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THE PERFORMANCE AND INTERACTIONS OF INDIVIDUAL PLANTS WITHIN A CROP COMMUNITY

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STATEMENT

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University and, to the best of my knowledge and belief contains no material previously published or written by another person, except when due reference is made in the text.

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SUMMARY

Two field experiments examined the effect of plant arrangement and density on the performance and competitive interactions of individual plants within a crop community.

In Experiment 1, with the barley variety Clipper, two plant arrangements (square planted and drilled rows) were used at three densities with nominal seeding rates of 17.5, 70 and 140 kg per ha. Repeated measurements were made on the same plants within permanent quadrats. The position of each plant within the quadrats was determined by measuring its co-ordinates from common base lines. Two non-destructive methods for weight estimation were developed, i.e. a 'matched tiller' method and a 'plant cylinder' method.

In Experiment 2, with the wheat variety Halberd, random spacing was used at two densities, with nominal seeding rates of 95 and 190 kg per ha. The plants were examined both by repeated measurements of the same plant within permanent quadrats and by eight successive harvests in other quadrats. Plant co-ordinates were also measured. Within the permanent quadrats individual plant weights were estimated by the 'matched tiller' method and the 'plant cylinder' method.

Correlation of the date of seedling emergence with individual plant weight gave an overall picture that the earlier emerged plants remained larger. In 30 quadrats examined at day 70, 25 showed negative correlation of dry weight with the day of emergence.

The phenomenon of dominant and suppressed plants within a ~~barely~~ BARLEY crop was clearly demonstrated. In the square planted plots the degree of plant dominance, expressed as the difference between the relative growth rate of the largest plants (top decile group) and the

smallest plants (bottom decile group), decreased with increasing density. In the drilled plots the effect of density was less obvious. In the randomly spaced wheat crop the degree of plant dominance was apparently also affected by density.

In examining the frequency distribution of individual plant weights, it was found that irregularity of plant spacing had a stronger influence on the skewness than did density. The skewness of frequency distribution of plant height (length of the longest tiller) was consistently negative, probably due to the determinate growth of the cereal tiller. Tiller number per plant was usually strongly correlated to plant weight, and had a similar pattern of frequency distribution.

In Experiment 1 light interception at day 39 of the square planted plots was more efficient than in the drilled plots. Variation in light pattern at day 39 can be viewed both as a reflection of unequal growth of plants, and as a factor influencing subsequent differences in growth. At day 88 both at half plant height and at ground level, the variability of light penetration adjacent to each individual plant again is usually greater in the drilled plots than in the square planted plots.

The pattern of ear emergence in Experiment 1 was mainly influenced by density. At high density ear emergence was concentrated in the earlier days of the period, while at low density ear emergence was more evenly spread over the ten day period. This is believed to be a result of the different proportions of main stems and first tillers to all tillers at the two densities.

In barley communities, the mean individual plant weight decreased with increasing density and the effect was stronger at later stages of growth. The effect of density on number of tillers, number of ears, ear weight, number of spikelets and leaf plus green stem area per plant were basically similar, i.e. they decreased with increasing density.

At low and medium density the variability of plant characters was greater in the drilled plots than in the square planted plots, but not at high density.

Means of individual plant weight, length of the longest tiller and number of tillers per plant recorded in the eight sequential harvests in Experiment 2 followed the expected pattern. The effect of density on mean green area per plant was not significant at day 50 but from then on it became highly significant, while its effect on number of spikelets, number of grains and grain weight per plant followed closely the yield-density relationship.

The effect of neighbours was closely examined. The hypothesis was that all plants within a given radius around the test plant affected the performance of the test plant. This compound influence of neighbours is termed 'competitive pressure'. For the relationship between weight of the centre plant and competitive pressure, the reciprocal equation of Shinozaki and Kira (1956) ($1/w = \alpha + \beta\rho$) was used by replacing density (ρ) by competitive pressure (z). The two equations were:

$$z = \Sigma \frac{w_{n_i}}{d^{\theta}_{n_i}}$$

where w_{n_i} is weight of neighbours
and d_{n_i} is distance of neighbours
and θ is constant.

$$\frac{1}{w} = \alpha + \beta z.$$

Data from Experiment 2 were used for this analysis. It was found that the values of β were proportionally very small compared with α, so that the effect of neighbours was very hard to detect. The reciprocal relationship of density and plant weight for crop community may not therefore be applicable for aggregates of plants within a crop community. The community performance may conceal the effect of close neighbours, or in other words, the overall effect of community density was stronger than the effect of highly localised density within the community. Individual plant performance was presumably affected by other factors such as date of seedling emergence and the local physical and chemical environments.

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INTRODUCTION

Concepts of the importance of individual plant performance in crops have developed from an initial awareness of differences between plants, to the realization that a knowledge of individual plant/environment interaction is necessary for explaining community behaviour.

Except in some of the horticultural crops, e.g. fruit trees and ornamental plants, where the production policy has emphasized quality, most expressions of plant performance in crops have been based upon the mean values of the population, for example, the common practice of deriving yield per plant from yield per unit area divided by density. However, as emphasized by Goodall (1960), this procedure obscured rather than clarified the relationship between yield and plant population due to the introduction again of the independent variable,density, in the derivation of the dependent variable,yield per plant.

In contrast plant physiologists have dealt mainly with isolated single plants. Physiological studies can follow closely the plant/environment interaction, but in the absence of neighbours are not able to explain the effect during growth of dynamic changes of the environment associated with inter-plant interaction in a crop community. The competitive stresses for each plant in a crop are very acute, though competitive ability does not necessarily indicate the capability of producing high yield.

A few workers (reviewed later) have concentrated on the study of individual plant performance. They used either a partly controlled environment, e.g. a uniform soil in a confined space, with repeated measurements on a small number of plants, or field experiments with destructive measurement, i.e. three to six harvests during the growing period. The main disadvantage of the first method is that it is not dealing with a field environment which has many dynamic variables, while the second method cannot follow the development of the same plant from its first stage of growth until harvest. This is a major handicap because the micro-environment differs between plants and with time.

An ideal method would be to study each plant individually within the field community, but there are two main limitations. The first is to find non-destructive methods of measurement which can be used without disturbing the plant's micro-environment and without causing damage to the plant. The second limitation is in monitoring the individual plant micro-environment. If these limitations could be overcome, e.g. by finding better methods of plant character estimation and further miniaturization of instruments, then we might be able to assess some of the more complicated problems, such as the spatial range of influence of each plant; the relative amount of 'space' occupied by a plant in the community compared with an isolated plant; the influence of neighbours, etc.

It is obvious from the literature that our knowledge of individual plant performance and competitive interaction within a crop community is limited and that further study is required. In the studies here reported an attempt was made to examine the effect of neighbours on interplant competition within cereal crop communities in the field and the variability of individual plant characteristics. Repeated measurements were made and the position of each observed plant in the field was recorded so that distances between plants could be calculated. Special attention was given to the phenomenon of dominant and suppressed individuals within a crop community, to the degree of skewness of the frequency distribution of plant weight and other plant characters, and to a quantitative account of plant interaction within the crop communities.

LITERATURE REVIEW

1. Mean plant performance within a crop community

Information on plant performances within a crop community has mainly been obtained from bulk samples taken from a unit area, giving mean characteristics of each plant. Even though it cannot be used to study the interaction between individual plants, the information is useful in the understanding of plant community - environment interactions. Since the subject of this literature review and thesis is not primarily with mean characteristics, e.g. mean yield per plant, but with individual characteristics, it is not the intention here to make a comprehensive review of density/ mean performance per plant: only two aspects will be discussed, i.e. the effect of plant density and the effect of plant arrangement respectively on mean plant production.

1.1 Effect of density on mean plant production

Yield per plant in a community is usually derived from yield per unit area divided by density. A typical relationship between weight per unit area and weight per plant with density is shown in figure 1 (from Verheij, 1970). Yield of total dry weight per unit area increases rapidly with density, but at higher densities levels to an asymptotic curve. Yield per plant decreases markedly with increasing density.

The relationships between dry weight per plant, density and time for wheat communities are shown in figure 2 (from Puckridge and Donald, 1967). At the final harvest, weight per plant at the highest density (density 5, 1078 plants/m^2) was 1.67 g, while at lowest density (density 1, 1.4 plants/m^2) the weight per plant was 89.9 g which means more

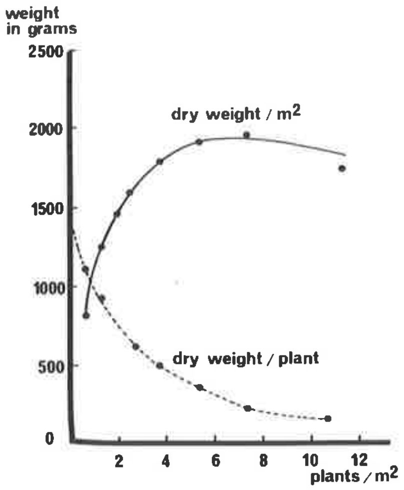

FIG. 1 : RELATIONSHIPS BETWEEN WEIGHT PER UNIT AREA AND WEIGHT PER PLANT WITH DENSITY IN BRUSSELS SPROUTS (VERHEIJ, 1970).

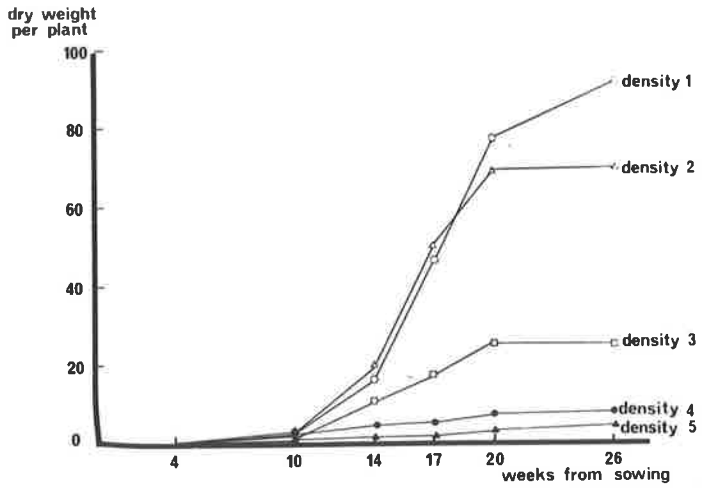

FIG. 2 : RELATIONSHIPS OF DRY WEIGHT PER PLANT TO DENSITY AND TIME IN WHEAT (PUCKRIDGE AND DONALD, 1967).

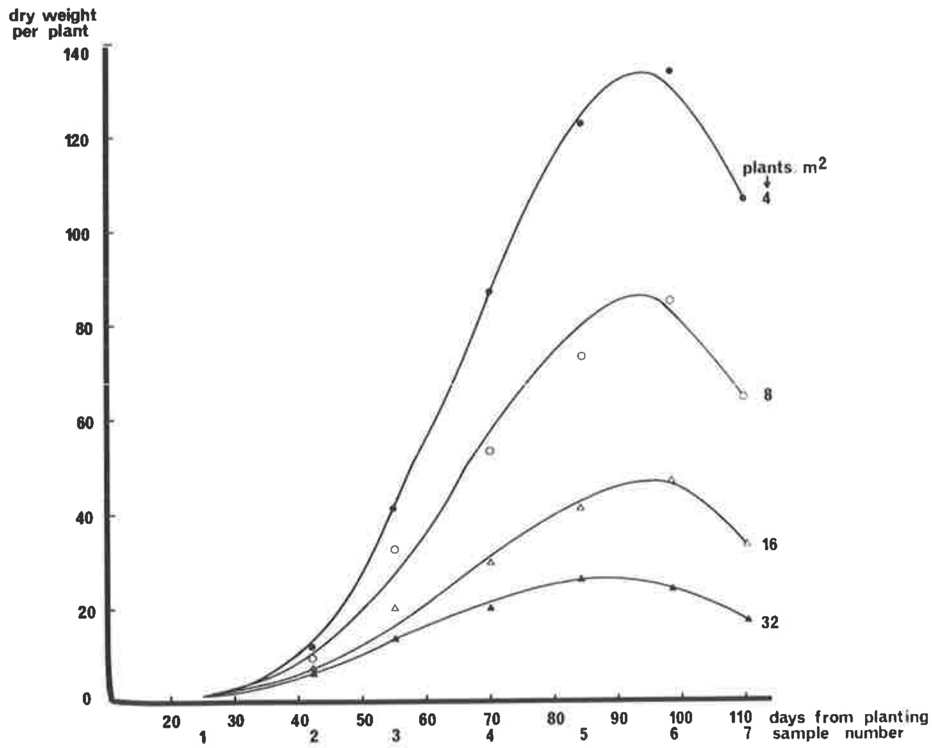

FIG. 3 : RELATIONSHIPS BETWEEN DRY WEIGHT PER PLANT TO DENSITY AND TIME. SYMBOLS REPRESENT ACTUAL TREATMENT VALUES, CURVES REPRESENT TRANSFORMED VALUES FROM REGRESSIONS FITTED IN LOG E FORM (BUTTERY, 1969).

than 53 times the weight per plant at highest density. At density 4 (184 plants/m^2) and 5 there was a marked effect of inter-plant competition at week 10, while plants at density 2 (7 plants/m^2) suffered no inter-plant competition until after week 17 when their dry weight progressively fell below those at density 1. At density 1 there was no evidence that plants suffered from inter-plant competition at any time. Mean tiller number for densities 1 to 5 were 16.4, 16.1, 13.7, 5.5 and 1.6 at week 10, with the differences becoming greater at later harvest. The number of tillers per plant was the main source of variation in dry weight per plant. Maximum weight per tiller occurred in the intermediate densities at 14 - 20 weeks; the mean weight per tiller at densities 1 to 5 were 1.12, 1.62, 1.73, 1.39 and 0.97. Puckridge and Donald (1967) concluded that there was an effect of strong inter-plant competition on plant and tiller size at high densitites, and acute inter-tiller competition within the abundantly tillered plants at very low densities, an effect discussed earlier by Donald (1963).

In barley, Kirby (1967) found that plants grown at a seeding rate of 314 kg/ha produced a maximum of 2 tillers per plant, compared with 6 tillers per plant at a seeding rate of 39 kg/ha. Similar results were also presented by Downey (1972) on the effect of density on a tillering variety of maize (variety NEH 1151). At all densities tillers were produced, but the higher the density the fewer the number of tillers produced. As density increased, the number of cobs per plant and per tiller decreased. There was a distinct trend for grains to be lighter and to be fewer per cob at the higher densities.

A somewhat different relationship of dry weight per plant to density and time is given by Buttery (1969) for soybeans (Figure 3), which shows a marked loss of weight later in the season. The reason for this loss of weight was not given by Buttery, but Koller *et al.* (1970) found a decrease in dry weight of pod wall, leaf and stem and petioles later in the season and this decrease was strongest in the stem and petioles. A curve similar to that of Puckridge and Donald (1967) in Figure 2 was obtained for the cumulative above-ground dry weight calculated by summation of component dry weight using the maximum observed component weight, but the method could lead to errors if significant redistribution of stored materials occurs among plant components prior to abscission.

Donald (1954)found for subterranean clover (*Trifolium subterraneum* L.) and Wimmera ryegrass (*Lolium rigidum* Gaud.) that, under conditions of adequate water and nutrient supply, dry matter production reached maximum values at moderate to extremely high densities, whereas the maximum number of seeds per unit area was given at moderate densities and declined at high densities. Although the widest spaced plants gave the greatest number of seeds per plant, somewhat closer spacing in Wimmera rygrass and all closer spacings in subterranean clover gave greater individual seed weight and greater numbers of seed per inflorescence. Donald explains the phenomena with the following hypothesis. At the widest spacing competition was absent during the early stages of growth. Floral primordia were laid down in each plant in huge numbers. As growth proceeded, inter-plant competition became progressively operative and reduced the efficiency of seed production in the individual inflorescence as shown by the reduced number of seeds per raceme and the reducing of seed size. In moderately dense stand, inter-plant competition was already operative at the time of flower initiation so that the number of floral primordia laid down or developed by each plant was reduced, and this reduced load was within the capacity of the plant to maintain as inter-plant competition intensified. Seeds per inflorescence and seeds per unit area achieved maximum value in these moderate stands.

Intense inter-plant competition can have a big effect on morphology, distribution and maturity of reproductive structures. Beech and Norman (1966) found for safflower plants grown at different densities, a marked reduction in the number of heads per plant with increasing density, due to changes in the number of both secondary and tertiary heads. For dwarf French bean (*Phaseolus vulgaris* L.) with wide spaced plants, Jones (1968) found two or three branches in each axil of the trifoliate mainstem leaves and each branch produced up to three leaves before terminating in an inflorescence. At wide spacing, flowering continued for several weeks. At close spacing, branching was suppressed, there were fewer pods per plant and flowering was compressed into 7 - 10 days.

For some plant products quality is more important than total weight. Below a certain standard of quality it could have no marked value. One of the earlier studies on the effect of density on quality of yield was made by Warne (1951b). Carrots (2 varieties), beet (3 varieties) and parsnips (1 variety) were grown at a uniform inter-row distance (45.7 cm) and at 5 thinning distances each giving plant populations per metre of row varying from 6.6 to 19.7 for beet, 5.6 to

14.4 for parsnips and 7.5 to 26.2 for one variety and 6.6 to 16.4 for the other variety of carrots. Rather surprisingly, there were inconsistent relations between yield of large (marketable) roots and plant densities. For Long Beet and parsnips there were no relations between yields of marketable roots and plant densities, but for Globe Beet and carrots maximum yields of marketable roots were obtained with the closest spacings.

A more consistent relationship between quality of yields and plant densities was presented by Rees and Turquand (1969) for bulbs of tulip. Effect of planting density on grading can be seen from the number of lifted bulbs above a selected size (11 cm or above) or from the spectrum of lifted bulb's size distribution (Figure 4). There was a contrast in the optimum density for maximum total yield and the optimum density for maximum lifted bulbs above the selected size (11 cm) for both cultivars.

On the relationship between plant density (ρ) and crop yield (Y) most reports base their analysis on mean values. A review on this is made by Wiley and Heath (1969). They considered there are basically five different equations (Table 1), and regarded the reciprocal equation as the best because it can describe both asymptotic and parabolic relationships, and it has biological meaningfulness.

The relationships of interest in this study are those which are based primarily on a consideration of the performance of the individual plant, even though they are applicable also to total yield, e.g. the Mitscherlich equation (1919, quoted from Wiley and Heath, 1969) and the reciprocal equation of Shinozaki and Kira (1956).

The Mitscherlich equation was based on the relations between yield of a plant and the supply of an essential growth factor,

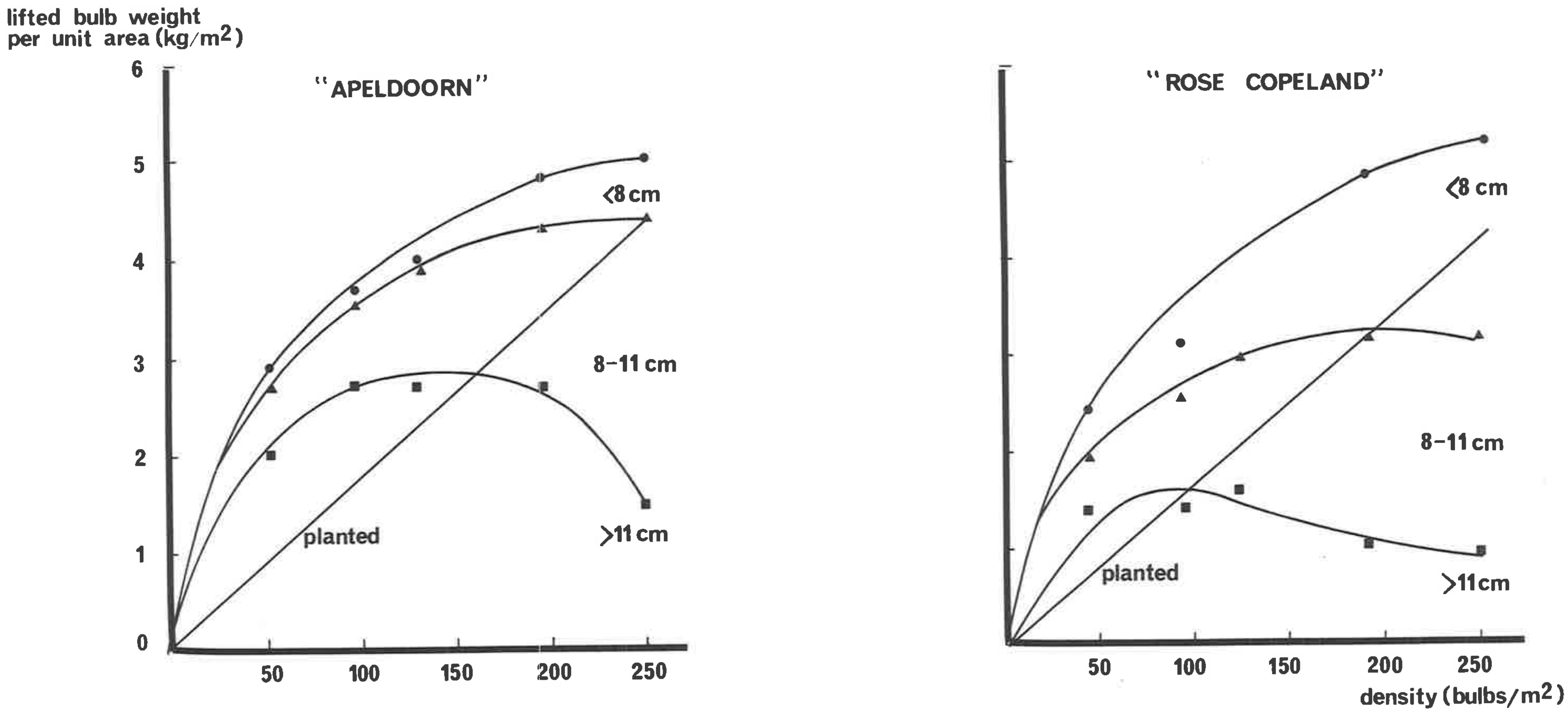

FIG. 4 : EFFECT OF PLANTING DENSITY ON LIFTED BULB WEIGHT (REES AND TURQUAND, 1969).

Table 1: Yield - Density Equations

Type of equation	The equation		
1. Polynomial equations	(a)	$y = a + b\rho + c\rho^2$	(Hudson, 1941)
(y = grain yield, ρ = density, a,b,c = constants)	(b)	$y = a + b\rho + c\sqrt{\rho}$	(Sharpe and Dent, 1968)
2. Exponential equations	(a)	$y = \rho K\ 10^{b\rho}$	(Duncan, 1958)
(y = yield per plant, ρ = density, b = slope of regression line, A,K = constants)	(b)	$y = \rho A\ K^{\rho}$	(Carmer and Jackobs, 1965)
3. Mitscherlich equation		$w = W\ (1-e^{-ks})$	(Mitscherlich, 1919)
(w = yield per plant, W = maximum yield per plant, K = constant, s = space)			
4. Geometric equations	(a)	$y = A\ (\rho)^{1-b}$	(Warne, 1951)
(y = yield per unit area, ρ = density, A, b,K = constants, w = yield per plant)	(b)	$w\ \rho^{a} = K$	(Kira *et al.*,1953)
5. Reciprocal equations	(a)	$\frac{1}{w} = a + b\rho$	(Shinozaki and Kira, 1956)
(w = yield per plant, ρ = density, a,b,c,θ = constants, γ = 1 or > 1)	(b)	$\frac{1}{w} = a + b\rho + c\rho^2$	(Holliday, 1960)
	(c)	$\frac{1}{w^{\theta}} = a + b\rho$	(Bleasdale and Nelder, 1960)
	(d)	$\frac{1}{w} = a + b\rho^{\gamma}$	(Farazdaghi and Harris, 1968)

$$\frac{dw}{df} = (W - w)c$$

where f is the level of supply of the factor, and c is a constant, w is yield per plant and W is maximum yield per plant. On integration the equation becomes

$$w = W(1 - e^{-cf})$$

Mitscherlich further suggested that the equation could be applied more generally on the relation between 'space' and plant growth,

$$w = W(1 - e^{-Ks})$$

where s is space per plant and K is a constant. This equation describes only the asymptotic relationship between density and yield.

Shinozaki and Kira (1956) based their equation on the assumption that the growth of a plant can be described by a simple logistic growth curve,

$$\frac{1}{w} \times \frac{dw}{dt} = \lambda(1 - \frac{w}{W})$$

$$w = \frac{W}{1 + ke^{-\lambda t}}$$

where w is the weight of the plant at time t, λ is coefficient of growth, and k is the integration constant. W and λ are assumed constant independently of time t. Another assumption is that λ is independent of density, and the final yield per unit area is constant, and independent of density. By combining the last equation and the law of constant final yield ($w\rho = K$), and determining the value of k when there is no competition at time zero, then the reciprocal equation can be derived

$$\frac{1}{w} = a + \rho b$$

where $a = e^{-\lambda t}/w_o$ and $b = (1 - e^{-\lambda t})/y$.

Bleasdale and Nelder (1960) and Farazdaghi and Harris (1968) made further refinement of the equation by putting a power factor on weight (Bleasdale and Nelder, 1960) or on density (Farazdaghi and Harris, 1968) so that it can describe both asymptotic or parabolic yield/density relationships. This means that it can be fitted to a wide range of total yields or grain yields.

