	14.0	180	0.59	14.7	3.68	24.8
1	5	5	192	0.51	10.11	2.02	13.9	144	0.85	17.1	3.42	23.9
2	1	2	480	0.12	6.18	3.09	17.3	360	0.17	8.4	4.21	26.5
2	2	4	240	0.35	8.80	2.20	14.6	180	0.57	14.3	3.59	24.5
2	4	8	120	0.79	9.90	1.24	10.9	90	2.00	24.1	3.01	22.4

2	5	10	96	1.27	12.72	1.27	11.1	72	2.78	27.8	2.78	21.5
2	8	16	60	2.03	12.71	0.79	8.7	-	-	-	-	-
2	10	20	48	3.44	17.19	0.86	9.1	36	9.88	49.4	2.47	20.3
2	20	40	24	8.47	21.18	0.53	7.1	18	37.42	93.6	2.34	19.7
3	1	3	320	0.23	7.70	2.57	15.7	240	0.32	10.8	3.59	24.5
3	2	6	160	0.68	11.41	1.90	13.5	120	1.12	18.6	3.11	22.8
3	4	12	80	1.47	12.23	1.02	9.9	60	3.81	31.7	2.65	21.0
3	5	15	64	2.36	15.74	1.05	10.0	48	5.50	36.7	2.45	20.2
3	8	24	40	3.89	16.22	0.68	8.1	-	-	-	-	-
3	10	30	32	7.06	23.53	0.78	8.7	24	19.83	66.1	2.20	19.2
3	20	60	16	17.43	29.05	0.48	6.8	12	76.69	127.8	2.13	18.8
4	1	4	240	0.34	8.54	2.14	14.4	180	0.54	13.5	3.37	23.7
4	2	8	120	1.02	12.70	1.59	12.4	90	1.88	23.5	2.93	22.1
4	4	16	60	2.06	12.86	0.80	8.8	45	6.64	41.5	2.60	20.8
4	5	20	48	3.34	16.69	0.83	9.0	36	9.45	47.3	2.36	19.8
4	8	32	30	4.78	14.95	0.47	6.7	-	-	-	-	-
4	10	40	24	8.98	22.45	0.56	7.4	18	35.57	88.9	2.22	19.3
4	20	80	12	18.42	23.03	0.29	5.3	9	142.9	178.6	2.23	19.3
6	1	6	160	0.62	10.32	1.72	12.9	120	1.05	17.5	2.92	22.1
6	2	12	80	1.83	15.28	1.27	11.1	60	3.75	31.3	2.61	20.9
6	4	24	40	3.29	13.71	0.57	7.4	30	13.33	55.5	2.31	19.6
6	5	30	32	5.80	19.32	0.64	7.9	24	19.49	65.0	2.17	19.0
6	8	48	20	7.78	16.20	0.34	5.7	-	-	-	-	-
6	10	60	16	15.83	26.38	0.44	6.5	12	73.70	122.8	2.05	18.5
6	20	120	8	31.40	26.17	0.22	4.6	6	309.4	257.8	2.15	18.9
12	2	24	40	5.18	21.57	0.90	9.3	30	13.71	57.1	2.38	19.9
12	4	48	20	7.74	16.13	0.34	5.7	15	52.29	109.0	2.27	19.5
12	5	60	16	16.92	28.20	0.47	6.7	12	75.91	126.5	2.11	18.7
12	8	96	10	19.07	19.86	0.20	4.5	-	-	-	-	-

12	10	120	8	47.23	39.36	0.33	5.6	6	315.7	263.0	2.19	19.1
12	20	240	4	96.71	40.30	0.17	4.0	3	1513	630.2	2.63	20.9

a *W*, *L*: Width, Length
-: Data not available for these plot dimension combinations

TABLE 2. Number of plots, variance among plots ($V_{(X)}$), comparable variance (V), variance per basic unit area (V_X), and coefficient of variation (CV) for all plot areas and shapes for row and broadcast sown wheat in 1997