1.2 Effect of plant arrangement on mean performance

Donald (1963) recognized three types of arrangement which might influence yield, i.e. a square grid or a progressively elongated rectangle, regular or irregular spacing in the row, and the direction of the rows (N-S, E-W). However, each arrangement still represents different types of plant interaction, since plant interaction is basically a function of distance and size of adjacent neighbours. In the square grid arrangement (Figure 5), there are two groups of neighbours, the co-ordinate neighbours (N_1 to N_4) and the diagonal neighbours (N_5 to N_8), and each group has certain influence on the middle plant. In the elongated rectangular arrangement there are three groups of neighbours, i.e. nearby co-ordinate neighbours (N_1 and N_2), distant co-ordinate neighbours (N_3 and N_4), and diagonal neighbours (N_5 to N_8). Each group of neighbours has a different effect on the middle plant, and the effect of the second and third groups of neighbours depend upon the degree of rectangularity. In row spacing with irregular spacing within the row, the effect of both groups of neighbours is strongly influenced by the irregularity of spacing within the row. These different types of plant interaction or effect of neighbours can be more clearly expressed in the following grouping of plant arrangement:

A. Regular in all directions.

Represented by a triangular or hexagonal arrangement. These

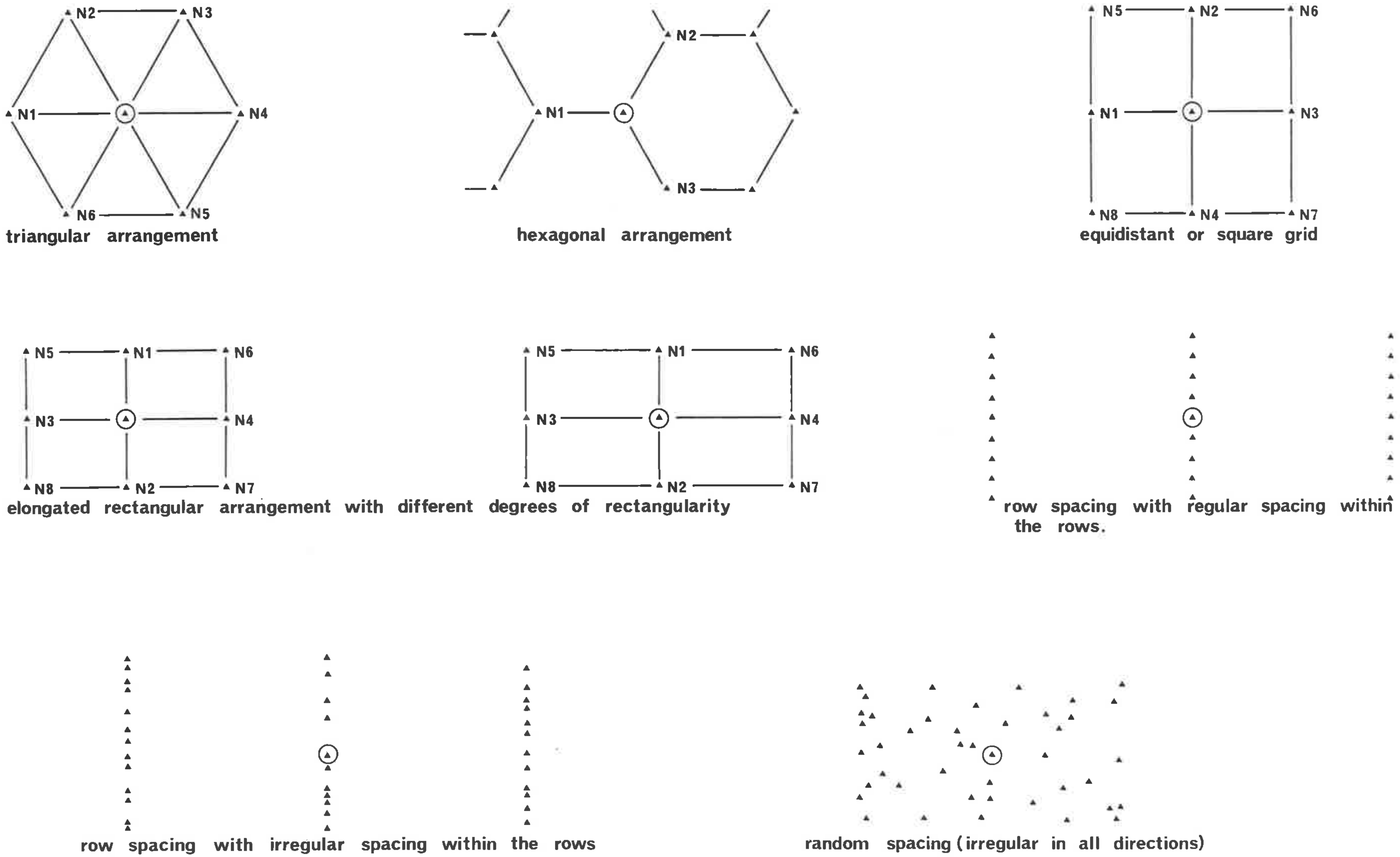

FIG. 5 : TYPES OF PLANT ARRANGEMENT (▲: PLANT POSITION, ⊙ : TEST PLANT).

arrangements have all the nearest neighbours (6 or 3 respectively) located at the same distance from any observed plant.

B. Regular in two directions.

(a) Equidistant: the plants are equally spaced in two directions at right angles (square grid in Figure 5).

(b) Rectangular: the spacing in two directions, at right angles to each other, is regular but not equal.

C. Regular in one direction.

This type of arrangement is usually achieved in row spacing with regular distances between the rows and irregular distances between the plants within the rows, as in drill sown cereals.

D. Irregular in all directions.

Obtained by broadcasting seeds without following any particular arrangement. In this arrangement the number of neighbouring plants which interact with a particular 'test plant' is most likely determined by a radial distance around it.

For B(b) and C a distinction should be made between different row directions, i.e. between N-S or E-W directions, due to the different pattern of shading in each direction.

On the effect of regularity of plant distribution on yields of drill sown cereals, Engledow and Doughty (Engledow, 1926; Doughty and Engledow, 1928) found that yield and number of plants per foot of drill row were positively correlated. They proposed that crop yield could be increased by increasing the number of plants within those foot-lengths with few plants. But Sprague and Farris (1931) concluded from their experiment with barley that variation in the number of seeds per foot-length with even spacing of seeds within foot-length, had no effect on yield per unit area. Smith (1937) from his experiments with wheat also found a positive correlation between the number of plants per foot and yield when density per foot was variable, but the yield per plot with variable spacings was not less than that of plots with even spacing at a density of equal to the dense foot-length of the variable spacing. His explanation of the phenomenon was: foot-lengths with few plants will be, on the average, surrounded by more densely planted areas, and foot-lengths with more than the average number of plants will be surrounded on the average by less densely populated areas, giving an increase or decrease in competitive advantage.

Equidistant planting is considered as potentially the highest yielding arrangement since it gives opportunity to each plant to use above- and under-ground resources without exposing it too early to the interference of the surrounding neighbours. In crops which were planted in rows, narrower spacing between the rows which means closer approach to square planting, also gave better yield as indicated in Table 2. Any results or arguments to the contrary, usually imply at least one factor which nullifies the advantage of the uniformly distributed arrangement, e.g. a density beyond the optimum density where intense inter-plant competition is effective very early, and they have to compete for all the resources whatever arrangement is used, or the occurrence of an adverse condition like dry weather. This creates a situation where the reduction of light competition in the uniformly distributed arrangement is superseded by a finite water supply as the prime limiting factor. A similar explanation was given by Rumawas *et al.* (1971) in comparing corn yield at 50 cm (nearer square planting) and 75 cm row spacing with the same density (44,000 plants/ha). They found a greater amount of soil moisture was available throughout the growth period in the 75 cm row spacing, probably due to differences in development of root systems. Plants grown at the 50 cm row spacing apparently failed to penetrate to depths attained by the 75 cm row spacing. They were thus unable to draw water from greater depths later in the season and this might account for the approximately 10% higher grain yield in the 75 cm row spacing.

The examples in Table 2 confirm the suggested advantage of a uniform plant distribution due to optimum usage of resources and less interference from neighbours, but whether this advantage will be expressed in better yield depends upon the particular circumstances, e.g. population density, plant characteristics, particularly plasticity and lodging resistance, resources which become limited, and possibly other cultural practices.

One of the most important aspects in studying the effect of plant arrangement on yield is obtaining a firm knowledge on the underlying phenomena, i.e. the effect of neighbouring plants. Sakai (1957) measured several characters of central plants of one cultivar of barley surrounded by 1 to 6 competing plants of another cultivar, compared with similar arrangement in pure stands. Both treatments were arranged in hexagonal pattern. The two varieties of barley used were Sizuoka-Siro, a 6 rowed cultivar which has strong competitive ability, and Chibakawa No. 3 with weak competitive ability. The results are shown in Figure 6 and he concluded that the effect of competing neighbours on a plant is linearly proportional to the number of surrounding competing individuals. A limitation of this study was that all the surrounding neighbours were of the same cultivar and exactly at the same distance from the centre plant, and it disregarded the fact that within a crop community there are both strongly competitive (dominant) and weakly competitive (suppressed)

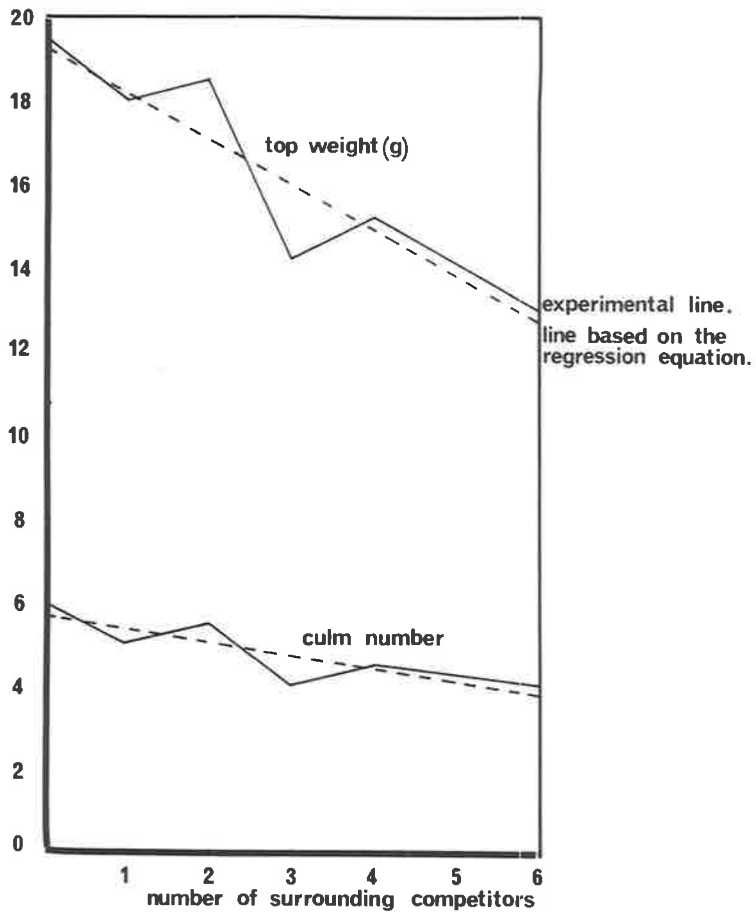

FIG. 6 : LINEAR RELATIONSHIPS BETWEEN THE NUMBER OF STRONGLY COMPETING SURROUNDING PLANTS AND THE TOP WEIGHT AND CULM NUMBER OF A CENTRE PLANT WHICH IS A WEAKER COMPETITOR (SAKAI, 1957).

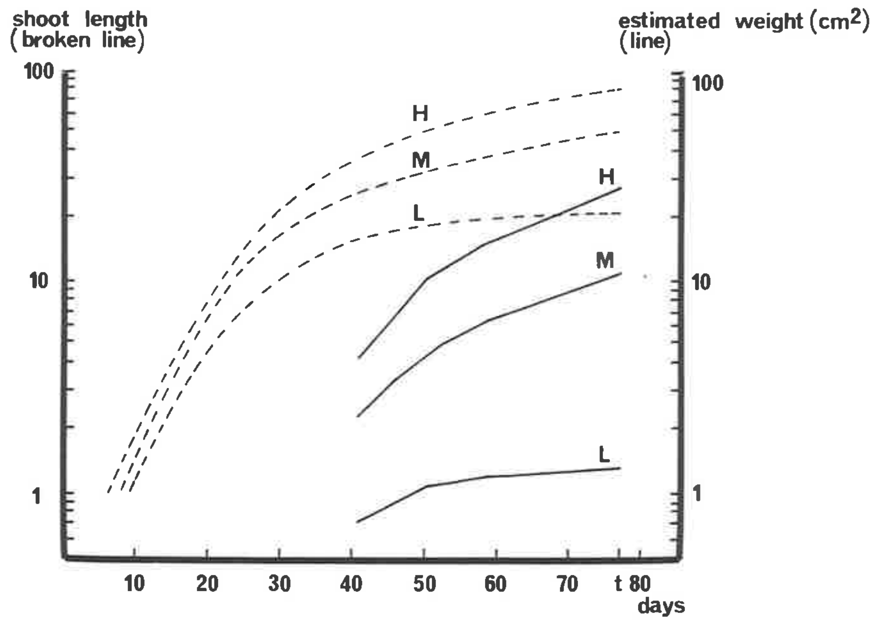

FIG.7a : GROWTH CURVE OF ROSE MALLOW (H. MOSCHEUTOS L.) ON HIGH DENSITY PLOT. M IS AVERAGE OF TOTAL 161 PLANTS, H IS AVERAGE OF 10 TALLEST AND L IS AVERAGE OF 10 LOWEST (YODA et al. 1957) .

Table 2: Crop Performances as Affected by Row Width

Crops	Arrangements	Performances
Grain sorghum		
Porter *et al.* (1960)	Row spacing: 30, 51, 76 and 102 cm at 4 seeding rates.	Three years average: yield in 30, 51 and 76 cm were significantly higher than in 102 cm spacing, while seeding rate had no significant influence on yield.
Grimes and Musick (1960)	Row spacing: 18, 36, 53 and 71 cm and 28, 56 and 84 cm Population: 22,680, 45,360 & 90,720 plants per ha.	Significant regression equations indicated that increased row width decreased yield at any particular density.
Maize		
Fulton (1970)	Row spacing: 50 and 100 cm Population: 39,500 and 54,400 plus extra 69,200 plants per ha for 50 cm rows only	Narrow rows increased yield at high population and with ample moisture supply.
Stivers *et al.* (1971)	Row spacing: 51, 76 and 102cm Population: 54,000 and 69,000 plants per ha	Average grain yields were increased 7.3% with row 51 cm wide and 4.4% with row 76 cm wide in comparison to 102 cm rows (mean of 2 densities)
Andrew and Peek (1971)	Row spacing: 76,91 and 102 cm Population: 40,000, 50,000 60,000 and 70,000 plants per ha uniformly spaced within the row	Yields in 76 cm rows averaged over 12 environments were higher than yields in conventional rows (91 and 102 cm) for each of the four hybrids and populations.
Soybean		
Weber *et al.* (1966)	Row spacing: 13, 25, 51 and 102 cm. Population: 10,500, 21,000, 42,000 and 85,000 plants per ha.	Highest seed yield in 25 cm rows at 42,000 plants per ha. Highest dry weight in 12.7 cm rows at 85,000 plants per ha.
Hicks *et al.* (1969)	Row spacing: 25 and 76 cm. Population: 7,750, 8,500 14,750 and 23,000 plants per ha for 1966 experiment and 8,000, 15,250 and 23,000 plants per ha for 1967 experiment.	No consistent effect of row spacing on seed yield.
Cooper (1971)	Row spacing: 17 and 50 cm. Seeding rate: in 17 cm rows: 6, 9 and 12 seeds per metre. In 50 cm rows: 18, 27 and 36 seeds per metre.	In the third planting date, at the lowest seeding rate average yields were significantly higher at 17 cm rows. In the first and second planting the higher percentage of lodging at 17 cm rows nullified the advantage of a more uniform distribution.

individuals, each of which is 'a centre plant' for different sets of neighbours.

Goodall (1960) concluded that the decrease in the logarithm of the weight of a plant is a satisfactory expression of the competitive effect of its neighbours. He went further by incorporating plant distance, and proposed that the yield of a plant in a row crop should be represented by

$$\log w = a + b_1 \log x_1 + b_2 \log x_2$$

where w is weight per plant, x_1 is spacing within the row and x_2 is spacing between the rows, or

$$w = a\, x_1^{b_1}\, x_2^{b_2} .$$

He admitted that his equation lacks a theoretical basis and fails at low densities. Donald (1963) indicated that a possible unsatisfactory feature of the equation is that it implies that if either of the power terms is greater than the other, then the optimum spacing at any given density would be obtained where the distance between plants was increased as wide as possible in one direction and decreased as close as possible in another direction. But this feature could even improve the goodness of fit provided that the greater power term is applied for x_1 since at the same density increasing the x_1 value and reducing the x_2 value, not otherwise, means approaching closer to square planting. Berry (1967) pointed out that in fitting Wiggans data (1939), Goodall's equation showed a poor fit of log w against log x_1 since log w and log x_1 would be linearly related for fixed values of x_2, instead of having a curvilinear relationship. By ignoring the curvature in fitting the relationship, it would be expected that different values of b_1 and b_2 would occur since x_1 and x_2 covered

non-overlapping ranges, and the differences correspond to different parts of the curve and do not indicate a row-orientation effect.
He proposed an extended simplified equation of Bleasdale and Nelder (1960) as an alternative to take into account the plant rectangularity, i.e.

$$\frac{1}{w^{\theta}} = a + b\left(\frac{1}{x_1} + \frac{1}{x_2}\right) + \frac{c}{x_1 x_2}$$

where *a*, *b* and *c* are positive constants and $0 < \theta < 1$. For a given density (i.e. for a fixed value of x_1, x_2) *w* is greatest where x_1 = x_2, i.e. for a square arrangement, since $\frac{1}{x_1} + \frac{1}{x_2}$ is at a minimum. The relationship is asymptotic or parabolic depending on whether θ is equal to or less than unity. For irregularly spaced crops he considered that it might be used as a first approximation, e.g. for a crop grown in rows, the arrangement is defined by the inter-row spacing and mean intra-row spacing. If this equation gives a better fit it may also be because it has more constants in it.

2. Individual plant performance within a crop community

2.1 Factors leading to variation in individual plant performance

2.1.1. Plant factors

Plants can be obtained either through vegetative propagation, e.g. cuttings, or from seeds. In the same environment plants of the same genotype should behave in the same way, but a natural population of a species which multiplies by seeds commonly consists of different genotypes and it is unlikely that a uniform performance would occur. From a crop community of a pure line a more uniform performance could be expected.

Differences in micro-environments when the seeds are still attached to their parents may cause minor differences in structure which could be associated with major differences in germination behaviour. It is possible that both the condition of the embryo and of the endosperm in the ripening grain may effect development during germination. Durham (1958, quoted from Wellington, 1966) excised mature embryos from one year old wheat grain and transplanted them onto the endosperms of grain harvested at different times after anthesis. The embryos of the latter were also placed on the mature endosperms. The mature embryos, whether placed on their own or on immature endosperms, started to elongate after 48 hours, but on immature endosperms the increase in dry weight was less at all stages. This suggests that the reserves in the immature endosperms were not as readily available for growth as those of mature endosperms. The increase in dry weight of mature embryos on mature endosperms were also greater than that of immature embryos either on their own or on mature endosperms. It seems there are changes in both the embryo and the endosperm as maturation progresses which enable the embryo to germinate more rapidly. In barley grains the rate of desiccation during ripening and the moisture content reached can be important factors in determining the proportion of grains which acquire the ability to germinate as soon as they are ripe (Wellington and Bradnock, 1964; Wellington, 1966).

Seed size is known to influence plant performance strongly. Bigger seeds usually produce bigger seedlings as shown in Table 3 for sunflowers (Kuroiwa, 1960).

Table 3: Relation between weight of seed and weight of seedling 10 days old. Mean of 20 individuals (Kuroiwa,1960).

Seed weight (mg)	Seedling weight (mg)	Seedling weight/ seed weight
68	101	1.48
58	88	1.52
43	59	1.37
17	27	1.59

For subterranean clover under spaced and sward conditions Black (1957) found that where plants were growing in non-competing spacing, the relative differences between plants from seeds of different weights were maintained unchanged until the end of the growing season. The relative growth rate of the three seed sizes were equal. Under sward conditions the relative differences between plants of different seed weights were maintained unchanged for the first 83 days, but from day 83 to day 125, there was a gradual approach to parity of the weights of the plants from the three seed sizes. Plants in swards from the largest seed size were the first to show a decline in growth rate due to competition followed in turn by those from medium and small seeds. Black suggested that swards from bigger seeds reach a critical leaf area, i.e. leaf area capable of intercepting all available light energy, earlier than swards from smaller seeds which still have an exponential growth rate.

2.1.2 Environmental factors

Early in growth, but still before competition is operative, various conditions can effect germination and seedling development. Local fertility can effect strongly the growth of plants in a particular location, e.g. local shallowness of top soil due to the presence of hard layers could inhibit root development and limit the availability of water or nutrient which leads to poor growth. On the other hand previous use of the site could also create local fertile spots, e.g. along the former footpath if the area was used for experiments in the preceding season, or around animal droppings if the area was previously used for grazing. Unfavourable soil micro-environment early in growth period could also put a seed or seedling at a continuing disadvantage compared with its neighbours, e.g. a site which is excessively wet or which becomes very hard when dry. According to Wiggans (1939) the formation of hard crust at soil surface after heavy rainfall could cause individual seedlings at thinner plantings to emerge slower or even fail to break through.

The effect of density in relation to the favourability of sites for seed germination on establishment was presented by Harper (1961). For *Bromus* seeds dropped on a caked cracked soil the chance of establishment was progressively reduced as the density of seed was increased, because there were only a limited number of crack sites suitable for the germination. These sites were filled at a relatively low density, whereas a rough soil surface offered many more potential germination sites.

In excessively deeply sown crops, deeper placed seeds take longer to emerge and the reserves in the endosperm may be depleted before the needs for carbohydrates and minerals can be fully supplied by leaves and roots, resulting in poorer seedling growth. Black (1956) in examining the effect of depth of sowing on early vegetative growth of subterranean clover (*Trifolium subterraneum* L.) came to the conclusion that depth of sowing had no effect on the subsequent growth, providing that a certain critical depth, determined by the size of seed, is not exceeded and especially that they emerged at the same time. This is due to the fact that even though a plant emerging from 1.3 cm depth has a higher cotyledon weight as compared to the one emerging from 5 cm depth, they had the same cotyledon area, and it had been shown that seedling growth depends directly on cotyledon area. Under field conditions he pointed out that plants from greater depths of sowing will be at a disadvantage as compared with those from shallower sowing since emergence will be progressively delayed as depth of sowing increases.

The effect of time of emergence on plant growth was studied by Black and Wilkinson (1963). They planted, on different dates, seeds of subterranean clover (*Trifolium subterraneum*, var. Bacchus Marsh) in seed boxes, at the same depth, with square arrangement. A delay of 5 days in emergence was sufficient to induce in most cases a 50% reduction in final weight, a delay of 8 or 9 days caused a 75% or greater reduction. In the studies reported in this thesis the effect of time of emergence was examined under field conditions at different density and plant arrangement.

Seed orientation can affect emergence and growth of corn (Patten and Van Doren, 1971). In controlled environments seeds planted with the proximal end down (D) averaged 10% greater emergence, 3 days earlier emergence and 20% greater penetration of wax-oil mix surface layers than plants with the proximal end up (U). Field emergence of corn was found to be 3 to 5 days earlier and about 12% greater with D orientation when averaged over 2 years and at three levels of irrigation, i.e. 0, 1.8 cm and 3.8 cm water per week. Seedling roots were longer and penetrated deeper with D planting. Seedlings (5 leaves or less) averaged 15% greater root length, 300% greater vertical root penetration, and 20% greater leaf area with D orientation.

2.2 Features of individual plant performance

When plants in a crop community start to compete with their neighbours the micro-environment of each plant is affected by the interaction between plants. There are two possible types of interaction between plants, i.e. co-operative interaction and competitive interaction (Hozumi *et al.*,1955). Of these, the competitive interaction plays a much more important role and will be discussed extensively.

The co-operative interaction was pointed out by Hozumi *et al.* (1955) when they examined the correlation between the length of shoot and the rate of shoot elongation of maize planted in single row. They found that shoot elongation is more rapid in earlier growth, and the correlations between the length of shoot and the rate of shoot elongation were mostly negative. An individual which had been lower in height on a certain day grew more rapidly during the days immediately after that and *vice versa*. Thus all the plants in a row tended to come up to a common height. The interaction which caused the height equalization effect was the co-operative interaction. They further said that shorter plants with faster elongation did not always succeed in overtaking taller plants whose elongation rate was relatively smaller, and they suggested that the co-operative interaction may be limited to or at least most evident in certain growth periods. What they call a co-operative interaction could be a survival reaction on the part of the suppressed plants, and the type and extent of the reaction may depend upon the factor which becomes less readily available, the stage of growth when this occurs, and genetical factors.

The competitive interaction among neighbours has stronger effects on individual plant performance. The smaller the distance between neighbours the earlier the competition starts and the more severe it becomes. If a plant is bigger than its neighbours due to factors mentioned earlier, it could utilize more resources from its surrounding, and the neighbouring plants must compensate for this competitive ability or will suffer from getting less and less from its surrounding. There are mainly four phenomena uncovered in the study of competitive interaction, i.e. plant dominance, alternation of plant weight, skewness in the frequency distribution of individual plant weight and self-thinning.

2.2.1 Plant dominance

One of the most important phenomenon uncovered in the study of plant interaction within a crop community is the presence of dominant and suppressed plants, as demonstrated by Yoda *et al.* (1957) and Kuroiwa (1960).

Kuroiwa's experiment used the sunflower variety 'Large-Russian'. Seeds were sown in square patterns at four spacings with 5,7,10 or 20 cm between plants in both directions (25, 100, 200 and 400 plants per square metre). Sixteen days after sowing, the plants were classified by size into three classes: dominant (D), intermediate (I) and suppressed (S). Measurements of weight, height and leaf area were made at day 30 and day 40 after sowing. As can be seen in Figure 7b for plant dry weight the dominant plants kept an almost constant relative growth rate with time, while the suppressed plants rapidly decreased in growth rate. The differences in the relative height growth rates of the dominant and suppressed plants was not so marked as in the weight growth rates. The frequency distribution curve of plant height and fresh weight of aerial parts at the highest density showed that for fresh weight the curve was transformed, from a normal type in the early period of growth, to strikingly skewed to the right at later stages of growth (45 days after sowing). For plant height the normal type was maintained throughout the development period. Kuroiwa differed from Koyama and Kira's (1956) hypothesis (see later) and suggested these phenomena were due to the increasing difference in weight growth rate and invariable equality in height growth rate among plant classes. Questions which still could be raised are whether a different plant arrangement, especially in the irregular spacing which could promote earlier and stronger competition between plants in closer spaced groups, could also affect the difference between dominant and suppressed plants in the early and later stages of growth. This question is examined in the studies reported in this thesis.

Yoda and his collaborators found that at high density taller plants grew more rapidly than the lower plants, both in shoot length and in fresh weight, all through the experimental period. At the lowest density a similar tendency also occurred, but the difference in growth rate is less obvious (Figure 7a). This result on the faster

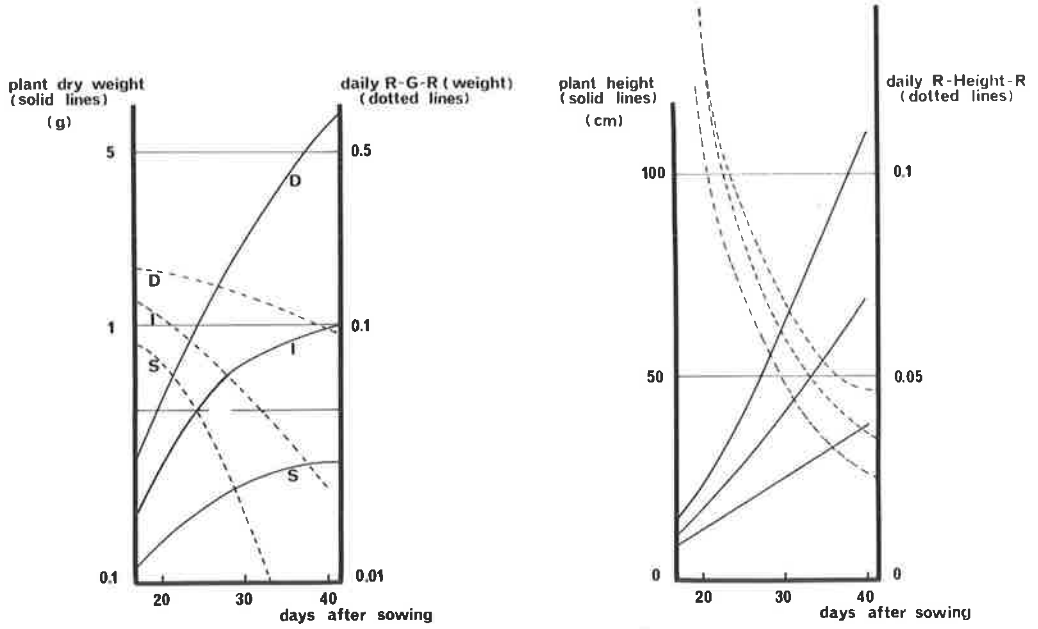

FIG.7b: GROWTH ANALYSIS OF SUNFLOWER PLANTS. D=DOMINANT, I=INTERMEDIATE, S=SUPPRESSED (KUROIWA, 1960).

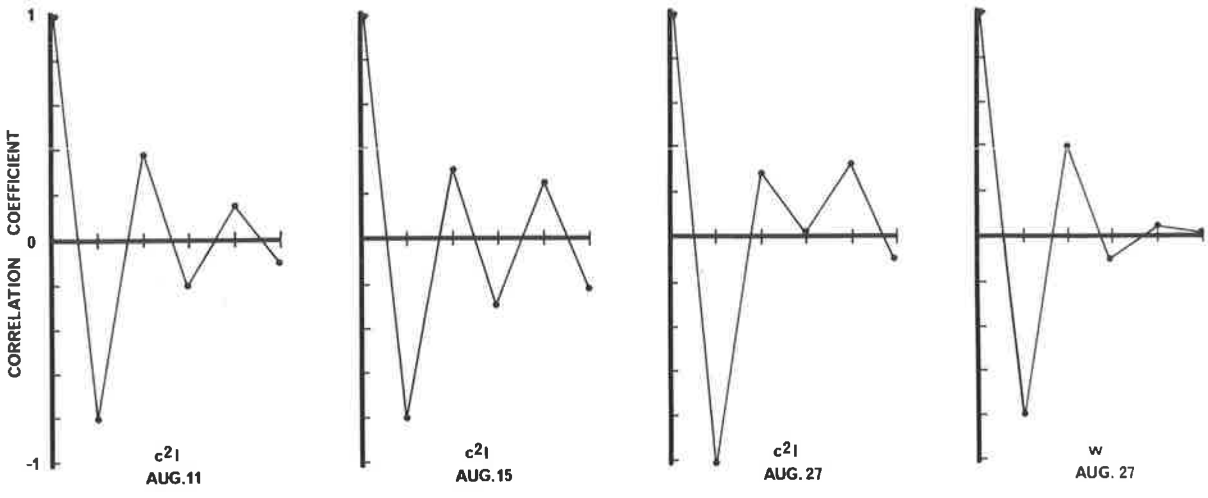

FIG. 8: THE CORRELATION BETWEEN THE WEIGHT OF SHOOT (ESTIMATED AND ACTUAL) OF A CORN PLANT AND ITS FIRST TO FIFTH NEIGHBOURS (HOZUMI et al., 1955).

rate of shoot elongation by taller plants differs from Hozumi's results (1956) mentioned earlier. The probable explanation is that they used different species and each has its own characteristics. Hozumi (1956) used maize, which being a Gramminae, has narrow leaves so that it provides better light penetration within the canopy, and is capable of making a rapid shoot elongation during its early growth period. These two characteristics make it less likely that taller plants will have an absolute domination so that 'co-operative interaction' during certain growth period is possible. Yoda *et al.* (1957) used rose-mallow, a broad leaf plant, which could block light penetration effectively, and since it also cannot make a relative rapid shoot elongation, the taller plants could acquire an absolute domination, both in foliage display and weight.

2.2.2 Alternation of plant weight

Hozumi *et al.* (1955) in their study of corn grown in a single row in a box, found an interesting form of dominance and suppression in the correlation between the weight of one plant with its first five neighbours. The correlograms in Figure 8 show the correlations between the weight of the n-th plant in a row and that of the (n + 1)th, (n + 2)th,......(n + 5)th. The correlations oscillate alternately between negative and positive and gradually decrease. The negative correlation with the first neighbour followed by a positive correlation with the second neighbour implies that the bigger the n-th plant, the smaller the (n + 1)th plant. The dominant effect of the n-th plant gives an opportunity to the (n + 2)th plant to become bigger due to weaker competitive effect from (n + 1)th plant, etc.

Yoda *et al.* (1957) in an auto-correlation analysis of their experiment with rose-mallow, sown in multiple rows one metre apart with spacings between plants of 2, 4 and 8 cm respectively, found somewhat different results to those presented by Hozumi *et al.* in 1955. The correlations between the weight of a plant and its nearest neighbour were always negative. However, Yoda *et al.* pointed out that with 2 cm spacing, the correlation of plant size (shoot length and estimated fresh weight) with the second neighbour was also consistently negative and those with third and fourth neighbours were negligibly small. It seems that at 2 cm spacing the direct influence of a plant rarely went beyond its second neighbour. The 4 cm plot showed a similar tendency, while the interaction between plants at 8 cm spacing seemed to be restricted to the nearest neighbour. The somewhat different results of these investigators is most probably due to different plasticity characteristics of the plants used in the experiment. They both confirmed the negative correlation between the n-th plant and its neighbour, but whether this will include the second neighbour or not may depend upon the ability of the particular variety used in the experiment to 'expand' itself under more favourable circumstances where there is a chance to dominate, and also depends upon plant distances. The important aspect recognized from these works is that plant interaction may extend beyond the nearest neighbours.

2.2.3 Skewness in the frequency distribution of individual plant weight

This phenomenon was reported by Koyama and Kira in 1956. In their study they used several plants, e.g. touch-me-not (*Impatiens balsamica* L.), radish, rose-mallow (*Hibiscus moscheutos* L.), soybean, pine (*Pinus densiflora* Thumb.), ragwood (*Ambrosia elatior* L.), bean (*Phaseolus chrysanthos* Savi.), turnip and dent corn. In looking at the frequency distribution of individual plant weight they found a gradual change from normal at the earliest growth stage to skewness to the right or 'L' shaped at a later growth stage (Figure 9). They concluded that the skew distributions found in the observed results most probably belong to the lognormal distribution, which is the normal outcome of the exponential nature of plant growth as well as of the variability of relative growth rate of normal distribution type. This is based on Blackman's (1919) exponential equation on plant growth,

$$w = w_o e^{rt}$$

where w is plant weight at time t, w_o is initial plant weight, and r is relative growth rate. The log form of this equation is:

$$\log w = \log w_o + rt$$

$$r = \frac{1}{t} (\log w - \log w_o)$$

They postulated four possible types of model population, with either w_o or r or both as a constant or as normally distributed values. The two types where w_o and r, or only r, are constant, were considered as too hypothetical, since it is difficult to imagine a population where each plant has a constant rate of growth even if it starts with an equal weight, i.e. when w_o is constant. The constant values of w_o can be achieved by using carefully selected uniform seeds, while normally distributed values are more usual. The value of r is certainly varied, and the variation is more complicated because the essential factors which affect individual plant growth are a dynamic complex which varies with time. They simplified the relationship by assuming that the r values are normally distributed, and this could be the major drawback of the model. If w_o is constant and

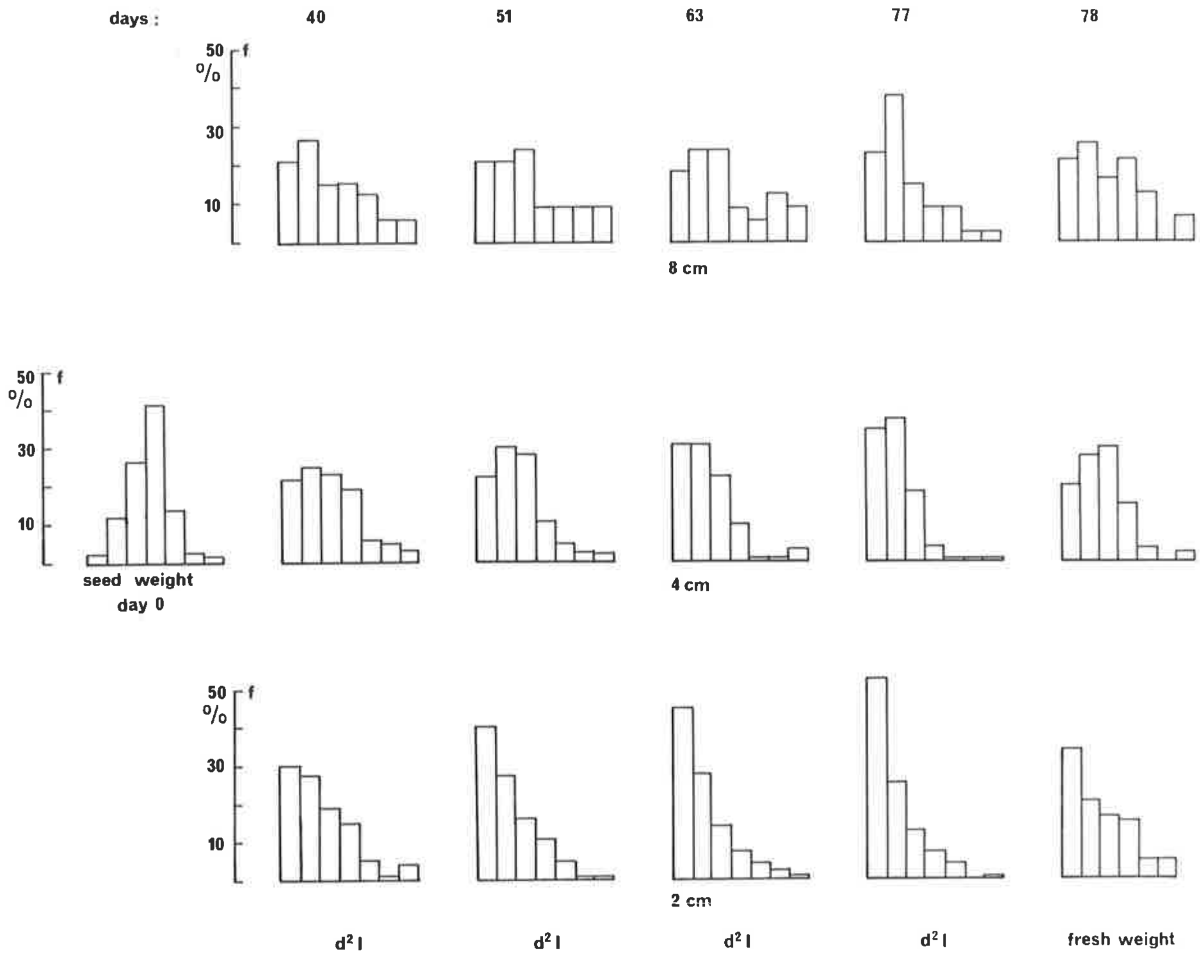

FIG. 9 : FREQUENCY DISTRIBUTION OF SEED WEIGHT, ESTIMATED PLANT WEIGHT (D^2L) AND FRESH WEIGHT PER PLANT (78 DAYS AFTER SOWING) IN ROSE MALLOW. f IS THE RELATIVE FREQUENCY IN PERCENT (KOYAMA AND KIRA, 1956).

r values are normally distributed, then the frequency distribution of w is lognormal at any values of t. They obtained similar results when the values of w_o are also normally distributed.

According to their explanation, the distribution of individual plant weight starts from normal type in the seed and seedling stage, and passes through an asymetric bell-shaped into an L-shaped type with the advancement of plant growth. They further said that the following conditions are necessary in order to maintain an apparently bell-shaped type for a longer period and to delay the appearance of an L-shaped distribution. First, the relative growth rate is not very variable or the standard deviation of r is small; second, the combination of the values of w_o (or w) and r is randomised. On the other hand the reverse conditions promote the appearance of an L-shaped distribution.

The evidence that skewness develops among non-competing plants was considered by Donald (1963) "as rather inconclusive". As can be seen in the data presented by Koyama and Kira (1956) on radish, a skew distribution was only found at the two highest densities while at three lower densities the distribution remained normal. With soybean the skewness was found at three higher densities but was normal at three lower densities, while for his other experiment on the same plant the skewness was unrelated to density. For pine the skewness at the lowest density was either very slight or uncertain, on turnip at two lower densities the distribution was normal. The data on fibre flax presented by Obeid *et al.* (1967) showed that at low density the distribution was normal up to final harvest. All the examples which contradict the Koyama and Kira hypothesis point out the importance of further studies for clarification. The work so far has not explicitly indicated the effect of this phenomenon, if any, on crop production.

2.2.4 Self-thinning

One of the first reports on self-regulation of numbers in population of plants was by Sukatschew in 1928 (quoted from Harper, 1967) who sowed *Matricaria inodora* at two densities in fertilised and unfertilised soil, and the result at the end of the season was that the percentage loss from the population was greater at the higher density and in fertilised soil. No information was given on the actual seeding rate and doses of fertiliser. Harper and McNaughton (1962) on their studies with *Papaver* species found that the relationship between number of seeds sown and the number of plants present at maturity was strikingly non-linear, and a quadratic equation was fitted to the relationship. The equation is:

$$Y = bx + cx^2$$

where Y is number of plants per plot and x is number of effective seeds sown. They explained that b might be taken as a measure of the chance that a seed will produce a plant irrespective of the influence of density, and c represents a measure of the role of density in affecting establishment. The fact that b and possibly also c differed significantly between blocks could only mean that local environment strongly affected the number of plants which reached maturity. Yoda *et al.* (1963) extended the observation on natural and artificial populations of several plant species, and concluded that the chance of a seed producing a mature plant declined with increasing density and that irrespective of the density of seeds sown there is a maximum population size of plants produced. They also concluded that the densities of overcrowded populations converge with time irrespective of the differences in initial density, and the resultant density was always lower on the more fertile soil, and closely correlated with plant size. They formulated a hypothesis linking the numbers of plants and their weight in pure stands with a mathematical equation,

$$w = C\ p^{-3/2}$$

where *w* is mean weight per plant and *p* is existing plant density. This relationship seems to be applicable for different species of plant including trees (White and Harper, 1970).

2.3 Quantitative analysis of individual plant performances

As emphasized in the introduction, individual plant performance has seldom been examined closely within the crop plant's own environment. Looking directly into individual plant performances and studying their dynamic interaction is a difficult study when done in the field. There are many independent and dependent variables, with degree of dependency changing with time. Because of this complexity, quantitative analyses have so far only explained part of the phenomenon.

In the study of individual plant performance, several methods have been used to measure the degree of competition in various situations. One of them is to look at the variation arising from inter-plant competition by calculating the coefficient of variation (Stern,1965). Stern found that at a low population density the coefficient of variation remained fairly stable for various stages of plant growth, but at high density it increased with time. The assumption in this method was that, if the relative variation is unaffected by different treatments, the shape of the frequency distribution would remain constant with the variance increasing proportionally to the square of the mean. However, if the distribution shape changes it is impossible to distinguish variation in the coefficient of variation due to increased relative variation from that due to shape changes in distribution.

The method (Hozumi *et al.*, 1955; Yoda *et al.*, 1957) of measuring the correlation between adjacent plants in a row, only supplies us with information on single direction individual plant interaction.

Mead (1966) realizing the importance of irregularity of spacing, described the arrangement of plants in an irregularly spaced crop by allocating a polygonal area of ground to each plant. The polygon is characterized by three parameters (Figure 10):

(1) Area of the polygon,

(2) Eccircularity (= λ), i.e. the extent to which the polygon is elliptical rather than circular in general shape, is given by

$$\lambda = D \sqrt{\frac{\pi}{\text{area}}}$$

D is mean distance of the centroid (= C = centre of gravity) from the vertices (= V_i = corner of polygon)

(3) Abcentricity = $\upsilon = \frac{[CP]}{D}$

where [CP] is the distance from C to P, and P is plant position in the polygon. Abcentricity is defined to be zero when the plant is at the centroid of its polygon and tends to equal one when the plant is near a vertex of the polygon.

In the experiment to test the hypothesis Mead used carrots planted at three densities and three row widths. The position and diameters of carrots in a fixed area in each plot (to give approximately 500 roots) were measured for each plot. He found that the best linear relationship between polygon parameter and plant yield, in this case root diameter, was as follows:

Carrot diameter = $\alpha + \beta_1$(log area) + β_2(eccircularity) + β_3(abcentricity)

α, β_1, β_2, β_3 are constants to be estimated and the logarithms are to

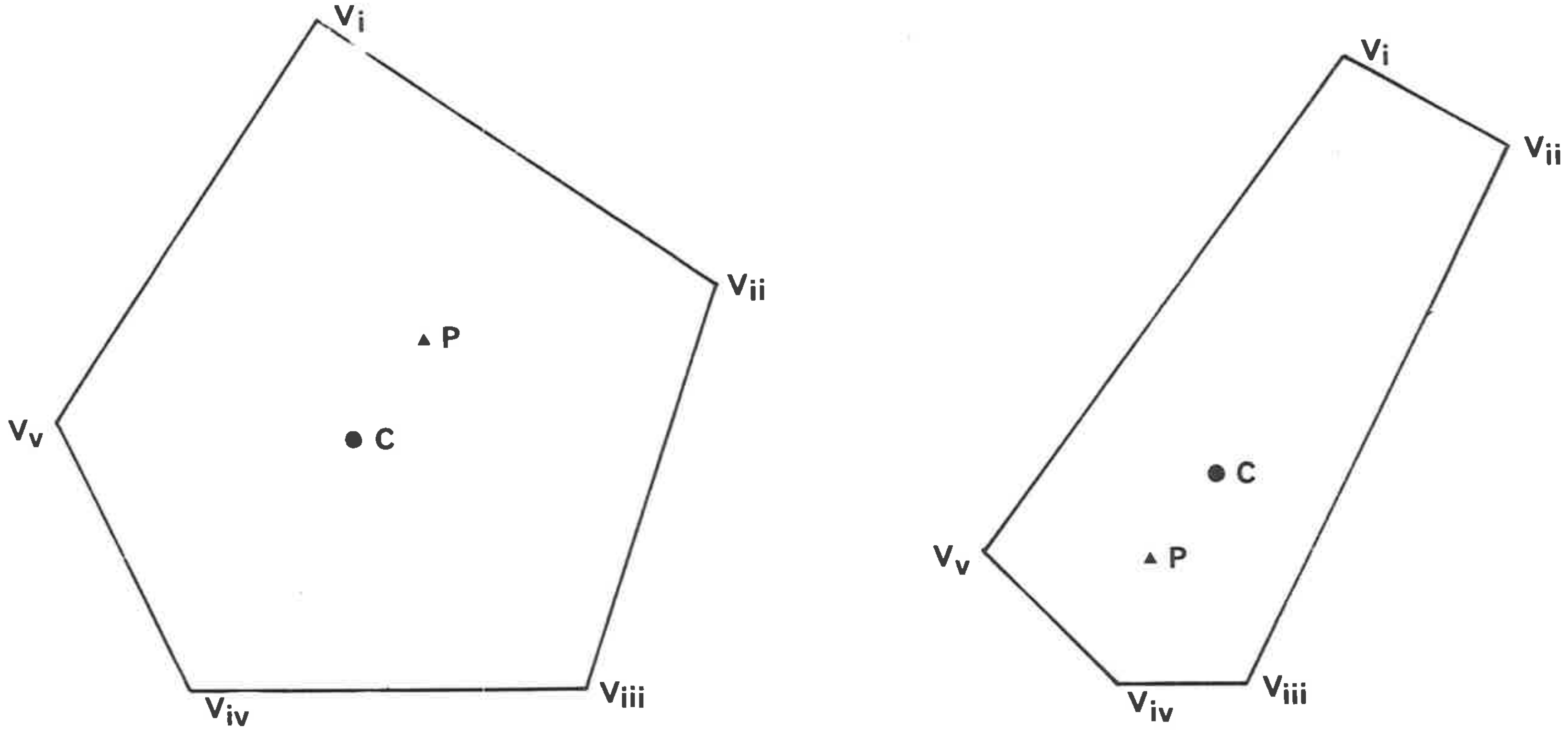

FIG 10 : TWO POLYGONS DIFFERING IN AREA, ECCIRCULARITY AND ABCENTRICITY. C IS THE CENTROID, P IS THE PLANT, AND V_{i-v} ARE THE VERTICES.

base e. In examining the relationship between the three parameters and the root diameter, it was found that the proportion of the total variation in plant yield attributable to polygon variation increased with time. The largest mean proportion of the variation in plant yield (out of two means from two experiments) at the final harvest was 20% and for individual plots as much as 55%. It would also be interesting to know the relationships between those parameters with yield per plant either in the form of total dry weight or plant-part/ dry weight. This system, even though very attractive in its design, also has some disadvantages, e.g. it does not take into account the size of the neighbouring plants or the fact that plants other than the immediate neighbour defined by the polygon might affect the plant especially at high density.

Another method for measuring inter-plant competition is by calculating the correlation between a plant's weight and the mean weight of its neighbours, as proposed by Mead (1968). He devised this method for a regular hexagonal pattern of plant arrangement and restricted the number of neighbours for each plant to the six nearest plants. A square arrangement was considered by him as more complicated because each plant has four close neighbours and four others a little more distant on the diagonals of the square. The competition model was:

$$E(\bar{y} - y_i) = \lambda\{(\bar{y} - y_1) + (\bar{y} - y_2) + \ldots\ldots(\bar{y} - y_j)\}$$

where

$\bar{y}$ = mean yield of the sample plants

y_i = yield of plant i

i = number of test plants

j = number of neighbours for each test plant

λ = competition coefficient of the sample

$E(\bar{y}-y_i)$ = expected value of the deviation of the yield of plant i from the mean plant yield.