Shape			Row sown					Broadcast sown			
W^a (m)	L^a (m)	Area (m^2)	Plots (no.)	$V_{(X)}$ (x 10^5)	V (x 10^3)	V_X (x 10^3)	CV (%)	$V_{(X)}$ (x 10^5)	V (x 10^3)	V_X (x 10^3)	CV (%)
1	1	1	720	0.05	4.9	4.9	19.2	0.03	2.5	2.5	15.6
1	2	2	360	0.12	6.2	3.1	15.3	0.06	3.1	1.5	12.1
1	3	3	240	0.22	7.5	2.5	13.7	0.20	6.8	2.3	14.8
1	4	4	180	0.33	8.2	2.1	12.4	0.32	8.0	2.0	13.9
1	6	6	120	0.64	10.6	1.8	11.5	0.66	10.9	1.8	13.2
1	8	8	90	0.95	11.9	1.5	10.6	1.18	14.7	1.8	13.9
1	9	9	80	0.45	5.0	0.6	10.8	1.21	13.5	1.5	12.0
1	12	12	60	2.06	17.1	1.4	10.3	1.85	15.4	1.3	11.0
1	18	18	40	4.49	25.0	1.4	10.2	3.03	16.8	0.9	9.5
1	24	24	30	6.07	25.3	1.1	8.9	4.48	18.7	0.8	8.7
2	1	2	360	0.16	7.8	3.9	17.1	0.09	4.7	2.4	15.1
2	2	4	180	0.40	9.9	2.5	13.7	0.30	7.5	1.9	13.5
2	3	6	120	0.74	12.3	2.1	12.4	0.56	9.4	1.6	12.3
2	4	8	90	0.80	10.0	1.3	11.1	0.95	11.9	1.5	12.0
2	6	12	60	0.18	1.5	1.5	10.5	1.97	16.4	1.4	11.5
2	8	16	45	3.06	19.1	1.2	9.5	3.02	18.9	1.2	10.7
2	9	18	40	4.18	23.2	1.3	9.9	3.71	20.6	1.1	10.5
2	12	24	30	6.88	28.7	1.2	9.5	5.77	24.0	1.0	9.8
2	18	36	20	16.06	44.6	1.2	9.6	9.32	25.9	0.7	8.3
2	24	48	15	20.78	43.3	0.9	8.2	9.47	19.7	0.4	6.3
5	1	5	144	0.69	13.7	2.7	14.4	0.49	9.8	2.0	12.8
5	2	10	72	1.75	17.5	1.8	11.5	1.42	14.2	1.4	11.7

5	3	15	48	3.23	21.5	1.4	10.4	2.74	18.3	1.2	10.8
5	4	20	36	4.59	23.0	1.1	9.3	4.74	23.7	1.2	10.7
5	6	30	24	8.94	29.8	1.0	8.6	10.06	33.5	1.1	10.4
5	8	40	18	12.38	31.0	0.8	7.6	16.11	40.3	1.0	9.8
5	9	45	16	17.76	39.5	0.9	8.1	19.60	43.6	1.0	9.7
5	12	60	12	28.58	47.6	0.8	7.7	30.06	50.1	0.8	9.0
5	18	90	8	71.77	79.7	0.9	8.2	52.97	58.9	0.7	7.9
5	24	120	6	8.54	7.1	0.6	6.7	47.66	39.7	0.3	5.6
10	1	10	72	1.67	16.7	1.7	11.2	1.42	14.2	1.4	11.7
10	2	20	36	3.82	19.1	1.0	8.5	4.95	24.8	1.2	10.9
10	3	30	24	8.04	6.8	0.9	8.2	9.48	31.6	1.1	10.7
10	4	40	18	11.36	28.4	0.7	7.3	17.41	43.5	1.1	10.2
10	6	60	12	25.96	43.3	0.7	7.4	38.02	63.4	1.1	10.1
10	8	80	9	37.38	46.7	0.6	6.6	63.04	78.8	1.0	9.7
10	9	90	8	50.95	56.6	0.6	6.9	74.44	82.7	0.9	9.4
10	12	120	6	100.9	84.1	0.7	7.3	129.9	108.2	0.9	9.3
10	18	180	4	233.9	130.0	0.7	7.4	229.7	127.6	0.7	8.3
10	24	240	3	313.9	130.8	0.5	6.4	219.5	91.4	0.4	6.1

a *W*, *L*: Width, Length

Row sown trials consistently measured a greater degree of soil heterogeneity than broadcast sown trials as indicated by the larger *b* coefficients (Table 3). Heterogeneity coefficients corre-sponding to variable dimensions of width and length for row sown trials were also consistently larger than those for broadcast sown trials in both years (Table 3); in row sown trials, coefficients related to plot width were slightly smaller than those related to the length of plots, while the reverse trend was observed for broadcast trials. For row sown trials, *b* coefficients of 0.476 and 0.455 with associated R^2 values of 74 and 98% were estimated in 1996 and 1997, respectively; the corresponding coefficients for broadcast sown trials were 0.240 and 0.270 with R^2 values of 95% and 96%. These coefficients indicate that the degree of heterogeneity within a trial is influenced not only by soil variability and plot orientation, but also by crop geometry resulting from the sowing method used. In the broadcast sown trials, the estimated value of the heterogeneity coefficient, *b*, could have been reduced due to: 1) modified inter-plant competition within plots and higher correlation between neighbouring plants; 2) lack of uniformity in plant density within plots which amplified crop geometry effects; and 3) uneven distribution of broadcast fertiliser which introduced heterogeneity and affected crop performance within plots.

TABLE 3. Coefficients of heterogeneity (*b*) and determination from Smith's empirical model relating among plot variance with plot size for grain yield of row and broadcast sown wheat

		1996		1997	
		Index	R^2	Index	R^2

Row sown	*W,*	0.467 (0.081),	95	0.447 (0.028),	98
	L	0.486 (0.090)	-	0.461 (0.020)	-
	b	0.476 (0.060)	74	0.455 (0.010)	98
Broadcast sown	*W,*	0.287 (0.028),	94	0.337 (0.048),	95
	L	0.215 (0.023)	-	0.210 (0.036)	-
	b	0.240 (0.018)	95	0.270 (0.033)	96

Values in parentheses are standard errors of the coefficients

The *b* coefficient was adjusted for infinite field size (i.e., to represent fields larger than the trial area used for this experiment) in order to extrapolate the results to the Holetta area as a whole. Adjusted *b* values were 0.504 and 0.324 for 1996 and 0.481 and 0.352 for 1997 for row and broadcast sown trials, respectively; mean *b* values were 0.493 and 0.338 for row and broadcast sown trials.

The analysis of variance indicated a significant log-linear relationship between variance per basic unit area and the width and length of plots for all trials. Examination of the residuals of the fitted model also indicated adequacy of the model for these data sets (data not shown). Hence, we considered *b1* and *b2* to be non-zero measures of heterogeneity along the width and length of both the broadcast and row sown trials.

The coefficients *B1* and *B2* measure incremental heterogeneity due to the use of rectangular or square shaped plots, respectively (Table 4). Heterogeneity coefficients due to rectangularity were non-significant ($P > 0.05$) in both years for both sowing methods. The heterogeneity of comparable variance for plots of equal size was found to be non-significant ($P > 0.05$) for both row and broadcast sown trials, suggesting that differing plot shapes of equal size are equally efficient for both sowing methods on the Holetta Nitisol. Hence, increasing the plot size of both rectangular and square plots reduced the magnitude of error variance at approximately the same rate.

TABLE 4. Heterogeneity coefficients corresponding to square (*B2*) and rectangular (*B1*) plots

		Index	
		B1	*B2*
Row sown	1996	0.0007 NS	0.593**
	1997	0.0070 NS	0.454**
Broadcast sown	1996	0.0157 NS	0.259*
	1997	0.0709 NS	0.266*

*,**: Significant at the 5 and 1% probability levels, respectively
NS: Non-significant

The t-test of the mean difference between *b1* and *b2* also exhibited non-significance ($P > 0.05$) for both row and broadcast sown trials, corroborating the previous observation that heterogeneity due to rectangularity was non-significant. For a given plot size X, V_X exhibited a minimal decrease as rectangularity increased, but this reduction, as already seen from the interpretation of the *B1* value, was not sufficient to warrant long and narrow plots. Comparing the two sowing methods, row sown trials exhibited a much lower index of heterogeneity due to rectangularity than did broadcast trials. Thus, irrespective of shape, plot size was paramount in the optimisation of plot dimensions for wheat experimentation.

The heterogeneity coefficient, *b*, was also estimated for fixed values of *W* by varying *L* and vice-versa for the row sown (Table 5) and broadcast sown trials (Table 6). The mean coefficients related to *L* and *W* for broadcast sown trials were 0.281 and 0.266 in 1996 and 0.263 and 0.288 in 1997; for row sown trials, the mean estimated coefficients were 0.582 and 0.581 for *L* and *W* in 1996 and 0.469 and 0.467 in 1997. The similarity of the *b* values estimated for fixed levels of *L* and *W* indicates equal soil heterogeneity along the width and length of the trial area; this indication agrees with the non-significance of *B1*.