The correct estimate of λ is the value which minimises the expression

$$P(\lambda)\ \Sigma_i(y_i - \Sigma_{j(i)} \lambda y_j)^2$$

where $P(\lambda)$ is a polynomial in λ depending on the arrangement of plants whose yields are being considered.

To examine the behaviour of the competition coefficient, he tested the model on radish, lettuce, cabbage and carrot crops which were planted in a regular hexagonal pattern at different densities. Log weight was used as the y-variate instead of weight because the variation of log weight is almost constant for widely differing mean weights. It was found that the errors of the treatment means were rather high, and if this is seen as a property of the method, then for the successful use of the competitive coefficient as a measure of inter-plant competition, a much larger number of samples per treatment must be used. An inconsistent result was also obtained from carrots, i.e. the density giving the most competitive values of the competition coefficient varied steadily with harvest. He explained that this could be due to the fact that the model only calculates the degree of competition between a plant with its six immediate neighbours.

It is obvious that so far there is no one satisfactory method for accounting quantitatively for all the interaction between individual plants within a crop community, and because of its complexity, most systems explain only part of the phenomena.

A possible better method of analysis of the effect of neighbours is by calculating what is considered as the 'competitive pressure'. As mentioned earlier the effect of neighbours on each plant is basically a function of distance and size of the neighbouring plants. The function form which could best relate the competitive pressure and the weights and distances of neighbours has to be formulated, and also the relationships between weight of a plant and the competitive pressure of that plant has to be determined. More about this will be discussed later. To test this system of analysis the weights of each plant and the distances between plants within the 'range of influence' must be known.

3. Concluding remarks

To know the individual plant performance within a crop community a study has to be made direct at the individual level within the community. Data which is derived from the population level is useful for visualizing average plant type and characteristics within the community, but it is of no value for understanding the individual plant interaction with its micro-environment in a crop community.

Due to multiplicity of factors and the complexity of interactions most of the work on individual plant performances has so far been done in a partly controlled environment with simplified designs from which have been obtained only certain aspects of individual plant interaction. Much more investigation is still needed before we can actually understand the whole phenomenon of individual plant response to its environment from its early stage of growth until harvest time under field conditions.

Several problems must be overcome in this study. The first one, as mentioned earlier, is to find a method of non-destructive field measurement of individual plant characteristics. This should be accurate enough to detect changes in plants in reaction to their individual environment, and fast enough so that sufficient plants can be measured in relatively short periods, without disturbing the community and consequently also the environment of each individual plant. Several methods have been proposed and some of them already found wide acceptance, e.g. leaf area estimation and plant weight estimation for non-tillering plants. Other methods still need to be developed before we can make a reliable growth analysis for single plants in the field. Some other methods are examined in this thesis.

The second handicap is instrumentation for monitoring the micro-environment of individual plant within the crop community. With further miniaturization of instruments there is a possibility that we should not have to wait too long before this problem can be overcome.

Another major problem is to find suitable designs and analyses for field experiments which could take into account all aspects of inter-plant competition. Methods of analyses so far available have limited applicability. For example, both Hozumi *et al.* (1955) and Yoda *et al.* (1957) in an auto-correlation analysis managed to confirm plant interaction beyond the first and second neighbours but only among neighbours within the row, while Mead (1966) in his polygon system analysis provided a method for assessing the effect of all surrounding nearest neighbours of each plant in an irregular arrangement, but disregarded the effect of second and third neighbours which he had established earlier.

In this study, attempts were made to analyse the effect of all nearest surrounding neighbours (first group) and also further surrounding neighbours.

PROGRAM OF INVESTIGATION.

Two field experiments were carried out in these studies.

In Experiment 1, density and plant arrangement were the variables in a barley crop. Three densities were used; the highest was just below the density where plant mortality was to be expected due to overcrowding, while in the lowest density ample space was given to each plant so that there was little interference from its neighbours. The medium density was approximately a normal commercial density. The nominal rates of density were 140, 70 and 17.5 kg per ha. The two plant arrangements were (a) drilled, where plant distance in one direction was regular (between rows) and in the other direction was irregular (within rows), and (b) square planted, where the distances between the plants in both directions were equal. Repeated measurements on the same plants were made and plant co-ordinates were measured.

In Experiment 2, with wheat, as a complement to Experiment 1, random plant arrangement was used. The two densities used were high density with a nominal seeding rate of 190 kg and medium density with a nominal seeding rate of 95 kg per ha. Plants were examined by both repeated measurements at the same plants and successive harvests (eight harvests). Plant co-ordinates were also measured.

The design of the experiment was based on the consideration that for the study of individual plant performance and the effect of neighbours, each plant community has its own plant/environment interaction which cannot be replicated even by another plant community in the same plot. In the analysis, each plant within each plot was looked upon individually, each quadrat (community) was analysed separately and then were tested as to whether a similar trend was obtained in each community.

MATERIAL AND METHODS

1. Experiment 1.

The effects of plant density (3 levels) and plant arrangement (drill sown *vs* square planted) on individual plant performance within a crop community (barley, *Hordeum vulgare* L.,cv.Clipper) in the field.

1.1 Site of experiment

This experiment was conducted on the Waite Institute's experimental field, W 11, which is gently sloping and located at approximately 100 m above sea level. Litchfield (1951) described the soil as a red brown earth usually with 25 cm or more of top soil of fine sandy loam texture, a prismatic structured clay subsoil and a calcareous deep subsoil, with variable waterworn gravel or stone.

This particular site was used for grass in 1968 and 1969, oats in 1970 with 102 kg per ha superphosphate, and in 1971 was planted with peas then plowed in spring and left fallow until cultivated for this experiment, first in April and again before sowing in July 1972.

Analysis of soil samples taken from the site on 17 May 1972 indicated that the available nitrate varied between 58 ppm and 113 ppm, a level usually indicative of an adequate nitrogen supply in this environment.

The rainfall pattern in 1972 was exceptional and caused prolonged delay in sowing. A normal beginning of the rainfall season in March-April was followed by an exceptionally long dry period of approximately two months, and not until the second week of July did the actual rainy season commence. It was opened by almost continuous rain for several weeks which again prevented sowing. After a brief period of sunny days, the site was cultivated and sown on July 23, 1972, involving 22 persons for one day. Since considerable bird damage occurs in this area, the whole experimental site was covered with netting. The installation of the frame structure and also the stretching of fishnet at a height of 2.2 metre on top of the strung wire were done before sowing and the sides were completed the day after sowing.

1.2 Treatment and design of experiment

The objectives of this experiment were to study the effect of density and plant arrangement on individual plant variability, and also to study the competitive effect on individual plants of their neighbouring plants. The experiment was basically a split-plot design, with density as the main treatment and plant arrangement as the sub-treatment.

There were three nominal densities, i.e. high density (333 plants/m^2), medium density (166 plants/m^2), and low density (42 plants/m^2) a ratio of 8:4:1. Two types of plant arrangements were used, i.e. square planted, where seeds were hand planted at the intersections of a square grid of wires; and drilled, where spacings between the rows were approximately constant (mean 17.7 cm) and spacings within the rows were irregular (Table 4).

For each of the 6 treatments, one large plot (1.6 m x 20 m) was sown. Border plots on each side of the treatment plots were drill sown at medium density (Figure 11). General view of the experiment at day 30 is shown in Plate 1. Five individual communities (quadrats) were randomly chosen for study within each major plot, serving as replicates. Each of the 30 quadrats was studied and analyzed as an individual community, and then the influence of density and plant distribution was tested.

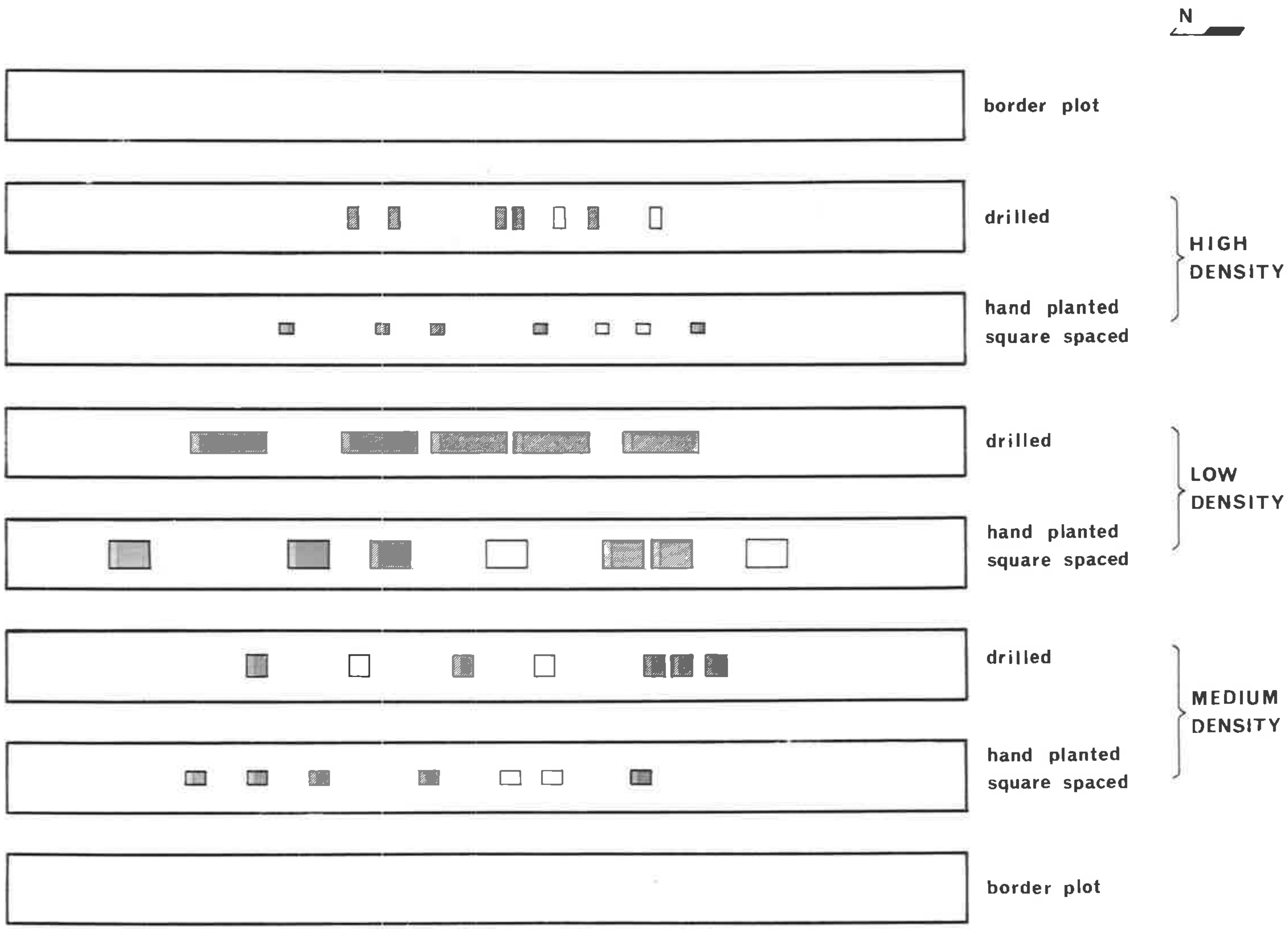

FIG. 11 : LAYOUT OF EXPERIMENT 1.

PERMANENT QUADRATS.

QUADRATS FOR GRAIN SAMPLES.

Plate 1: General view of experiment 1 at day 30. In the bottom left hand corner is a border plot which is subsequently followed by high density, low density and medium density plots, each with one plot drilled and one plot square planted, and another border plot.

Table 4: Nominal seeding rate, co-ordinates, number of plants per square metre and number of rows per plot of each treatment. Experiment 1.

Treatment	Nominal seeding rate (kg per ha)	Nominal density (plants/m^2)	Number of rows in the plot*	Plant arrangement	
				Mean ordinates (cm)**	Area per plant (sq.cm)
High density: drilled	140	333	9	17.7 x 1.7	30.09
square planted	140	333	29	5.5 x 5.5	30.25
Medium density: drilled	70	166	9	17.7 x 3.4	60.18
square planted	70	166	20	7.7 x 7.7	59.29
Low density: drilled	17.5	42	9	17.7 x 13.6	240.72
square planted	17.5	42	10	15.5 x 15.5	240.25

* In each arrangement the term 'rows' is applied along the length of the plot. In the square planted plots there are only nominal 'rows' since the spacing is equal in each direction.

** In the drilled plots these figures indicate the average distances between rows, which is constant in all densities, and the calculated mean distance between the plants within the rows. In the field the spacing between plants was irregular (see Results).

1.3 Plant material

Barley was considered better suited for the late season time of sowing. The variety Clipper, recently bred at the Waite Institute, was chosen as a variety which is a strong grower with flexible performance, adaptable to seasonal environmental factors.

The seeds were machine graded and then hand selected to remove any shrunken, deformed and broken seeds which had passed through the machine grader. Germination tests were made and the results used for calculating the actual seeding rate.

1.4 Soil preparation and establishment of the experiment.

The sowing of this experiment was delayed until July 23 because of the unusual seasonal conditions. The site was cultivated early in the morning and at the same time a basal superphosphate dressing was applied at the rate of 112.5 kg per ha.

In the drilled plots the drilling was done approximately an hour after cultivation to give time for the soil surface to dry so that the drill could effectively till the soil. The drill was set at a high density rate for all plots; for the medium and low densities the viable seed was mixed with dead seed proportionate with the intended density. The drill hoes were 17.7 cm apart.

After cultivation the plots for hand planting were raked to get a fine and even soil surface, then a square grid of wire was laid on the soil. The grid could cover the whole width of the plot, and the size of its squares was in accord with the spacing required (Table 4). Holes of standard depth, i.e. 3 cm, were made at the corner of each square with sticks which had stoppers set 3 cm behind the tapering end. Two seeds were planted in each hole.

The soil preparation during sowing was comparable with hand raking in the hand, square-planted plots. These cultivations were not identical but are believed not to have influenced the phenomena under study.

Each plot was covered with polyethylene sheet to keep rain off and prevent it from compacting the soil before seedling emergence. These Red Brown Earths can form a very hard crust when soaked and exposed to a dry period afterward, a condition which reduces substantially the establishment rate and gives a poor growth of seedling. The covering sheets were removed as soon as the seedlings started to emerge.

In the square planted plots, thinning to a single seedling at each point was done 14 days after sowing by pulling out carefully the weaker of the two seedlings.

1.5 Pest control

The plants were sprayed with 0.2% D.D.T. at day 12 and day 15, and snail bait was applied soon afterwards by scattering Baysol's pellet at the rate of approximately 75 pellets per square metre. These precautions seemed to give ample protection to the young plants.

At the later stage of growth disease problems became more prominent. The most common, especially in the higher density plots, were powdery mildew (*Erysiphe graminis* f.sp. *hordeae*) and *Rhynchosporium secalis*, which were controlled by spraying a mixture of metasystox 500 ppm active ingredient and milstem 200 ppm active ingredient. It was sprayed thoroughly so that each leaf within the canopy was properly covered. The first application was given at day 45 and the second at day 74. A virus disease, barley yellow dwarf, also became obvious mainly in the lower density and medium density of the drilled plot. Plants affected by this disease were marked.

1.6 Data collected and methods of collection

1.6.1 The quadrats

There were two different kinds of quadrats in this experiment, i.e.

(a) Permanent quadrats for repeated measurements, in the same position throughout the experiment. There were five permanent quadrats (= 5 replicates), each providing an individual community, in each plot. The size of each permanent quadrat varied between treatments (Table 5). In drilled plots each quadrat was placed in the middle three rows and was intended to contain approximately 30 plants. In square planted plots each quadrat was placed in the middle four rows and contained 28 plants. In Plate 2 is shown one quadrat in the square planted low density plot and one quadrat in the drilled low density plot. The location of the quadrats within each plot was determined by dividing the plots into units of quadrat's size and then selecting five quadrats at random (Figure 11). In the square planted plots care was also taken that each quadrat had 100% establishment within its near surroundings. The details of the quadrats and the number of plants which were observed during the experiment is shown in Table 5.

(b) Quadrats for grain samples. It was intended that the permanent quadrats continue to be observed until the grain was ripe. However because of a lodging problem, discussed later, the permanent quadrats were harvested at early dough stage.
The plots were then surveyed to see whether unlodged portions would be available to provide additional quadrats at the ripe grain stage. Suitable quadrat sites were available in all treatments except in the drilled low density plot, in which the permanent

Table 5: Quadrat sizes and number of plants in each quadrat. Experiment 1.

Treatment	Size of quadrat		Number of plants per quadrat					Number of observed plants per treatment	Mean plants/m^2
	Structure	Dimensions (cm)	1	2	3	4	5		
High density: drilled	3 row lenths of 26 cm, rows 17.7 cm apart	26 x 53.1	31	49	35	30	31	176	255*
square planted	4'rows' 5.5cm apart, of 7 plants, 5.5 cm apart	22 x 38.5	28	28	28	28	28	140	331
Medium density: drilled	3 row lenths of 51 cm, rows 17.7 cm apart	51 x 53.1	44	39	43	39	46	211	156
square planted	4'rows'7.7 cm apart, each of 7 plants 7.7 cm apart	30.8 x 53.9	28	28	28	28	28	140	169
Low density: drilled	3 row lengths of 204 cm, rows 17.7 cm apart	204 x 53.1	39	41	37	44	46	207	38
square planted	4'rows'15.5cm apart, each of 7 plants 15.5 cm apart	62 x 108.5	28	28	28	28	28	140	42

* This is the mean number of established plants per m^2. Even though the nominal seeding rates for both drilled and square planted plots were equal for each density, the plant establishment in the square planted plots was nearer to the nominal rate because of special precautions (double seeding per hole and thinning out later)

Plate 2: Experiment 1: Close-up view of the permanent quadrats in square planted low density plot (above) and drilled low density plot (below) at day 30. The observed plants (above: in four middle rows, below: in three middle rows) were labelled individually.

quadrats had occupied a considerable proportion of the plots, so that no additional quadrat site with ample border plants was available. Two quadrats were harvested from each treatment plot other than the drilled low density plot.

The sizes of these quadrats were exactly the same as the size of the permanent quadrats in the respective treatments.

1.6.2 Date of emergence

One of the phenomena looked at closely in this study is whether the date of seedling emergence plays an important role in determining the size of each plant within a crop community. For this purpose the emergence of each plant in this experiment was recorded. The recording was done every day, starting at the first day of seedling emergence, i.e. day 5, by dropping a coloured ring, approximately 2 cm in diameter, made out of plastic insulated wire, on each seedling. Each day had a different colour coding. The last emergence was observed at day 12, and in all about 10,000 plants were ringed. The date of emergence of each plant was to be related to its growth characteristics.

1.6.3 Distance between plants

To study the effect of neighbours it is necessary to know the exact position of each plant so that the distance between plants can be calculated. The position of each plant in the quadrats of the drilled treatments was determined by measuring the plant co-ordinate from common axes near two borders of quadrats. These axes were fixed by heavy pegs (Figure 12). In the square spaced plots the position of each plant was already known.

1.6.4 Non-destructive measurements

Non-destructive measurements were used for growth analysis of selected plants from their early stage of growth until harvest time. The problem with this type of measurement is to find an accurate method which can be done fast enough and without too much disturbance of the micro-environment. The simplest method was the measurement of the length of longest tiller and counting the number of tillers per plant. This was done twice, i.e. at day 50 and day 90. All measurements were done from a supported plank across the plot (Plates 3 and 4).

For non-destructive measurement of leaf area there are two main methods:

(a) Linear measurements of each leaf which are then converted into leaf area by an empirical relationship (Darrow, 1932; Hopkins, 1939; Davis, 1940; Thirumalachary, 1940; Lal and Subba Rao,1950; Ackley *et al.*, 1958; Kemp, 1960; McKee, 1964; Carleton and Foote, 1965).

(b) By matching leaves with standards of known area (Bald, 1943; Williams, 1954).

In this experiment, efforts to make linear measurements of each leaf were discontinued because it was too time consuming; on the average it took approximately one day for a team of two persons to finish measurements in one permanent quadrat at that stage (day 40) since there were 100 - 700 leaves to be measured. Individual leaf matching also proved impractical, because it was even slower than linear measurement.

Plant weight estimation can be done for example in maize by measuring basal stem circumference and stem length (Yodda *et al.*,1957). This type of measurement is however impracticable in tillering cereals

Plate 3: Doing non-destructive measurements on a supported plank across the plot - Experiment 1.

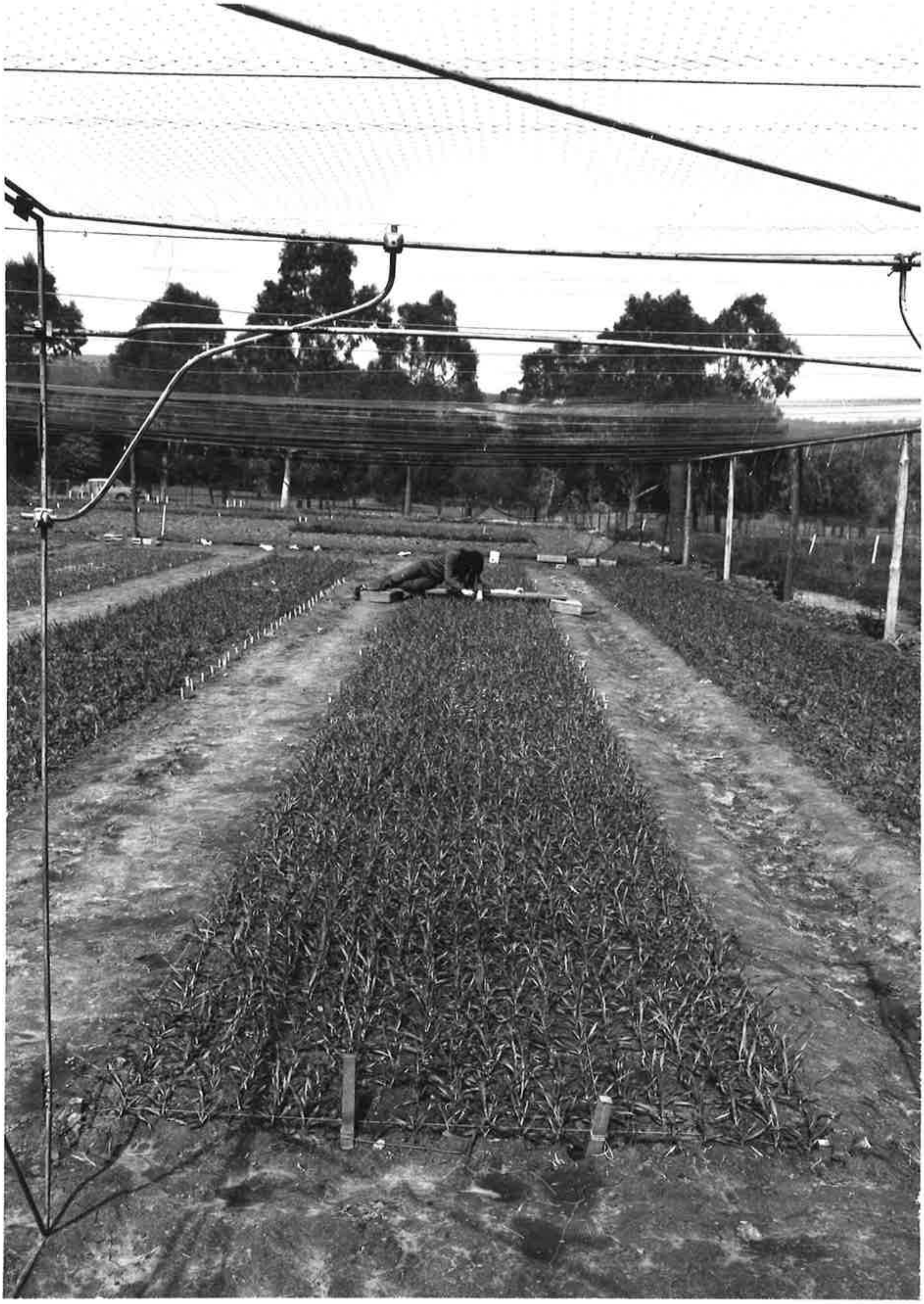

Plate 4: Close-up view in measuring length of longest tiller in the permanent quadrat of the medium density square planted plot - Experiment 1.

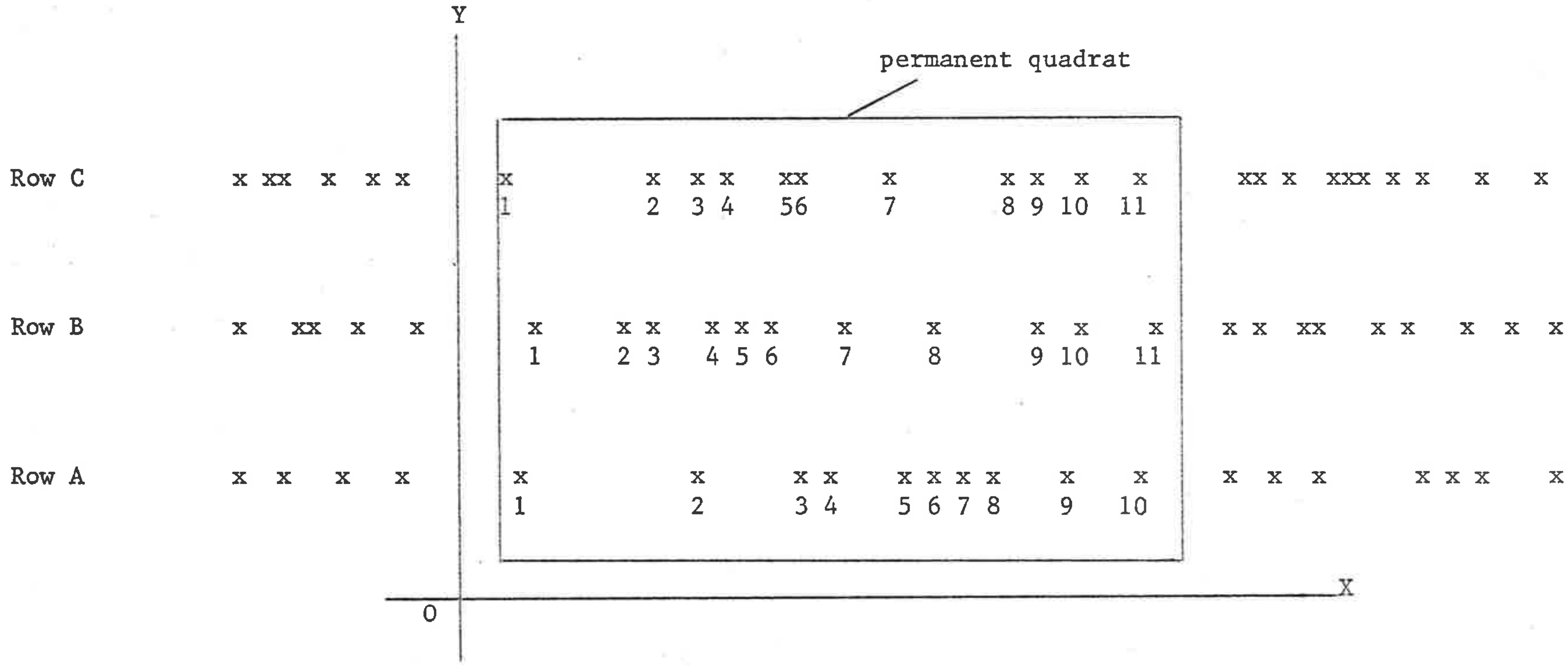

Figure 12: Schematic location of each plant (A_1,.....A_{10}; B_1,.....B_{11}; C_1,.....C_{11}) within a permanent quadrat in a drilled plot. OX and OY are the base lines from which plant co-ordinates were measured.

like wheat and barley because of the difficulties in reaching down to the stem base without breaking too many leaves, especially at the high density, and since it has to be done on each tiller it is also too time consuming when thousands of tillers have to be measured.

Two other methods were developed during this experiment, i.e. by matching tillers with standards of known weight and by using the 'plant cylinder' as a weight estimator.

(i) In the matched tiller method a standard was prepared for each treatment. For preparing the standard a sample of 100 plants was taken from each plot, then all the tillers were grouped into: one leaf tillers, two leaf tillers, three leaf tillers, etc. In each of those, a range of sizes was selected, from the smallest to the biggest. After a set of standards was obtained they were weighed and then mounted on cardboard and Xerox copied. The Xeroxing was considered the best method of obtaining instant reproduction of actual size. As an example a set of standards for two leaf tillers is shown in Figure 13. The weight estimation in the field was done by examining each tiller separately, counting its leaves, holding the standard set as close as possible and then recording its class size. Measurement with this method at this stage (advanced tillering stage) was also considered too time consuming and was discontinued. (This method was used later. See Expt. 2.)

(ii) The 'plant cylinder' method of weight estimation can be done more quickly. This is an adaptation from the method of plant weight estimation used by Yoda *et al.* (1957), which is best suited for non-tillering plants with bigger stem, e.g. *Hibiscus* sp., sunflower, maize, even trees (Figure 14a).

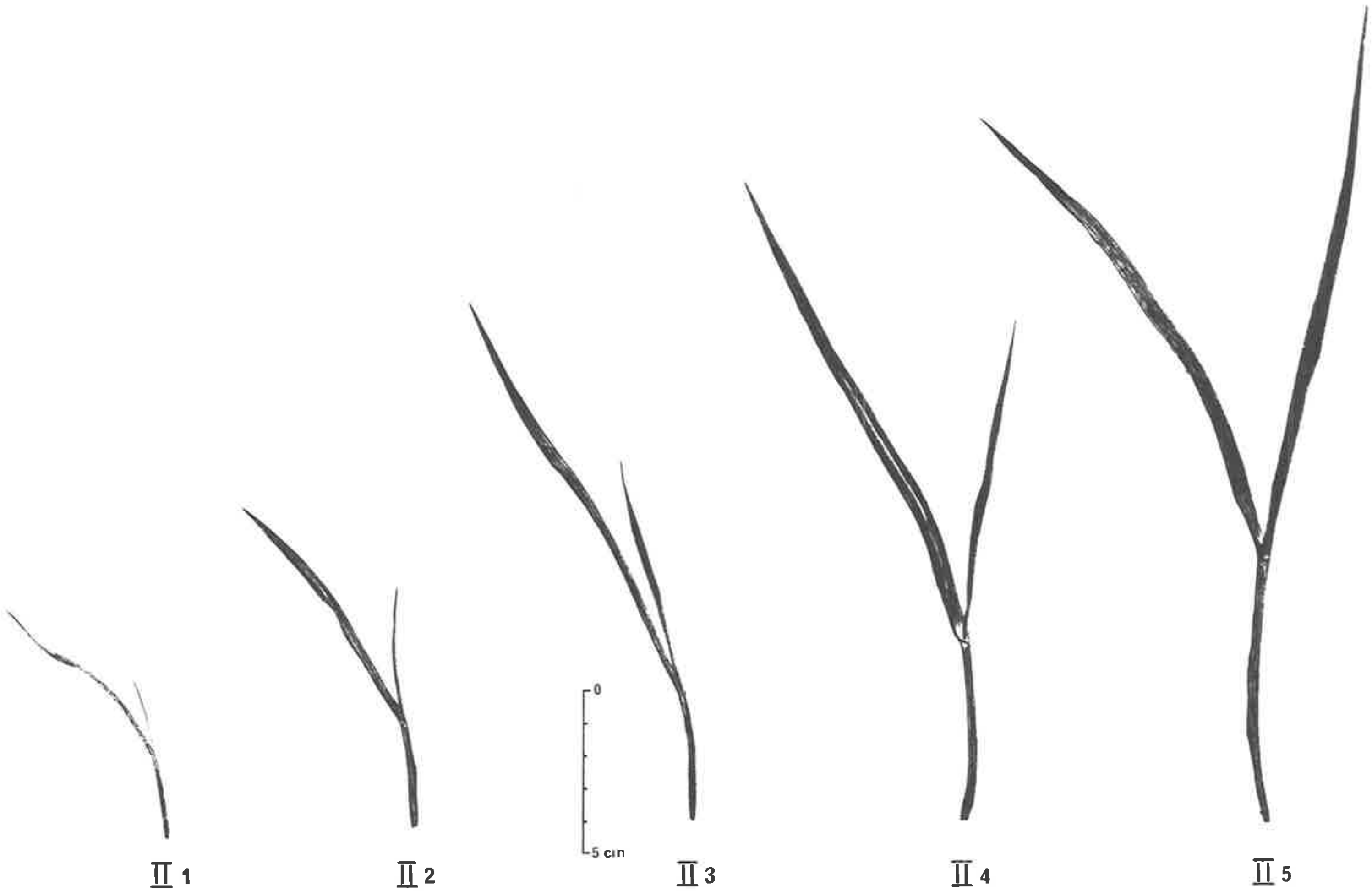

FIG. 13 : EXAMPLE OF A SET OF STANDARDS OF TWO LEAF TILLER WHICH WERE PHOTOCOPIED BY XEROX MACHINE. USED FOR PLANT WEIGHT ESTIMATION.

The estimation is based on transformation of a normal habit of tillering plant in a crop into a 'compact' cylinder (from b_1 into b_2 Figure 14). The circumference and length of the plant cylinder is measured after holding all the tillers together and pulling the leaves upwards (Figure 14b_2). The circumference measurement is done with a measuring tape which is circled around the base of the plant (10-20 cm above ground level), then tightened until it becomes firm but before it causes any damage to the plant (Figure 14b_3). The length of cylinder is measured from the base of a stem up to the point where the cylinder tapers strongly. This method was tested thoroughly before being used, and the results of these tests are reported. One set of measurements in all permanent quadrats was done with this method at day 70.

1.6.5 Final harvest

(i) The permanent quadrats, on which the several non-destructive observations had been made, were harvested before the grain was ripe (at early dough stage) at day 90 due to lodging in the high density following rain and wind on day 85 (15 October 1972). Each plant within the permanent quadrat was harvested by pulling it out, shaking off the soil, placing it in a labelled plastic bag and storing in the refrigerator. Measurements which were done on each of the 1014 plants were:

(a) Length of longest tiller from the base of the plant to the tip of the longest leaf. The plant was then cut at the base and each tiller was carefully separated.

(b) Number of tillers per plant.

(c) Number of ears per plant.

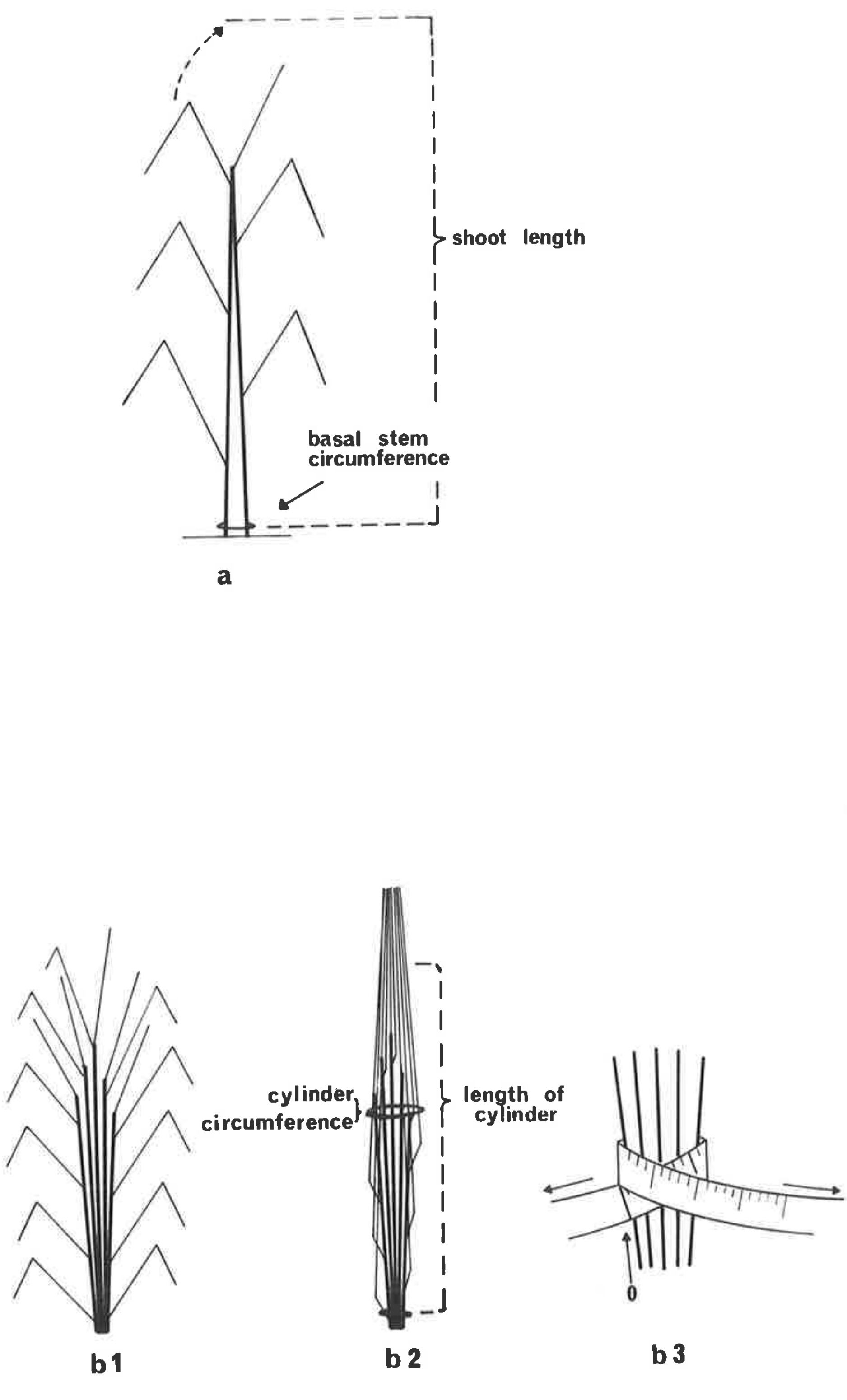

FIG. 14: DIAGRAM SHOWING METHOD OF PLANT WEIGHT ESTIMATION:
(a) AS USED BY YODA
(b) AS PROPOSED IN THE PLANT CYLINDER METHOD.

From each tiller were separated the green leaves, senescent leaves and dead leaves, ear and stem, for the following measurements:

(d) Dry weight of stem.

(e) Dry weight of ear.

(f) Dry weight of green leaves.

(g) Dry weight of senescent leaves.

(h) Dry weight of dead leaves.

(i) Number of spikelets per ear.

(j) Leaf area.

(k) Length of stem (total and green) and mean stem diameter.

The dry weight measurements were made after the materials were placed in an oven at 80^{o}C for 48 hours. The measurements of leaf area, dry weight of stem, ear, green leaves, senescent leaves and dead leaves were done for whole plants in four replicates and for individual tillers in the fifth replicate.

(ii) The harvest of the grain sample quadrats was made at the end of November 1972. During this final harvest each plant was replaced by a labelled stick which was pushed into the ground for subsequent plant co-ordinate measurement. Data collected for the harvested material were:

(a) Date of seedling emergence, by recording the colour code of the ring.

(b) Height of tillers measured from the base to the tip of ear.

(c) Dry weight per tiller.

(d) Number of grains per ear.

(e) Weight of grain per ear.

(f) Total weight of non-productive tillers and other remnants of plant parts.

1.6.6 Light readings

The light penetration at the position of each plant was measured twice. At day 40, (31 August 1972) the relative light intensity was measured at ground level adjacent to the stem base of the plant on its east side. The measurement gave an account of the variability of light penetration within the community. The instrument used was the omnidirectional photometer. The second set of measurements were made on day 88 (18 October 1972), after ear emergence. The relative light intensity was measured at ground level and at half the height of the crop. Due to lodging on the high densities and on the medium density square planted plot, the measurements were confined to the low densities and to the medium density drilled plot.

2. Experiment 2

The effect of plant density (two levels) on plant performance throughout the season within a crop community (wheat, *Triticum aestivum* cv., Halberd) at random spacing in the field.

2.1 Site of experiment

The experiment was conducted at the Waite Institute near to the site used for experiment 1. The site was fallowed in 1968, then in 1969 and 1970 planted with oats which were cut for hay. In both oat crops 102 kg per ha of superphosphate was used as basal dressing. In 1971 it was used for an experiment with barley and left fallow after ploughing in spring of 1972.

Bird netting was again installed over the whole experimental site.

2.2 Treatments and experimental design

In this experiment the plants were randomly arranged, i.e. irregularly spaced in both directions, i.e. differently from experiment 1 which had two types of plant arrangement - regularly spaced in both directions (square planted) and regularly spaced in one direction (drilled).

The two densities used were high density with a seeding rate of 190 kg per ha or approximately 300 seeds per square metre, and medium density with a seeding rate of 95 kg per ha, or approximately 150 seeds per square metre. The actual number of plants per square metre varied considerably.

Six experimental plots were used with a border plot on each side (Figure 15). Each density treatment had three plots (replicates). Each plot was 23 metres long and 2.5 metres wide. General view of the experiment is shown in Plate 5.

2.3 Soil preparation and establishment of the experiment

The seed used in this experiment was machine graded and treated against soil born diseases. Seed germination tests were made and the results were used in calculating seeding rate.

To obtain a random plant arrangement, a modified 14-row drill was used. The seed-hoses were taken off and underneath the holes of the seed box a metal sheet was hung at an angle. In running the seed drill, the seeds fell through the holes of the seed box on to the metal sheet and were scattered, apparently at random.

Cultivation and sowing were done on June 7th, 1973. A basal dressing of lindane superphosphate was applied during cultivation at the rate of 112.5 kg per ha. To prevent uneven performance due to uneven cultivation, the wheel marks of the cultivating tractor were hand cultivated and the harrowing was done by pulling the harrow by four people. The drill was set for sowing high density, and for medium density an equal quantity of dead seeds was mixed with viable seed. The drill was pulled by cable from a stationery winch outside

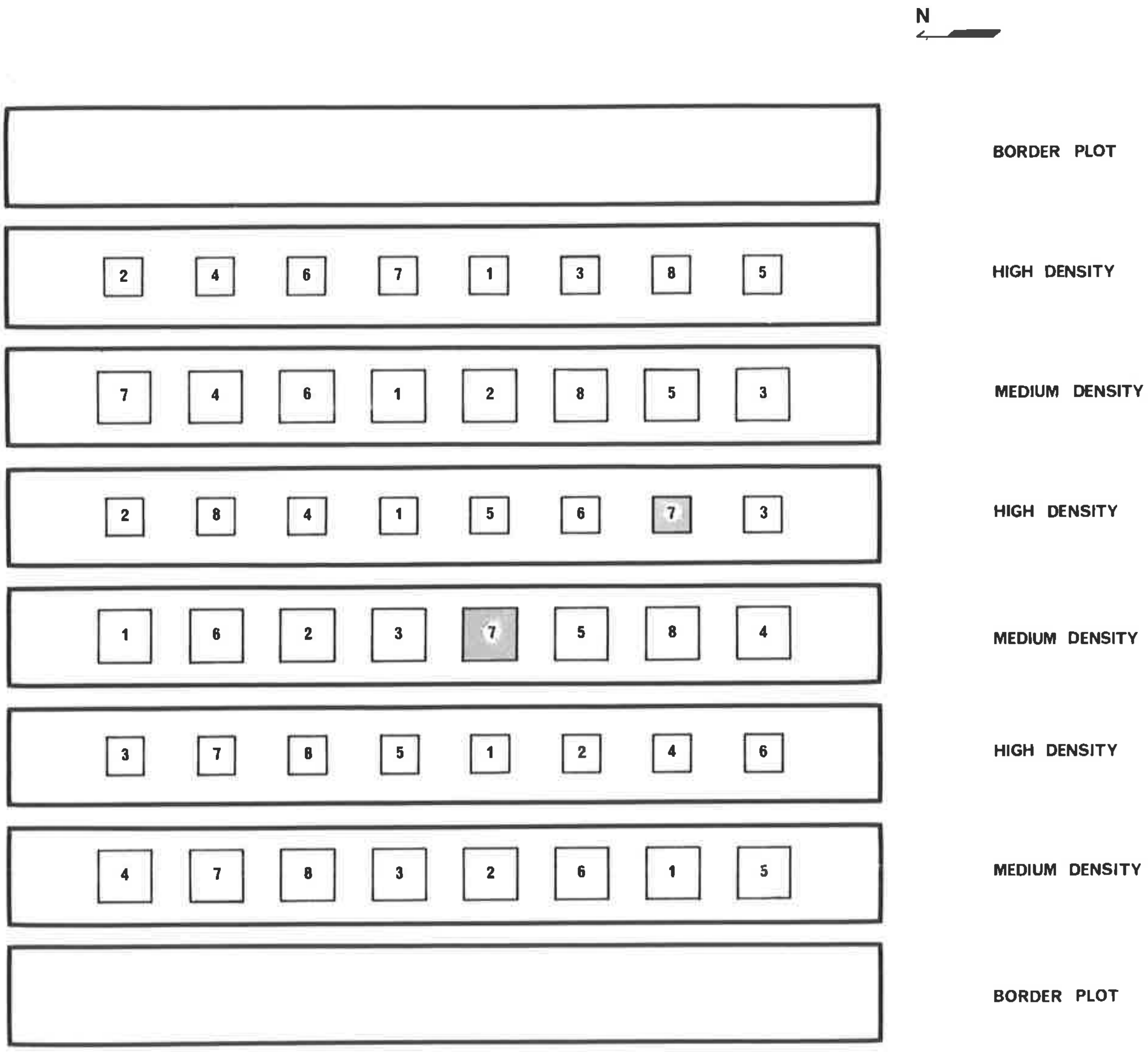

FIG.15: LAYOUT OF EXPERIMENT 2.

PERMANENT QUADRATS

QUADRATS FOR SEQUENTIAL HARVEST

Plate 5: General view of experiment 2 at week 4. In the bottom left hand corner is the border plot followed by high density and low density plots, each replicated three times.

the experimental site. To cover the seed, harrows were pulled behind the drill.

After sowing, the experimental plots were covered by polyethylene sheet to keep rain off, thus maintaining a good soil structure and ensuring a better establishment. The sheets were removed eight days after sowing.

To protect the plants from powdery mildew (*Erysiphe graminis* f.sp. *tritici*) applications of milstem 100 ppm were given at day 62, day 95 and day 138. The sprayings were done thoroughly to ensure a complete coverage. At the end of the growing season, due to an exceptionally wet period, there was an outbreak of stem- and leaf-rust which is uncommon in South Australia. An attempt was made to control the disease by spraying with dithane M 45 at the rate of 2.27 kg per ha on day 96, but no satisfactory results were obtained. This disease might have influenced the weight of grain per plant.

The harmful effect of lodging on wheat is well known. Lodging first occurred on 6th August, 60 days after sowing. It was only a patchy type of lodging in high density plots, and the plants recovered quickly after drops of water were knocked off their leaves. Three days later a more severe lodging occurred and it was then considered necessary to install a net to keep the plants standing. Nylon fish-net 2.5 metres wide and 30 metres long with 10 cm squares was used. It was tied to wires which were strung on steel droppers erected around each plot. The first net was 30 cm above the ground and the second net was installed later at about 80 cm above the ground. These two nets kept most plants straight until the end of the experiment, except for a few places near the end of the high density plot.

2.4 Data collection

2.4.1 The quadrats

Within each plot there were eight quadrats and the numbering of the quadrats in each plot (from 1 to 8) was made in random order. There were thus three quadrats of each number in each treatment, one in each of the three plots. At each harvest it was possible to collect individual plant data only from one quadrat in each treatment. The procedure was as follows. The three quadrats carrying the same randomly chosen number in the three replicate plots were rated for yield. The quadrat of intermediate yield among the three was then taken for harvest. This method is a combined use of randomness and rating. The quadrats were 1 m x 1 m in high density plots and 1.4 m x 1.4 m in low density plots. It was intended that each had approximately 300 plants, which was considered sufficient for the study of individual plant performance within its community, and could supply hundreds of 'test plants' in the middle of the quadrat for studies of the effect of neighbours.

There were two types of quadrats,

(a) permanent quadrats for measurements on the same plants on days 43 and 82.

Each treatment had one permanent quadrat, which was randomly chosen among the eight quadrats of the three replicate plots, as above. In the permanent quadrats each plant was labelled. The weight of each plant was estimated on days 43 and 82. Both the matched tiller method and the plant cylinder method developed in experiment 1 were used. The matched tiller method was used in the first estimate at day 43. The numbers of tillers per plant and the length of longest tiller were also recorded.

The second measurements were done at day 82 for number of tillers, length of the longest tiller and plant weight estimation using the plant cylinder method. This measurement could only be done at the medium density. At high density even identifying each plant was becoming impossible without causing damage to the plant.

(b) Quadrats for sequential harvests.

There were eight sequential harvests, including one (harvest 7) from the permanent quadrat. In each harvest, from each treatment, one quadrat out of the three quadrats which had the same number, was taken based on rating as above.

The harvests were taken at the following stages:

Harvest 1: early vegetative stage, day 30 (5.7.73).

Harvest 2: early tillering stage, day 50 (25.7.73).

Harvest 3: advanced tillering stage, day 70 (14.8.73).

Harvest 4: late tillering stage, day 95 (10.9.73).

Harvest 5: jointing stage, day 110 (26.9.73).

Harvest 6: anthesis, day 130 (15.10.73).

Harvest 7: dough stage, day 140 (24.10.73).

Harvest 8: mature, day 180 (4.12.73).

The harvesting was done by pulling out each plant within the quadrat, shaking off the soil and then placing it individually in a labelled paper bag. Data collected from each plant at each harvest are indicated in Table 6. Every tenth plant was taken as a sub-sample to determine leaf area and for green stem measurement. Leaf area was measured using an electronic planimeter. Stem area was determined by measuring the diameter and length of the green part.

Table 6: Experiment 2. Data collected from each plant (or from sub-sample plants) at each harvest.