TABLE 5. Heterogeneity coefficients for fixed plot widths (*W*) and lengths (*L*) for row sown wheat

Values for fixed plot widths (m)							
1996				1997			
W	*b*	R^2	d.f.	*W*	*b*	R^2	d.f.
1	0.532**	99.2	3	1	0.513**	98	9
2	0.585**	99.7	6	2	0.463**	98	9
3	0.553**	99.5	6	5	0.447**	99	9
4	0.604**	99.4	6	10	0.446**	98	9
6	0.612**	99.3	6	-	-	-	-
12	0.602**	98.8	5	-	-	-	-
Values for fixed plot lengths (m)							
1996				1997			
L	*b*	R^2	d.f.	*L*	*b*	R^2	d.f.
1	0.543**	100.0	4	1	0.432**	98	3
2	0.509**	100.0	5	2	0.514**	99	3
4	0.644**	99.8	5	3	0.491**	99	3
5	0.558**	99.9	5	4	0.539**	98	3
8	0.659**	99.7	4	6	0.484**	99	3
10	0.554**	99.9	4	8	0.506**	99	3
20	0.604**	99.7	4	9	0.465**	99	3
-	-	-	-	12	0.438**	99	3
-	-	-	-	18	0.385**	99	3
-	-	-	-	24	0.434**	99	3

**: Significant at the 1% probability level

TABLE 6. Heterogeneity coefficients for fixed plot widths (*W*) and lengths (*L*) for broadcast sown wheat

Values for fixed plot widths (m)							
1996				1997			
W	*b*	R^2	d.f.	*W*	*b*	R^2	d.f.
1	0.315**	59	3	1	0.283**	88	9
2	0.278**	98	5	2	0.326**	93	9

3	0.282**	98	5	5	0.294**	95	9
4	0.260**	97	5	10	0.249**	96	9
6	0.256**	96	5	-	-	-	-
12	0.203*	94	4	-	-	-	-
Values for fixed plot lengths (m)							
1996				1997			
L	*b*	R^2	d.f.	*L*	*b*	R^2	d.f.
1	0.387**	77	4	1	0.241**	97	3
2	0.304**	99	5	2	0.254**	87	3
4	0.275**	99	5	3	0.255**	97	3
5	0.281**	99	4	4	0.237**	99	3
10	0.243**	98	4	6	0.225**	99	3
20	0.198 NS	95	4	8	0.230**	97	3
-	-	-	9	-	0.243**	99	3
-	-	-	12	-	0.252**	98	3
-	-	-	18	-	0.294**	97	3
-	-	-	24	-	0.396**	98	3

*,**: Significant at the 5 and 1% probability levels, respectively
NS: Non-significant

To broadly assess the effect of plot shape on the measurement of soil heterogeneity, the plots were divided into three groups on the basis of *W*, *W*=*L*, or *W*>*L* (Table 7), as suggested by Narayana Reddy and Ramanatha Chetty (1985). For the row sown trials, estimated *b* coefficients were similar for the three groups each year, indicating that square and rectangular plot shapes are equally efficient in reducing error variance. For broadcast sown trials, the *b* coefficients for the square (i.e., *W*=*L*) group seemed higher than for the two rectangular groups (i.e., *W* and *W*>*L*). However, model fit, as indicated by the R2 values, was poor due to the low magnitude of the degrees of freedom for error.

TABLE 7. Coefficients of heterogeneity and determination for groups based on the criteria *W*, *W*=*L* and *W*>*L* for row and broadcast sown trials in 1996 and 1997

	W < *L*		*W* = *L*		*W* > *L*	
	1996	1997	1996	1997	1996	1997
Row sown						
b	0.595**	0.464**	0.606**	0.492**	0.592*	0.484**
R^2	99.4	98.0	99.4	99.8	98.9	99.0
d.f.	9	25	2	1	14	11

Broadcast sown						
b	0.254*	0.279*	0.293*	0.315**	0.236*	0.234*
R^2	97.9	94.0	68.9	79.0	91.9	99.0
d.f.	15	25	2	1	13	11

*,**: Significant at the 5 and 1% probability levels, respectively

The small numerical discrepancy between the results of the equation of Narayana Reddy and Ramanatha Chetty (1983) and the method of dividing plots into three groups might be related to the unequal numbers of widths and lengths used in estimating *b1* and *b2*. When the equation of Narayana Reddy and Ramanatha Chetty (1983) was fitted to the row sown data, *L* seemed to be associated with a marginally higher index of heterogeneity, but when Smith's index of heterogeneity (Smith, 1938) was fitted to the three groups, square plots exhibited a marginal superiority, although not significant, relative to rectangular plots. For the broadcast trials, although an equal number of plots were used for the estimation of the effects of *L* and *W*, application of the Narayana Reddy and Ramanatha Chetty (1983) equation revealed a considerable rectangular effect due to *W*, while the method of Smith (1938) seemed to favour square plots. This is probably due to the inclusion of a higher proportion of small plots for the estimation of *W*, since small plots exhibited relatively greater heterogeneity in the broadcast sown trials.