Data	Harvest 1	2	3	4	5	6	7*	8
1. Length of longest tiller	x	x	x	x	x	x	x	x
2. Number of tillers	x	x	x	x	x	x	x	x
3. Leaf area**		x	x	x	x	x	x	
4. Green stem area**		x	x	x	x	x	x	
5. Green ear area**						x		
6. Number of ears						x	x	x
7. Number of spikelets per ear							x	x
8. Number of grains per ear								x
9. Ear weight							x	x
10. Grain weight per ear								x
11. Total dry weight	x	x	x	x	x	x	x	x
12. Plant co-ordinates.	x	x	x	x	x	x	x	x

* Permanent quadrat harvested prematurely due to lodging.

** Measured from a subsample, comprising 10% of the plants harvested.

At harvest 6 there were two additional measurements, i.e. number of ears per plant and ear area. Ear area was added to leaf area and green stem area as parts of plant active in photosynthesis. The ear area was estimated by measuring its length and width.

2.4.2 Distances between plants

As in experiment 1, the exact position of each plant within the quadrats was determined by measuring the plant co-ordinates from base lines (X - Y axes). To avoid disturbance of plant's micro-environment, the measurements were done after harvest on labelled sticks which replaced the harvested plants (Plate 6).

2.4.3 Light reading

As in experiment 1, this measurement was mainly to determine the variability of light penetration. Due to the large number of plants within each quadrat, light penetration measurement on all individual plants was impracticable. Light measurements were made on three occasions, i.e. before harvest 4, before harvest 5 and before harvest 6. The quadrats were divided into ten strips across the plot (Figure 16). In each strip the light intensity was measured at several levels. On the first occasion (day 92), measurements were made at three levels, i.e. at ground level, at half the height of the crop and above the crop. On the second occasion (day 110), at four levels, i.e. at ground level, at 40 cm and 60 cm height and above the crop. On the third occasion (day 130), at six levels, i.e. at ground level, at 40 cm, 60 cm, 80 cm, 100 cm height and above the crop. The instrument used was a light probe with 5 photo cells mounted on its ca 40 cm long probe.

Plate 6: Close-up view of one quadrat for sequential harvest at high density plot before (above) and after (below) harvest 1 at day 30. Sticks were used to mark plant position for co-ordinate measurements.

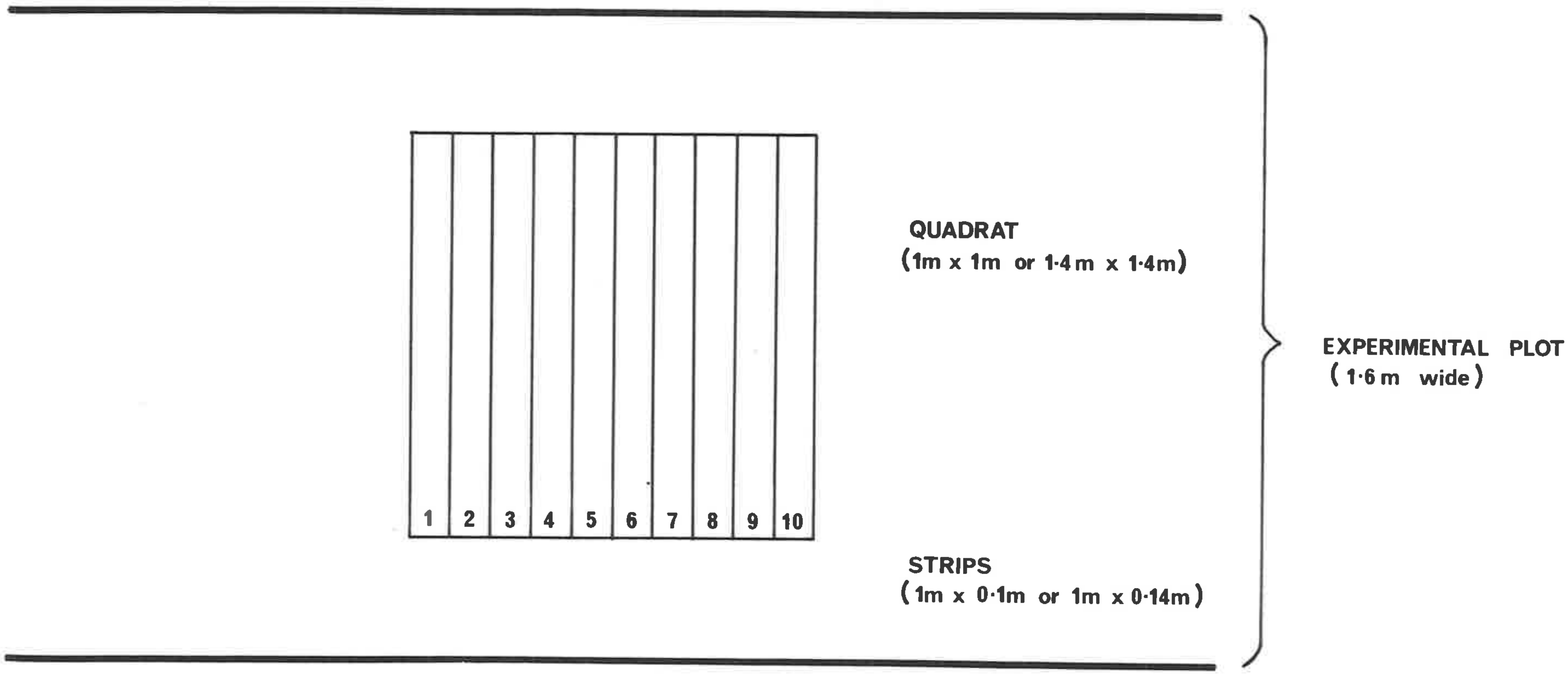

FIG.16 : TEN STRIPS WITHIN THE QUADRATS FOR LIGHT PENETRATION MEASUREMENT

RESULTS

1. The 1972 and 1973 seasons

The total monthly rainfall and evaporation, hours of bright sunshine (mean daily values for each month) and maximum wind velocity (km per day) in each month of 1972 and 1973 are shown in Figure 17. A detailed listing of meteorological data for the Waite Institute during 1972 and 1973 is given in Table 1 and Table 2 of the appendix. Average figures for 48 years (from 1925 to 1973) are given in Table 3 of the appendix.

Rainfall in 1972 was in marked contrast to 1973. The yearly total of 1972 (506.9 mm) was below average (626.2 mm), while in 1973 (836.7 mm) it was well above average. The growing season, i.e. when the rainfall exceeds one third of the evaporation (Trumble, 1937), normally begins in April and finishes in early November. In 1972 rainfall in March, May and June was exceptionally low, in April slightly below the average and in July almost 50% above the average. This pattern of rainfall delayed considerably the sowing date of Experiment 1. The 1973 season started normally but had a prolonged wet period until October, which caused an epidemic of leaf- and stem-rust, an unusual occurrence in South Australia.

2. Lodging

The wind velocity during the 1972 and 1973 growing seasons is given in Tables 4 and 5 of the appendix, where the number of days per month with light winds (maximum wind velocity less than 24 km per hour), moderate winds (maximum 24-31 km per hour), strong winds (maximum 31-40 km per hour), and very strong winds (maximum more than 40 km per hour) are given. Wind strength can affect crop yield by causing lodging, with adverse affect on crop yields (Laude and Pauli, 1956). What has

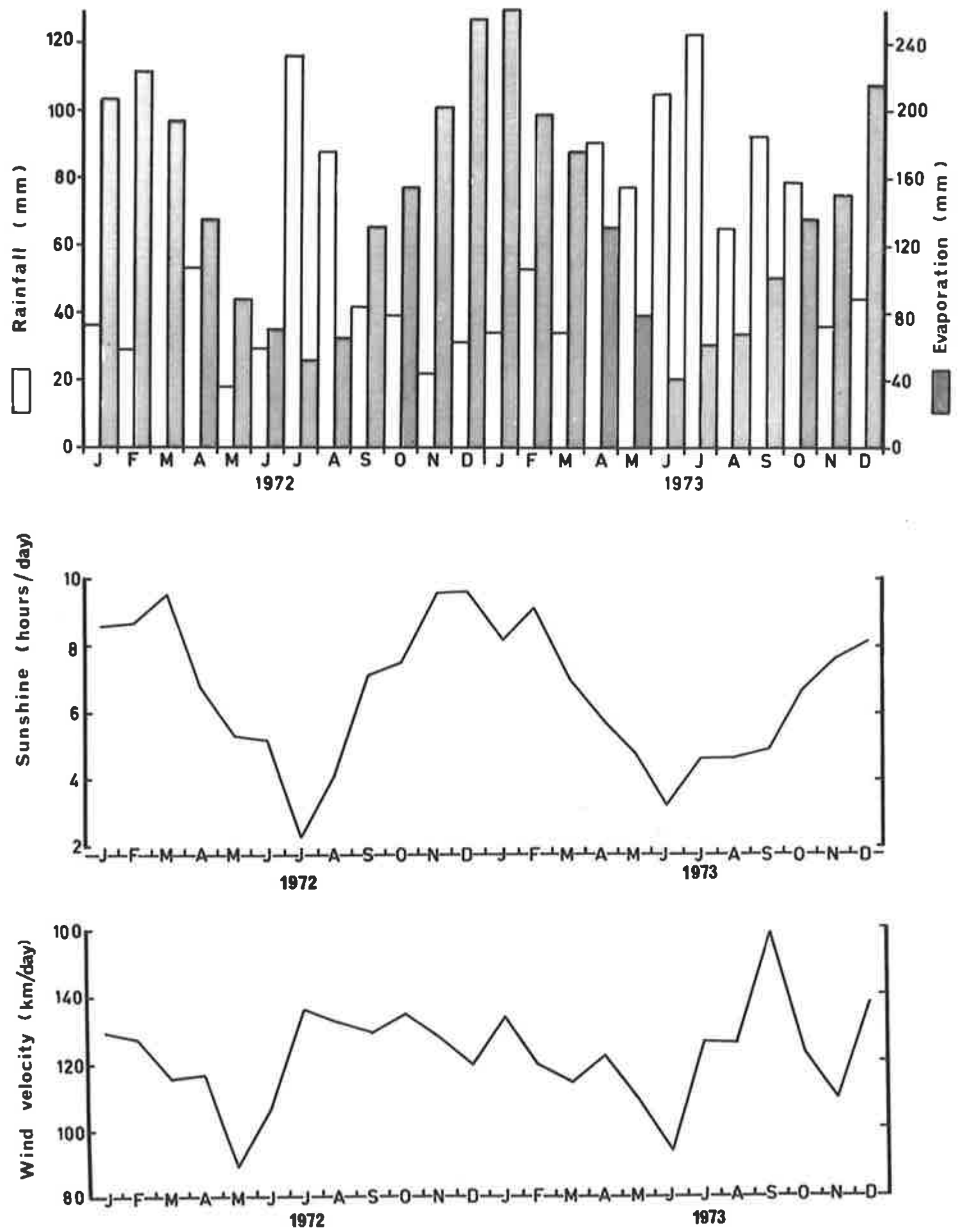

FIG. 17: RAINFALL (mm), EVAPORATION (mm), HOURS OF BRIGHT SUNSHINE PER DAY AND WIND VELOCITY (km/day) AT THE WAITE INSTITUTE, 1972 AND 1973.

not been described is the particular environmental situation which has caused crop lodging in cereals. Two main factors are wind and rainfall. In Figure 18 and Figure 19 the daily maximum wind velocity and total rainfall are presented during a period of 14 days, a week before and a week after lodging for 1972 and 1973 respectively.

In Experiment 1 (1972) there were two lodgings, the first occurred at day 47 and the second at day 85. In Experiment 2 (1973) there were also two period of lodging on days 60 and 135 and a period of bending and 'creasing' of the sheath of the flag leaves against the supporting net at day 109.

It will be noted that similar environmental conditions always occurred before lodging in both 1972 and 1973, i.e. a period with a very strong wind with a maximum velocity of more than 40 km per hour accompanied by heavy rainfall with a daily total of more than 30 mm. It seems that the continuous strong wind bent the plants almost horizontally which made it possible for water drops to stay on plant's leaves. This tremendous load of water drops laid the plants almost flat on the ground. It is apparent that in these crops, only a combination of wind and rain led to lodging; no lodging occurred with only one of these factors.

3. Plant weight estimation

3.1 The 'matched tiller' method

In Experiment 1 a quadrat of 29 plants outside the permanent quadrats was randomly chosen from the drilled medium density plot, and was used to test this method. The testing was done at day 61 by three observers, each using the same set of standard tillers for the same test plants. At this stage the number of tillers per plant

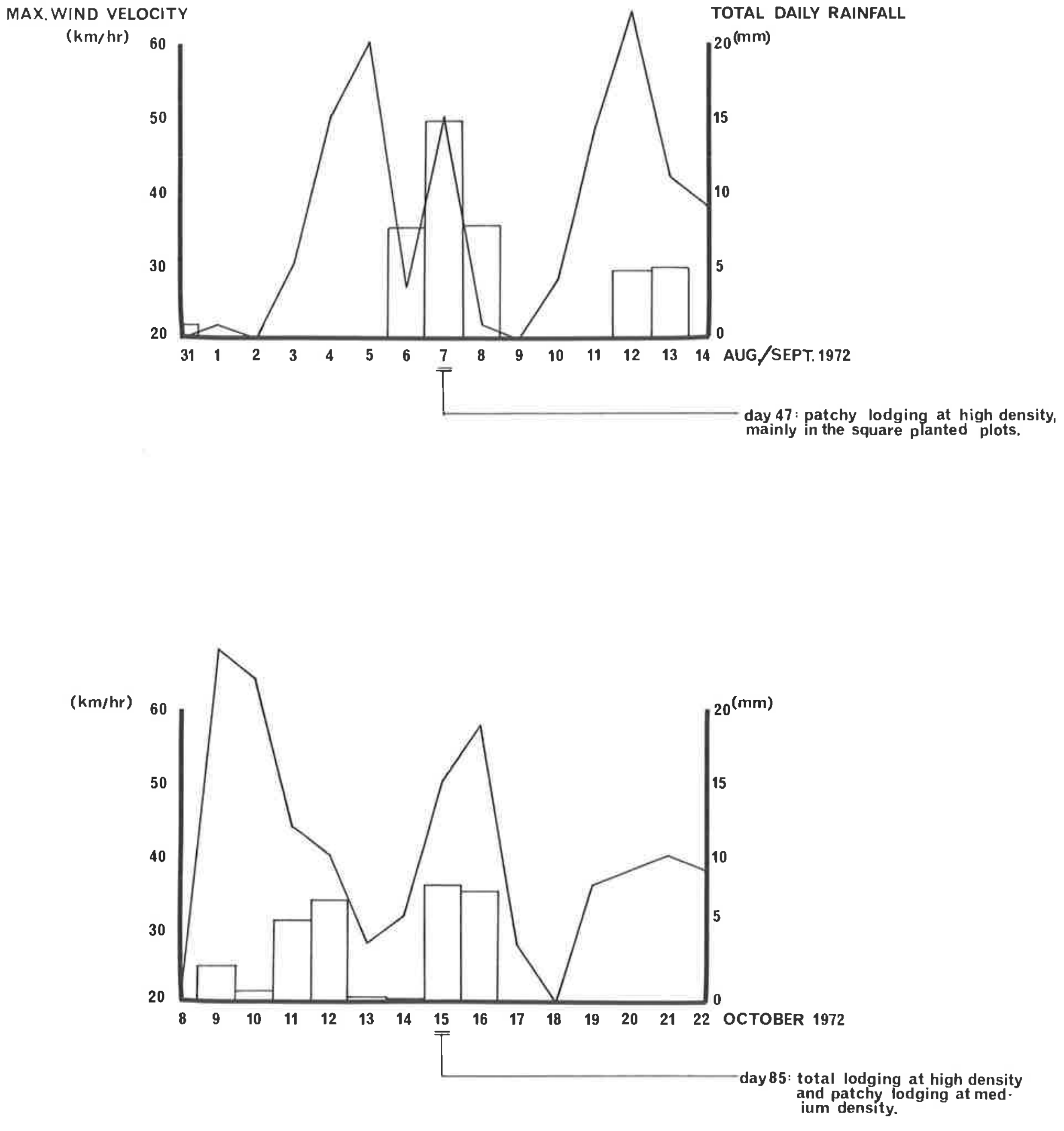

FIG.18: DAILY MAXIMUM WIND VELOCITY AND RAINFALL DURING THE WEEK BEFORE AND THE WEEK AFTER CROP LODGING AT DAY 47 AND DAY 85 IN EXPERIMENT 1.

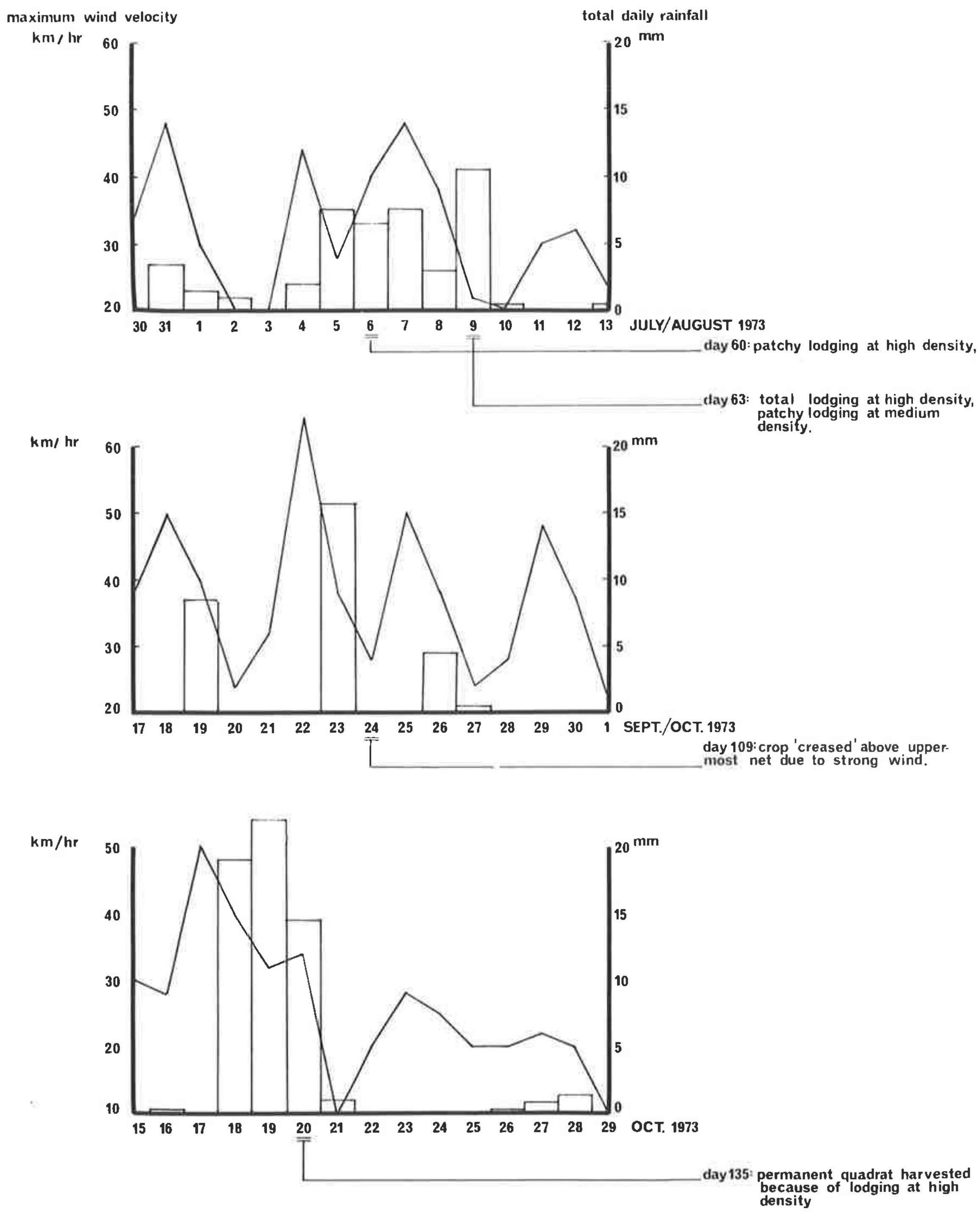

FIG. 19 : DAILY MAXIMUM WIND VELOCITY AND RAINFALL (HISTOGRAM) DURING THE WEEK BEFORE AND THE WEEK AFTER LODGING OR "CREASING". EXPERIMENT 2.

varied between 3 and 7. The grade and weight of each of the standard tillers is shown in Table 5 of the Appendix (it was considered necessary that each treatment has its own standards due to varying habits of growth, especially with density), and the results of measurements (aggregate tiller estimates for each plant) by each observer is given in Table 6 of the Appendix. Moderate correlations between estimated weight and actual weight were obtained by each of the three observers (Table 7a), and the regression equations presented in Table 7b are highly significant (Table 8). Nevertheless, as seen in Table 6 of the Appendix, the estimated value of particular plants by individual observer was for:

Observer A : consistently low even though the correlation was good.

Observer B : the absolute values and correlation were both good.

Observer C : the absolute values and correlation were both rather poor.

Absolute values tended to vary between observer, but moderate accuracy could be obtained for correlation. For an advanced tillering stage, with 3 to 7 tillers per plant, it became too time consuming and for this reason the measurements were discontinued. This method would probably be suitable for an earlier tillering stage where each plant has only 2 to 4 tillers.

3.2 The 'plant cylinder' method.

The same quadrat which was used for testing the 'matched tiller' method was also used for testing this method and the tests were also done by the same three observers. After the 'cylinder' measurements were completed, the 29 plants from the quadrat were harvested and their actual weights recorded. Results of the measurements for each observer, in the form of the product of the length and circumference of cylinder multiplied by a constant, are given in Table 7 of the Appendix. Strong correlations were obtained between estimated and actual weight (Table 7b), and the regression equations are also highly significant (Table 9).

3.3 Discussion

The 'matched tiller' method is based on matched leaf techniques for leaf area estimation as proposed by Darrow (1932) for strawberry, Thirumalachary (1940) for cotton, Bald (1943) for potato, and Williams (1954) for tomato. It has the advantage of permitting quick estimation of plant weight, much quicker than matching individual leaves, which like the linear measurements of individual leaf for leaf area estimation, involves estimation of the individual leaves on each tiller of each plant. Another advantage of this method is that the standard for matching tillers, which consisted of Xerox copies of selected standard tillers, could be prepared in less than a day, so that the standards for each treatment could be prepared the day before the scheduled observations. However it is impossible to use this method at the advanced tillering stage, because of crowding by other tillers and the size of each tiller. It takes longer to 'isolate' each tiller and it becomes harder to place the standard next to the tiller to be measured without causing broken leaves. This difficulty in putting the standard next to the observed tiller might cause the varying results obtained by the three observers. The method can be recommended for early tillering stage where individual leaf measurements are already too tedious and it is still too early to use plant cylinder method.

The plant cylinder method of weight estimation seems very well suited for small tillering plants such as barley and wheat, and is especially useful when most of the plants are already in their advanced tillering stage. Before using this method an observer should familiarize himself with the measurement of the length and circumference of plant cylinder, and make simple calibrations by measuring a set of plants outside the observed area and harvesting them to calculate the correlation.

The method recommended for non-destructive plant weight estimation for each stage of vegetative growth of cereals such as wheat and barley in the field would be:

before tillering	:	linear measurement (stem diameter and plant height; not tested in this study)
early tillering	:	the 'matched tiller' method
advanced tillering	:	the 'plant cylinder' method.

Table 7 : Results in testing methods of plant weight estimation

(a) The 'matched tiller' method

Observer	Correlation (estimated weight - actual weight)	Regression equation	Estimated plant weight		Mean actual plant weight
			Mean	S.D.	
A	0.74	y = 4.45 + 0.68x	8.283	4.03	10.126*
B	0.88	y = 0.98 + 0.92x	9.904	3.56	10.126
C	0.84	y = 3.42 + 1.04x	6.466	3.02	10.126

* Only one value since all the observers using the same plants (S.D. = 3.73).

(b) The 'plant cylinder' method

Observer	Correlation (estimated weight - actual weight)	Regression equation	Estimated plant weight		Mean actual plant weight
			Mean	S.D.	
A	0.90	y = -3.14 + 0.12x	108.2*	27.4	10.126
B	0.91	y = -2.75 + 0.10x	128.7	33.7	10.126
C	0.92	y = -2.46 + 0.10x	135.5	36.8	10.126

* The product of length and circumference of 'plant cylinder'.

Table 8 : Analysis of variance of testing 'matched tiller' method for weight estimation

A : (First observer)

Source	D.F.	S.S.	M.S.	F ratio
Regression	1	212.768	212.768	32.664**
Residual	27	175.873	6.514	

B : (Second observer)

Source	D.F.	S.S.	M.S.	F ratio
Regression	1	303.228	303.228	95.854**
Residual	27	85.413	3.163	

C : (Third observer)

Source	D.F.	S.S.	M.S.	F ratio
Regression	1	275.494	275.494	65.741**
Residual	27	113.146	4.191	

Table 9 : Analysis of variance of testing 'plant cylinder' method for weight estimation

A : (First observer)

Source	D.F	S.S.	M.S.	F ratio
Regression	1	316.281	316.281	118.015**
Residual	27	72.360	2.680	

B : (Second observer)

Source	D.F.	S.S.	M.S.	F ratio
Regression	1	318.451	318.451	122.499**
Residual	27	70.190	2.600	

C ::(Third observer)

Source	D.F.	S.S.	M.S.	F ratio
Regression	1	326.896	326.896	142.945**
Residual	27	61.745	2.287	

4. Effect of date of seedling emergence on plant performance

In Experiment 1 the dates of seedling emergence of each plant within the permanent quadrats were recorded. The seedling was considered as emerged when its coleoptile protruded above the ground. The first seedlings emerged on day 5, and the last emergence was observed on day 12. Modal day of emergence and the mean duration of emergence in each treatment are shown in Table 10. The H values in the Kruskal-Wallis one-way analysis of variance are:

for modal day $H = 23.57$, and for $df = 5$, $p < 0.001$

for mean duration $H = 24.01$, and for $df = 5$, $p < 0.001$

so that the hypothesis that all values belong to the same population is firmly rejected. The critical range method for testing all possible pairs is used to examine differences between the means of each treatment and the significant differences are indicated in Table 11. The effect of density on both the duration of seedling emergence and modal day, i.e. the day where most of the seedlings emerged, was not significant. Method of planting, i.e. drilled *vs* square planted, had a stronger influence. Seedlings in the drilled plot emerged later than in the square planted plots, i.e. with a modal day at 9-12 days *vs* 5-8 days after sowing, and it also had longer mean duration of emergence.

The probable reason for the difference in the time of peak emergence is that in the drilled plots the cultivation tended to cover most of the seeds with a thicker layer of soil. In other words, the difference is due to the difference in depth of sowing and in the time needed to penetrate the soil layer above the seeds. In the drilled plots, the variation of soil layer thickness above each seed was probably also greater than in the square planted plots, with a consequence of a longer period of emergence.

Table 10 : Mean duration and modal day of seedling emergence and their ranked values

		Emergence				Rank	
Treatment	Replicate	Interval (days from sowing)	Mode (days from sowing)	Mean duration (days)	C.V. %	Mode	Mean duration
1	1	8-12	9	5.2	16	21.5	22
	2	8-11	9	5.3	14	21.5	23
	3	8-11	9	5.0	14	21.5	20
	4	7-11	9	4.9	27	21.5	18
	5	7-11	9	4.7	26	21.5	17
2	1	7-12	9	4.9	30	21.5	19
	2	7-12	9	5.1	23	21.5	21
	3	8-12	9	6.1	19	21.5	29
	4	9-12	10	6.0	14	29	28
	5	6-12	12	6.5	23	30	30
3	1	8-11	9	4.6	17	21.5	16
	2	9-11	9	5.4	14	21.5	26
	3	9-12	9	5.4	17	21.5	24.5
	4	7-11	9	5.4	20	21.5	24.5
	5	8-11	9	5.7	17	21.5	27
4	1	5- 8	6	2.1	47	4	1
	2	5-12	8	3.6	40	14	14
	3	5- 9	6	2.5	42	4	5
	4	6- 8	7	3.1	25	10	10.5
	5	6- 9	9	4.0	24	21.5	15
5	1	5-10	7	3.1	46	10	10.5
	2	5-10	6	2.6	76	4	6
	3	5- 9	6	2.1	47	4	2
	4	5- 9	5	2.2	73	1	3.5
	5	5- 8	6	2.2	43	4	3.5
6	1	5- 9	7	3.2	39	10	13
	2	6- 9	7	2.9	23	10	8
	3	6- 8	7	2.8	27	10	7
	4	6- 8	7	3.2	23	10	12
	5	6-10	7	3.1	34	10	9

Treatments 1,2,3 are drilled, and 4,5,6 are square planted, each at high, medium and low density respectively.

Table 11 : Critical range method for testing all possible pairs of treatment

A: Differences in mean duration of emergence.

Treatment	Rank sum	5	4	6	1	3	2
		25.5	45.5	49	100	118	127
5	25.5						
4	45.5	20					
6	49	23.5	3.5				
1	100	74.5	54.5	51			
3	118	92.5*	72.5	69	18		
2	127	101.5**	81.5*	78	27	9	

B: Modal day of emergence

Treatment	Rank sum	5	6	4	1	3	2
		23	50	53.5	107.5	107.5	123.5
5	23						
6	50	27					
4	53.5	30.5	3.5				
1	107.5	84.5*	57.5	54			
3	107.5	84.5*	57.5	54			
2	123.5	100.5**	73.5	70	16	16	

Treatments 1, 2 and 3 are drilled at high, medium and low density respectively, while 4, 5 and 6 are square planted also at high, medium and low density respectively.

Correlations between the date of seedling emergence and estimated individual plant weight at day 70 and actual individual plant weight at day 90 are given in Table 12. At both day 70 and day 90 the correlations varied from significantly positive to significantly negative, and the proportions of each type of correlation are as follows:

At day 70:

negative : 83.3%, significantly negative : 30%

positive : 16.7%, significantly positive : 3.4%

At day 90:

negative : 70%, significantly negative : 16.7%

positive : 30%, significantly positive : 6.7%

In testing whether the replicate correlations were from the same population or not, it was found that they were not from the same population, except in the drilled-high-density and square-planted-low-density treatments at day 70 and the square-planted-high-density treatment at day 90. The pooled value of r was -0.26**, -0.29** and -0.125 respectively for these three treatments (Table 8 of the Appendix).

The frequency of negative correlations and significantly negative correlations in each treatment at day 70 and day 90 are indicated in Table 13 A and B. The significantly negative correlations tended to decrease with time in both drilled and square planted plots. The effect of density was inconsistent.

Conclusions that can be taken on the effect of date of seedling emergence on individual plants in the 60 units of crop communities examined are:

Table 12 : Correlation among individual plants between the number of days from sowing to seedling emergence and plant weight at day 70 and plant weight at day 90 respectively (Experiment 1).

	Date of emergence - weight at day 70					Date of emergence - weight at day 90				
	Replicate					Replicate				
	1	2	3	4	5	1	2	3	4	5
Drilled										
High density	-0.35	-0.30	-0.10	-0.46*	-0.13	-0.04	-0.20	-0.27	0.47*	-0.44
Medium density	-0.19	-0.46**	-0.45**	0.10	-0.29	-0.50**	-0.38*	-0.37*	0.23	-0.27
Low density	-0.004	-0.11	-0.24	-0.47*	-0.47	0.66**	-0.18	0.28	0.05	-0.27
Square planted										
High density	0.09	-0.53**	+0.43*	0.10	-0.30	-0.03	-0.21	-0.20	0.12	-0.23
Medium density	-0.52**	-0.005	-0.38*	-0.50**	-0.29	-0.47*	0.48	-0.25	-0.33	-0.23
Low density	-0.27	-0.38	-0.15	-0.35	0.01	0.25	-0.11	-0.19	-0.70*	0.14

* significant (at 5% level); ** highly significant (at 1% level).

Table 13 : The frequency of negative correlation (A) and significantly negative correlation (B) between seedling emergence and plant weight at days 70 and 90 (Experiment 1).

A: The negative correlations

Treatment	Day 70	Day 90	Treatment	Day 70	Day 90		Day 70	Day 90
Drilled - High density	5	4	Square planted - High density	2	4	Total - High density	7	8
Medium density	4	4	Medium density	5	4	Medium density	9	8
Low density	5	2	Low density	4	3	Low density	9	5
Total	14	10	Total	11	11	Grand Total	25	21

B: The significantly negative correlations

Treatment	Day 70	Day 90	Treatment	Day 70	Day 90		Day 70	Day 90
Drilled - High density	1	-	Square planted - High density	1	-	Total - High density	2	-
Medium density	2	3	Medium density	2	1	Medium density	5	4
Low density	2	-	Low density	-	1	Low density	2	1
Total	5	3	Total	4	2	Grand Total	9	5

(a) There were appreciable numbers of significantly negative correlations (30% at day 70 and 16.7% at day 90), which indicated that even under the field conditions the earlier a seedling emerges the greater its relative size in the community.

(b) Among the non-significant correlations, most of them, i.e. 80% at day 70 and 70% at day 90, were negative correlations, so that the overall tendency was for the earlier emerged plants to remain larger.

(c) Closer examination of the groups which had significant negative correlations revealed that weight regression decreased with increasing density (column 3 in Table 14 and Figure 20). At day 70 the regression was -550 mg per day at low density, -261 mg at medium density and -155 mg at high density. The maximum possible contribution to the mean weight of individual plants at day 70 due to day of seedling emergence for low, medium and high density was 38%, 52% and 62% respectively. (Regression of weight at day 70 on date of emergence x range in day of emergence x 100 ÷ the difference between maximum and minimum weight at day 70.)

(d) There was a significant positive correlation between date of emergence and plant weight (3.4% of instances at day 70 and 6.7% at day 90), presumably because particular local environmental conditions (including the proximity of neighbours) caused the earlier seedlings to become the smaller plants.

Table 14 : Contribution to the weight of individual plants due to day of emergence, in the replicates which had significant negative correlation between estimated plant weight at day 70 and the day of seedling emergence

	Range in weight at day 70	Regression of weight at day 70 on date of emergence (mg)	Range in day of emergence	Maximum contribution due to day of emergence (g)	As % of range in plant weights
High density:					
drilled - replicate 4	1.57 - 3.64	112	5 (7-11)	0.56	27
square planted - replicate 2	0.78 - 3.16	199	6 (5-10)	1.19	50
Medium density:					
drilled - replicate 2	0.64 - 3.41	253	6 (7-12)	1.52	55
drilled - replicate 3	0.72 - 2.89	239	5	1.20	55
square planted - replicate 1	1.84 - 4.59	242	6 (8-12)	1.45	53
square planted - replicate 3	1.26 - 4.94	287	4 (5- 9)	1.15	31
square planted - replicate 4	0.82 - 4.19	286	8 (5-12)	2.29	68
Low density:					
drilled - replicate 4	2.73 - 6.05	465	5 (7-11)	2.32	70
drilled - replicate 5	1.77 - 6.46	634	4 (8-11)	2.54	54

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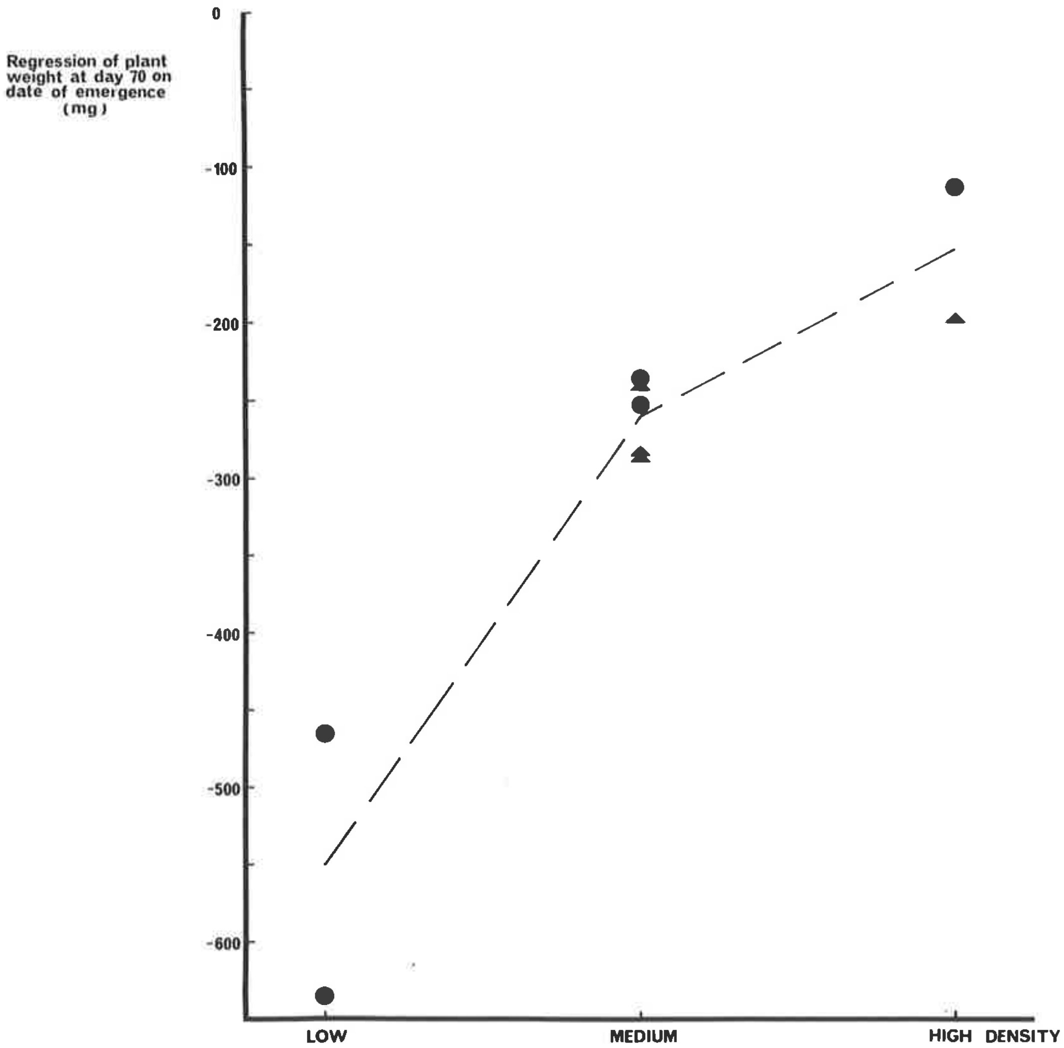


FIG. 20 : REGRESSION OF PLANT WEIGHT AT DAY 70 ON DAY OF SEEDLING EMERGENCE IN THOSE PERMANENT QUADRATS WITH A SIGNIFICANT NEGATIVE CORRELATION BETWEEN INDIVIDUAL PLANT WEIGHT AND DATE OF SEEDLING EMERGENCE (● DRILLED, ▲ SQUARE PLANTED).

5. Plant dominance within a crop community

5.1 Experiment 1

In this experiment, individual plant weight of barley was estimated at day 70, while the actual weight of the same plants was measured at day 90. It was intended to make more than two weight measurements, but since the linear measurements for weight estimation were discontinued because they were too time consuming and a new method had to be developed, the first weight estimations were not obtained until day 70. The direct further measurements on the same plants were made at day 90 when they were harvested.

In Figures 21 and 22 regression lines of plant weight at day 90 on plant weight at day 70 in each crop community (within the permanent quadrat of each treatment) and the mean regression lines for each treatment are illustrated. At each density there is greater variation between crop communities in the drilled plots than in the square planted plots. The mean regression lines for both the drilled and the square planted plots show similar relationships, i.e. that with increasing density the values of the regression of day 90 on day 70 also increase (Figure 23). The mean regression equations are shown in Table 15.

To examine weight increases of smaller and larger plants during the 20-day period from day 70 to day 90, plant weights at day 70 were divided into 10 equal groups and of these, three groups, i.e. the top decile group which consisted of the largest plants, the fifth decile group which consisted of medium sized plants, and the bottom decile group which consisted of the smallest plants, were examined. Their mean values at day 90 are compared with their values at day 70

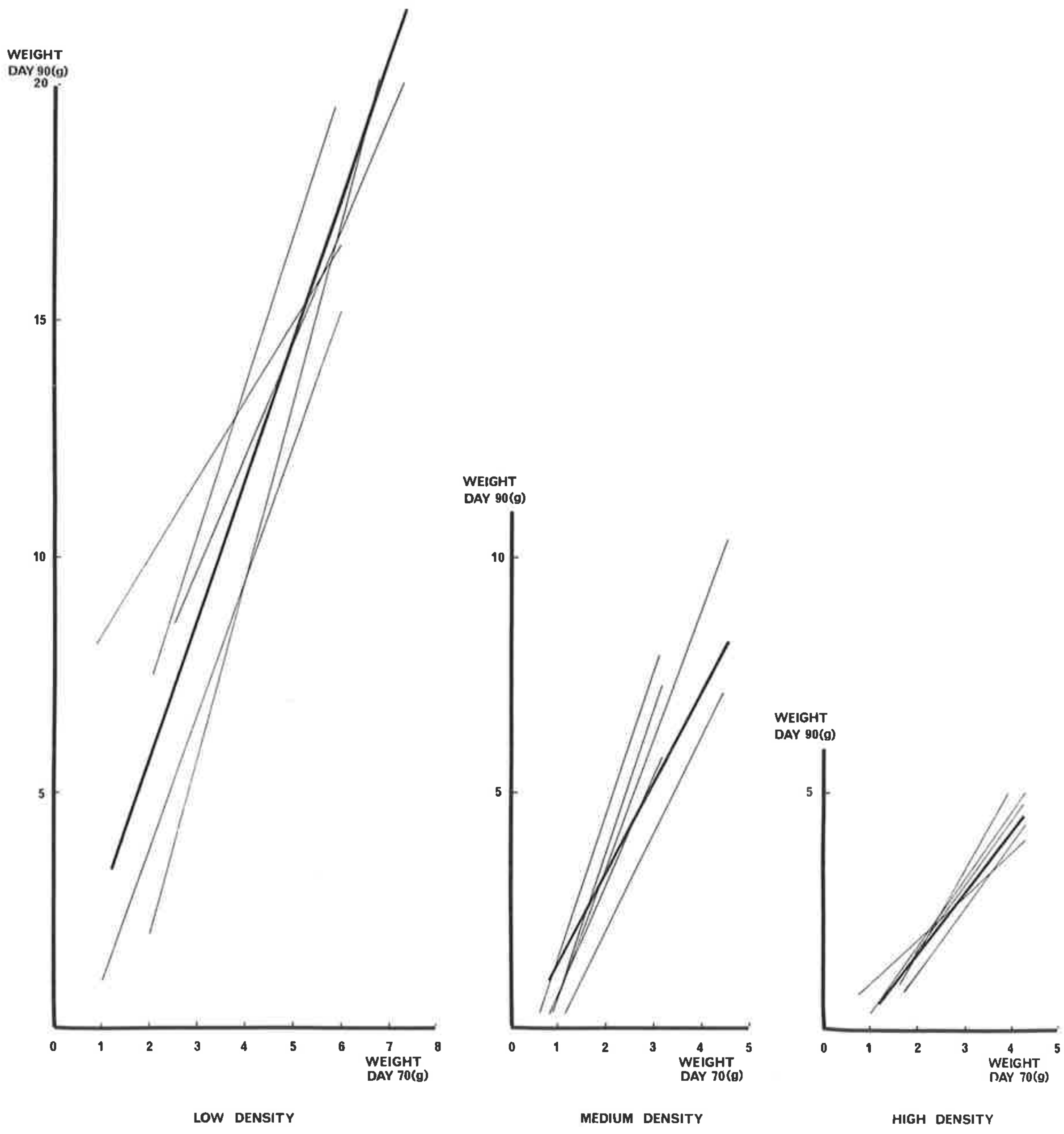


FIG. 21: REGRESSION OF PLANT WEIGHT AT DAY 90 ON PLANT WEIGHT AT DAY 70 IN THE DRILLED PLOTS.

——— regression in each quadrat.

━━━ average regression for each density.

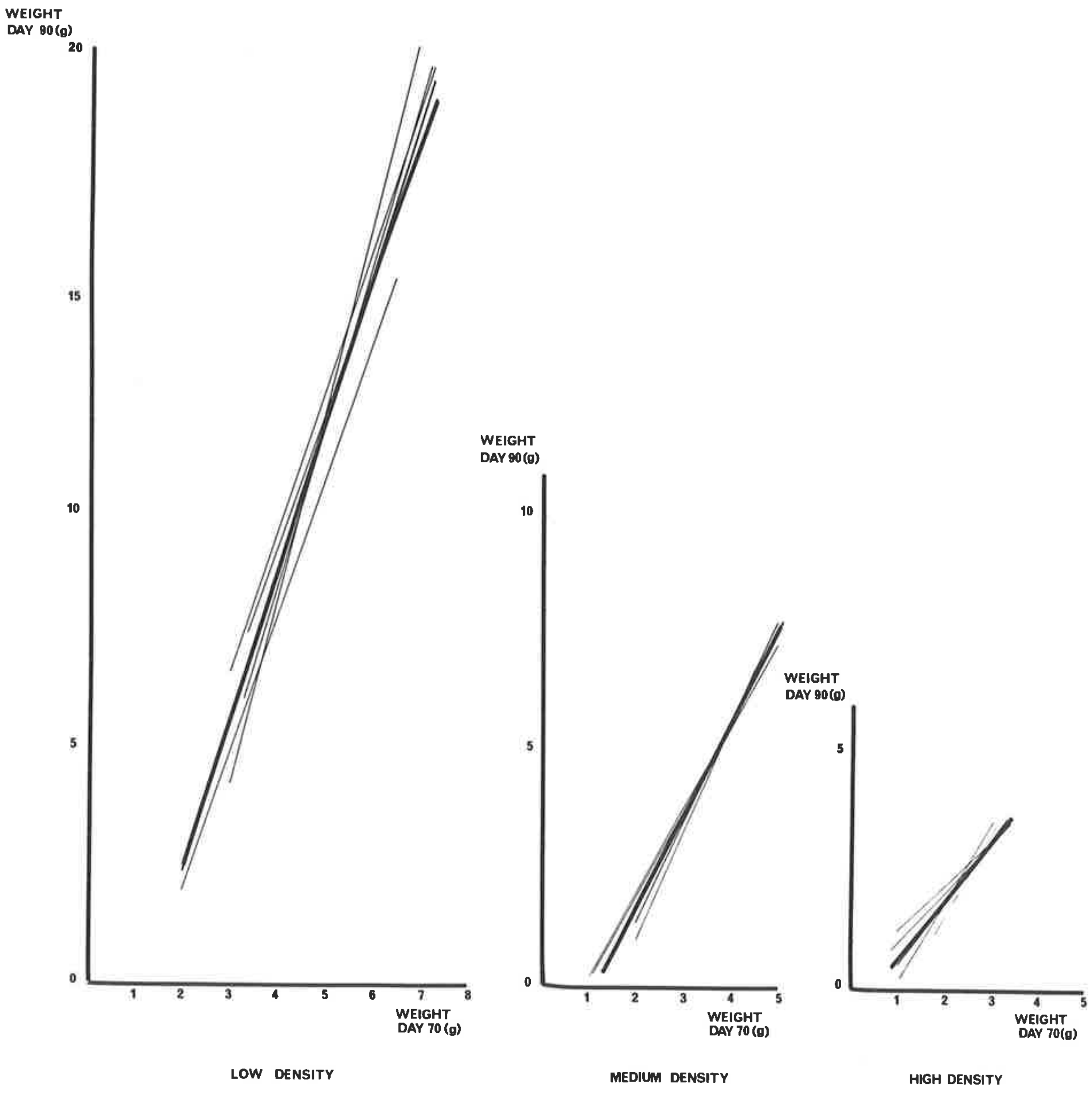


FIG.22: REGRESSION OF PLANT WEIGHT AT DAY 90 ON PLANT WEIGHT AT DAY 70 IN THE SQUARE PLANTED PLOTS.

——— regression in each quadrat.

▬▬▬ average regression for each density.

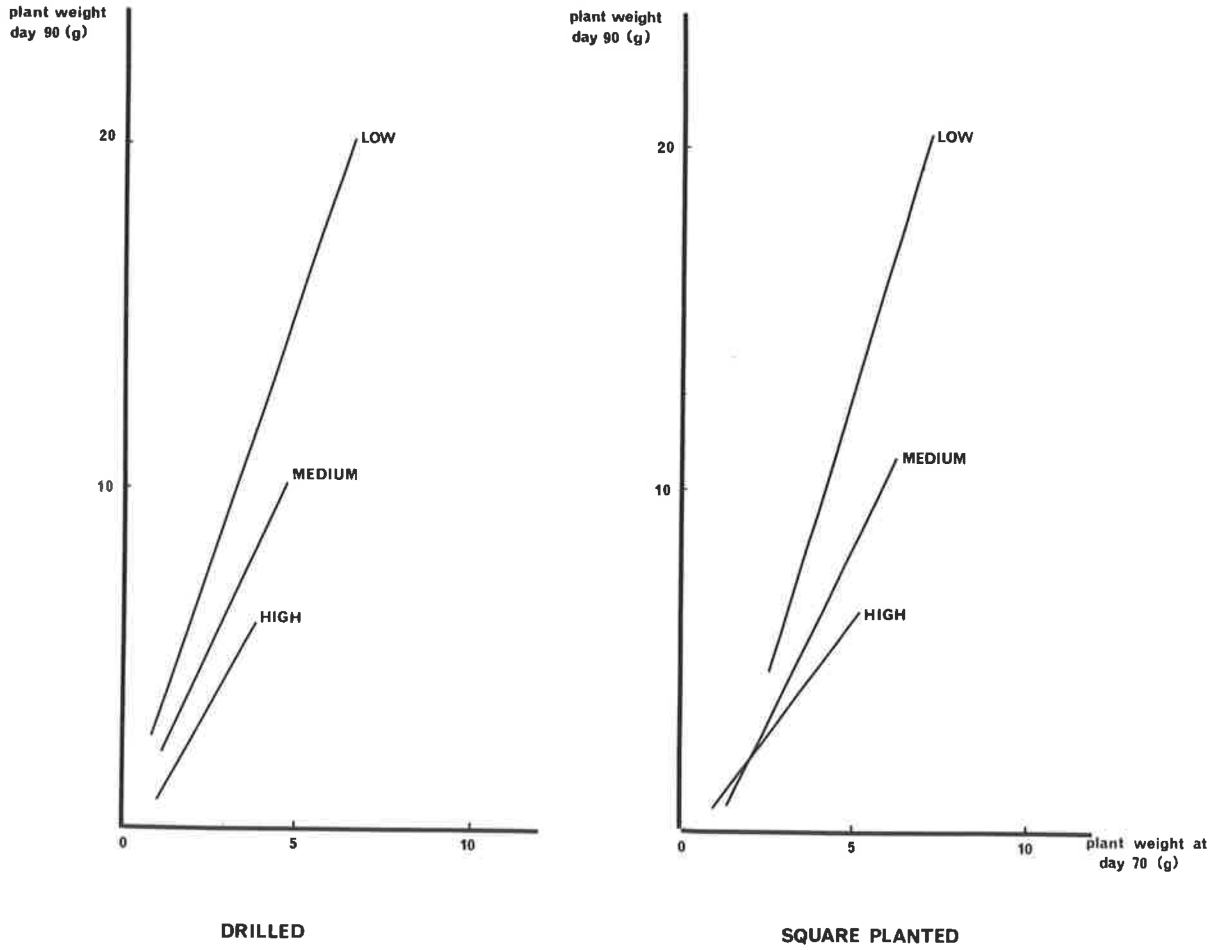


FIG.23: THE AVERAGE REGRESSIONS OF PLANT WEIGHT AT DAY 90 ON PLANT WEIGHT AT DAY 70 FOR EACH OF THE THREE DENSITIES, i.e. HIGH, MEDIUM, AND LOW DENSITY.