Optimum plot size, corresponding to the point of maximum curvature on the graphical relationship between true treatment difference and plot size, was estimated for replication numbers ranging from 2 to 12 for both sowing methods in each year (Table 8). The value of *d*, the true treatment difference expressed as a percentage, is presented graphically against plot size for *r*=2 (Figs. 1 and 2 for the 1997 row and broadcast sown trials, respectively). Estimated optimum plot sizes for both row and broadcast sown wheat were smaller for the 1997 trials relative to the 1996 trials across the range of replication numbers simulated (Table 8). This is probably due to variation in the degree of soil heterogeneity of the different fields used each year.

TABLE 8. Optimum plot size (m^2) corresponding to the point of maximum curvature in the graphical relationship between true treatment difference and plot size across a range of replication numbers

		Replication number					
		2	4	6	8	10	12
Row sown	1996	12.3	8.8	7.3	6.4	5.8	5.3
	1997	10.7	7.7	6.4	5.6	5.0	4.7
	Mean	11.5	8.3	6.9	6.0	5.4	5.0
Broadcast sown	1996	7.5	5.6	4.8	4.1	3.7	3.4
	1997	4.5	3.2	2.7	2.3	2.1	2.0
	Mean	6.0	4.4	3.8	3.2	2.9	2.7

Figure 1. Relationship between plot size (x) and true treatment differences to be detected as significant, expressed as percentage (row sown, 1997).

Figure 2. Relationship between plot size (x) and true treatment differences to be detected as significant, expressed as percentage (broadcast sown, 1997).

As the number of replications was increased, estimated optimum plot sizes decreased (Table 8). Increasing the number of replications from two to four reduced the estimated optimum plot size by 28 and 27% for row and broadcast sown trials, respectively. However, increasing the number of replications beyond eight for both row and broadcast sown trials had a minimal effect on optimum plot size (i.e., reducing optimum plot size by < 10%); thus, this level of replication could be considered as a point of convergence. This suggests that the use of replication numbers greater than eight for either sowing method would not increase precision, representing an unnecessary cost of experimentation.

The trial design parameters currently used by wheat agronomists in Ethiopia, viz., broadcast sown trials with net plot areas of 3.0 by 3.0 m and two to three replications (Tanner *et al*., 1992), compare favourably with the optimum plot dimensions and shape estimated for broadcast sown trials in the current study. However, comparing the design parameters of wheat varietal trials, viz., row sown with net plot areas of 2.0 m^2 and four replications (Desalegn *et al*., 1996), with the estimated optimum plot sizes (Table 8) indicates that breeders' plots are markedly smaller than necessary to optimise experimental precision.

By adopting optimal plot sizes corresponding to a specific replication number and sowing method, researchers maximise the utility of information generated per unit of experimental area. It warrants emphasis that the optimum plot sizes estimated in this study are applicable only to experiments with one treatment stratum or to the split unit in a multi-stratum experiment: optimum plot sizes for treatments that require larger plot dimensions for the practical application of technologies (e.g., mechanised tillage, irrigation) have not been determined in the current study. The determination of optimal block size is dependent upon the plot size, the number of treatments, and the experimental design used in a specific trial. Optimal block shape is dependent upon gradient patterns (i.e., fertility, slope, drainage, soil depth) within a specific field since the block should be configured to reduce differences in productivity level among plots within a block.

CONCLUSIONS

Row sown trials consistently measured a greater degree of soil heterogeneity than broadcast sown trials; broadcast sown plots were characterised by greater variability. The analyses suggested a marginal superiority for square plot shapes for broadcast sown trials, while for row sown trials rectangular and square plot shapes were equally precise in measuring soil heterogeneity. A comparison of the trial design parameters currently favoured by wheat researchers in Ethiopia with the optimal parameters estimated in the current study suggests that: (a) the design characteristics of broadcast sown wheat agronomic trials appear close to optimal, but (b) the net plot areas harvested from row sown wheat breeding trials are markedly suboptimal.

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