Table 15 : Average regression of weight at day 90 on weight at day 70 in each treatment

Treatment	Mean regression equation	Variance ratio (F)	
		Slope	displacement
Drilled:			
High density	y = -0.989 + 1.313x	1.818	3.874**
Medium density	y = -0.516 + 1.921x	2.916*	24.699***
Low density	y = 0.124 + 2.970x	1.382	5.884***
Square planted:			
High density	y = -0.645 + 1.226x	4.144***	1.163
Medium density	y = -2.253 + 1.997x	1.009	2.201
Low density	y = -4.117 + 3.281x	0.766	2.720*

Table 16 : Mean plant weight, weight ratio, proportion of total weight and relative growth rate (R-G-R) of the top, fifth and bottom decile groups *as ranked at day 70*

	Square planted low density	Square planted medium density	Square planted high density	Drilled low density	Drilled medium density	Drilled high density
1. Mean plant weight (g):						
Day 70:						
Top decile group	2.23	1.63	1.20	1.55	0.86	1.59
Fifth decile group	4.96	3.28	2.12	3.88	1.94	2.34
Bottom decile group	6.83	4.30	2.97	6.04	3.72	3.49
Day 90:						
Top decile group	17.93	6.38	3.02	15.01	5.97	4.21
Fifth decile group	11.29	4.03	1.99	11.36	2.93	2.19
Bottom decile group	2.71	1.60	0.97	3.56	1.18	1.59
2. Weight ratio day 90/ day 70						
Top decile group	2.63	1.48	1.01	2.48	1.61	1.20
Fifth decile group	2.27	1.23	0.94	2.93	1.51	0.93
Bottom decile group	1.21	0.98	0.81	2.29	1.36	1.00
3. Proportion of total weight of crop in quadrat (%) day 70:						
Top decile group	14.11	13.33	13.81	15.70	16.95	13.80
Fifth decile group	10.26	10.16	9.84	10.07	8.86	9.76
Bottom decile group	4.61	5.06	5.58	4.04	3.93	6.26
day 90:						
Top decile group	15.88	15.08	15.23	15.21	16.61	17.21
Fifth decile group	10.00	9.54	10.08	11.52	8.16	9.35
Bottom decile group	2.40	3.79	4.90	3.61	3.27	6.79
4. R-G-R from day 70 to day 90						
Top decile group	0.048	0.020	0.001	0.045	0.024	0.009
Fifth decile group	0.041	0.010	-0.003	0.054	0.021	-0.003
Bottom decile group	0.010	-0.001	-0.011	0.041	0.015	0.000

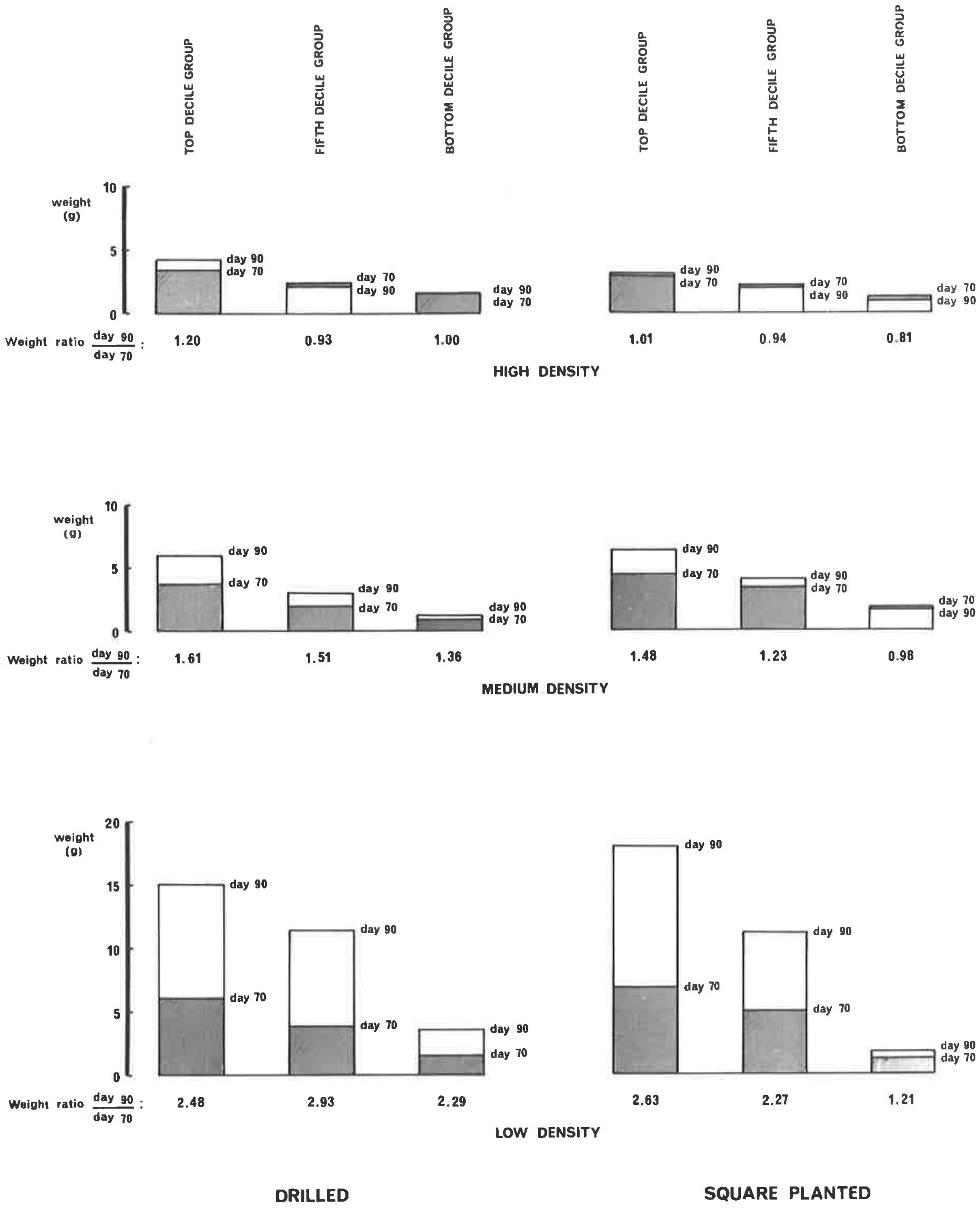


FIG.24: MEAN INDIVIDUAL PLANT WEIGHT INCREASE FROM DAY 70 TO DAY 90 IN THE TOP DECILE GROUP, FIFTH DECILE GROUP, AND BOTTOM DECILE GROUP AS RANKED AT DAY 70.

(Table 16). The mean weight values at days 70 and 90 and the ratio of mean weight at day 90 to mean weight at day 70 are also illustrated in Figure 24. A weight ratio of less than one indicates that due to the effect of neighbours, plant weight after day 70 decreased, as was found in the medium sized plants (fifth decile group) at high density both in the drilled and square planted plots, and also in the smallest plants group at high and medium density of the square planted plot. These groups of plants truly represented the suppressed individuals. To these groups the dominance of their neighbours was already operating strongly at day 70.

The maximum ratio of weight at day 90 to weight at day 70 was 2.93 which was found in the fifth decile group of the drilled low density plot, while the minimum ratio, which was 0.81, was found in the bottom decile group of the square planted high density plot.

The proportions of total weight of crop in the permanent quadrats contributed by the top, fifth, and bottom decile groups are also indicated in Table 16. In the square planted plots the patterns are consistent, i.e. contribution by the smallest groups of plants (bottom decile group) decreased with time, while contribution by the largest plant's groups increased with time. Contribution by the medium sized plants (fifth decile group) remained consistently around 10%. In the drilled plots there is no consistent pattern of change from day 70 to day 90.

The relative growth rates (R-G-R) from day 70 to day 90 among the largest plants, medium sized plants and smallest plants are shown in Figure 25. The greater the difference between the R-G-R of the top and bottom decile group, the stronger is the expression of plant dominance in the crop community. It is clearly illustrated that in

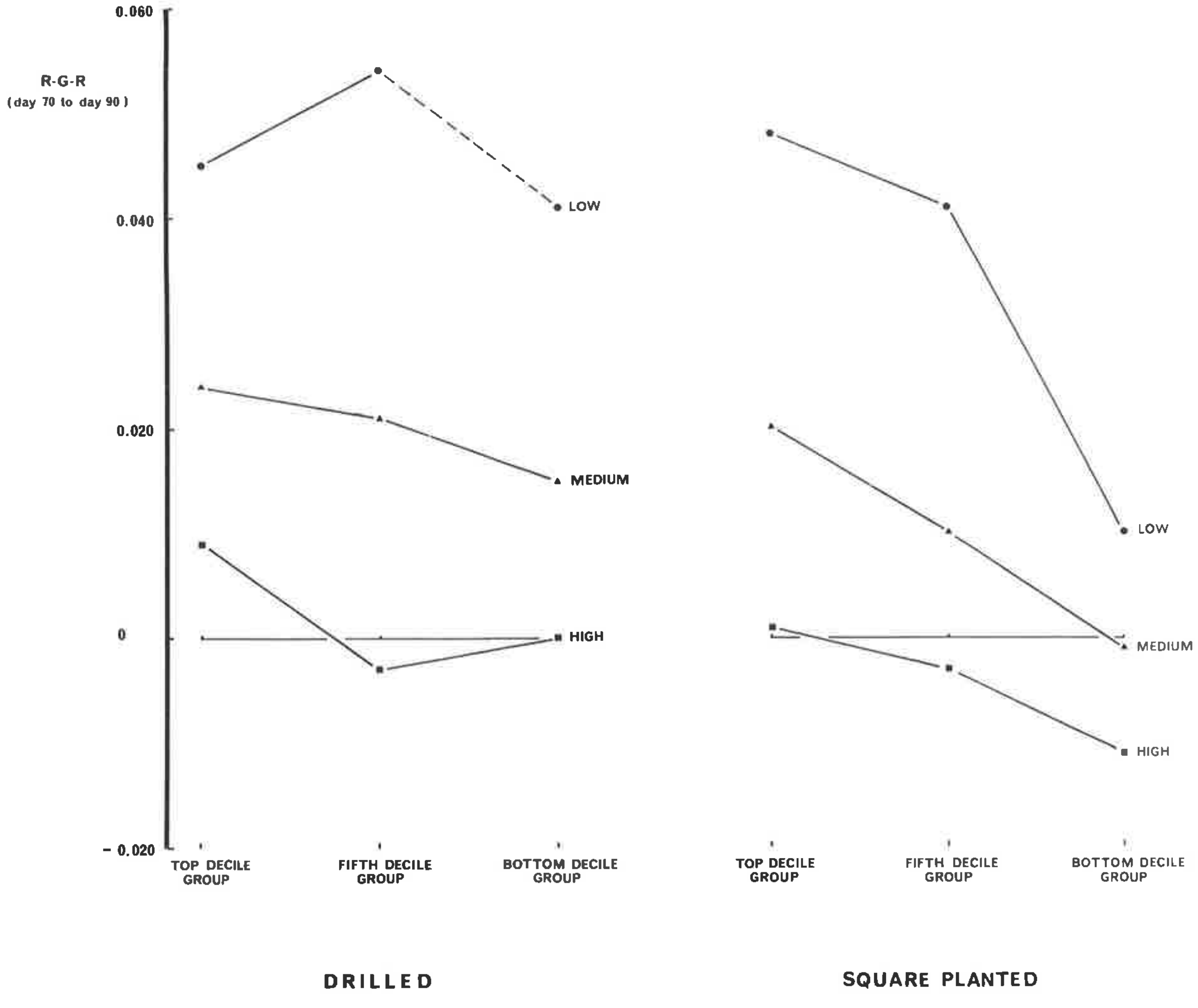


FIG.25 : THE RELATIVE GROWTH RATE (R-G-R) OF BARLEY FROM DAY 70 TO DAY 90 AMONG THE LARGEST PLANTS (TOP DECILE GROUP), THE MEDIUM SIZED PLANTS (FIFTH DECILE GROUP), AND THE SMALLEST PLANTS (BOTTOM DECILE GROUP) AS RANKED AT DAY 70, AT LOW, MEDIUM AND HIGH DENSITY.

the square planted plot plant dominance is strongest expressed at low density, whereas in the drilled plots it is similar at all densities. This last mentioned phenomenon in the drilled plots should be looked upon with a considerable degree of reservation since the occurrence of 'barley yellow dwarf' disease in the low density plots distorted the interaction between large and small plants. For this reason the line to this point in Figure 19 is shown as a dotted line.

At medium density the degree of dominance in square planted plots is higher than in the drilled plot, i.e. in the square planted plot the difference in R-G-R between the top and bottom decile group is 0.021 while in the drilled plot it is only 0.009 (see Table 16). At this density in the square planted plot the depressing effect on the smaller plants after day 70 was already in such extent that their weight was actually reduced, even though only slightly, whereas in the drilled plot the weight even of the smallest plants was still increasing.

The presence of dominant and suppressed individuals within a cereal crop community is demonstrated, and it is influenced by plant density and plant arrangement. In equidistant spacing (square planted) the degree of dominance decreases with density, whereas in row spacing (drilled plot) the degree of dominance is only slightly affected by density.

5.2 Experiment 2

Repeated measurements on the same plants were done in the permanent quadrats at days 43, 82 and 140, but as mentioned earlier, the measurements in high density plots at day 82 were discontinued due to the impossibility of identifying each plant at that stage without

without damaging them, so that there are only two sets of weight data of the same plants at hand, i.e. estimated weight at day 43 and actual weight at day 140.

Plant weights at day 43 are divided into 10 groups and out of these, three groups, i.e. top decile group, fifth decile group and bottom decile group are examined. Their mean weights at day 140 are compared with their weights at day 43 at both densities, and with the weights at day 82 at medium density. These weight values and also the absolute relative increase of plant weight are shown in Table 17.

On the absolute increase of plant weight, the bigger plants (top decile group) consistently had greater increase than the smaller plants (bottom decile group) both at high and medium densities at all observation dates. On the relative increase in weight from day 43 to day 140 at high density the bigger plants (top decile group) had greater increase than the smaller plants (bottom decile group), i.e. 1319% *vs* 765%. At medium density the similar trend was only found from day 82 to day 140, but from day 43 to day 82 the smaller plants had the greater increase.

In this experiment, in both high and medium density, plant dominance did not reach the extent that prevented the smallest plants from gaining weight with time. At random spacing plant dominance was stronger expressed at high density than at medium density.

Table 17 : Mean plant weight at days 43, 82 and 140 at medium density, and days 43 and 140 at high density for the three decile groups (ranked at day 43) and their absolute and relative increases

	Top decile group	Fifth decile group	Bottom decile group
	(ranked at day 43)		
(a) Plant weights (g):			
High density:			
mean weight at day 43	0.325	0.198	0.100
mean weight at day 140	4.611	2.344	0.865
Medium density:			
mean weight at day 43	0.243	0.154	0.043
mean weight at day 82	3.277	2.981	1.327
mean weight at day 140	9.277	6.166	1.745
(b) Absolute increase in plant weights (g):			
High density:			
day 43 to day 140	4.286	2.146	0.765
Medium density:			
day 43 to day 82	3.479	2.827	1.284
day 82 to day 140	5.555	3.185	0.418
day 43 to day 140	9.034	6.012	1.702
(c) Relative increase in plant weights (%):			
High density:			
day 43 to day 140	1319	1084	765
Medium density:			
day 43 to day 82	1432	1836	2986
day 82 to day 140	149	107	31
day 43 to day 140	3718	3904	3958

6. Frequency distribution of plant weight and other plant characters.

6.1 Individual plant weight.

6.1.1 Experiment 1

Results from the permanent quadrats.

Due to several factors, mentioned earlier, only two sets of weight data were obtained in this experiment, i.e. estimated weight at day 70 and actual weight at day 90. For each set of data ten weight classes were determined between the maximum and minimum weight of individual plants. The number of plants in each of those weight classes, expressed as percentages of the total number of plants, were used to make histograms of the frequency distribution of individual plant weight as shown in Figure 26. Their degree of skewness is indicated in Table 18. In the appendix is also shown the skewness of the frequency distribution in each replicate.

In the drilled low density plots, due to the incidence of barley yellow dwarf disease at later stage of growth which stunted the severely attacked plants, two types of histogram are presented for day 90, i.e. by including and not including the diseased plants (shaded part of the histogram). Both steps, i.e. by including or excluding the plants severely affected by the virus disease, creating some departure from the normal plant interaction, so that it is best to consider this particular result with a degree of reservation.

In the square planted plots at day 70 the frequency distributions are practically normal (with insignificantly negative or positive skewness, see Table 18), while at day 90 the skewness was negative at all densities, significantly so at low and medium density.

In the drilled plots at day 70 the distributions were practically normal, except at medium density where it was significantly positive.

Table 18 : Mean degree of skewness of three plant characters, i.e. individual plant weight, length of the longest tiller and number of tillers per plant. Experiment 1.

	Sq.L.††	Sq.M.	Sq.H.	D.L.†	D.M.	D.H.
1. Individual plant weight						
Skewness - at day 70	-0.170	-0.210	0.160	-0.171	0.303*	-0.220
at day 90	-0.554**	-0.820**	-0.294	0.248 (-0.040)	0.989**	0.419**
2. Length of the longest tiller						
Skewness - at day 50	-0.955**	-0.172	-0.142	-0.346*	0.216	-0.582**
at day 90	-0.956**	-1.740**	-1.036**	-1.058**	-1.214**	-2.032**
3. Number of tillers per plant						
Skewness - at day 50	9.306**	0.326*	0.540*	-0.035	0.578**	8.964**
at day 90	0.953**	-0.002	0.939**	0.124	0.909**	0.779**

† Skewness of individual plant weight at day 90 in drilled, low density plots, has two figures: the top figure is the value for all the plants within the permanent quadrats, while the bottom figure (in brackets) is the value after the diseased plants (barley yellow dwarf) are excluded.

†† Sq.L., Sq.M. and Sq.H. are square planted at low, medium and high density respectively. D.L., D.M. and D.H. are drilled at low, medium and high density respectively.

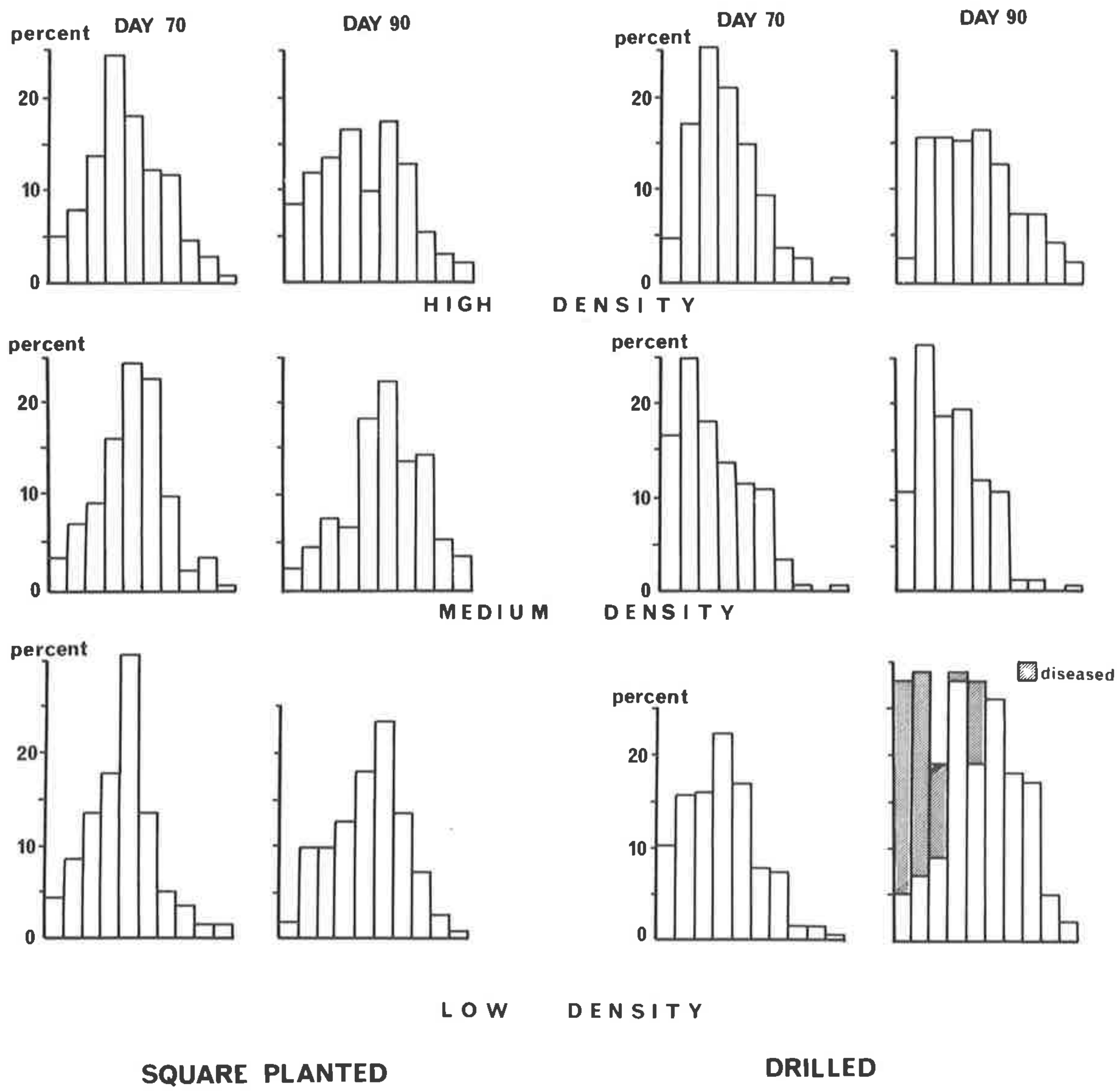


FIG.26: FREQUENCY DISTRIBUTION OF INDIVIDUAL PLANT WEIGHT OF BARLEY AT DAY 70 AND DAY 90.

At day 90 they were all positive, significantly so at medium and high density.

The general trend of these results is that the frequency distribution of individual plant weight changed from normal at day 70 to significantly skew at day 90, except in the drilled medium density plot where the skewness was already significantly positive at day 70. The most interesting aspect of the results is that at later stage of growth (day 90), in the square planted plot the skewness became significantly negative (most plants in 'large' classes) while in the drilled plot they became significantly positive (many small plants).

6.1.2 Experiment 2

(A) Results from the permanent quadrats

In the permanent quadrats, three sets of weight data were obtained at days 43, 82 and 140. But as explained earlier, at day 82 no data were obtained from the high density plot due to the difficulty in identifying individual plants without incurring damages to the plants. Histograms of the frequency distribution of individual plant weights are illustrated in Figure 27 and the degrees of skewness are indicated in Table 19.

In this random spacing the skewness of the frequency distribution of plant weight also changed with time, i.e. from practically normal (slightly skewed) to significantly positively skewed at both medium and high density. This result is similar to the one obtained from the drilled plots in Experiment 1.

(B) Results from the sequential harvests.

In the sequential harvest eight harvests were taken, including one from the permanent quadrat (harvest 7). The results are shown

Table 19 : Degree of skewness of plant weight, height and number of tillers of wheat at different stages of growth, in the permanent quadrats of Experiment 2.

	At day 43	At day 82	At day 140
Skewness of plant weight at:			
high density	0.133	-	0.970**
medium density	-0.194	0.241*	0.483**
Skewness of plant height at:			
high density	-0.256*	-	-1.764**
medium density	-0.380**	-0.236*	-3.013**
Skewness of tiller number per plant at:			
high density	0.356**	-	0.489**
Medium density	0.285**	1.032**	-0.184

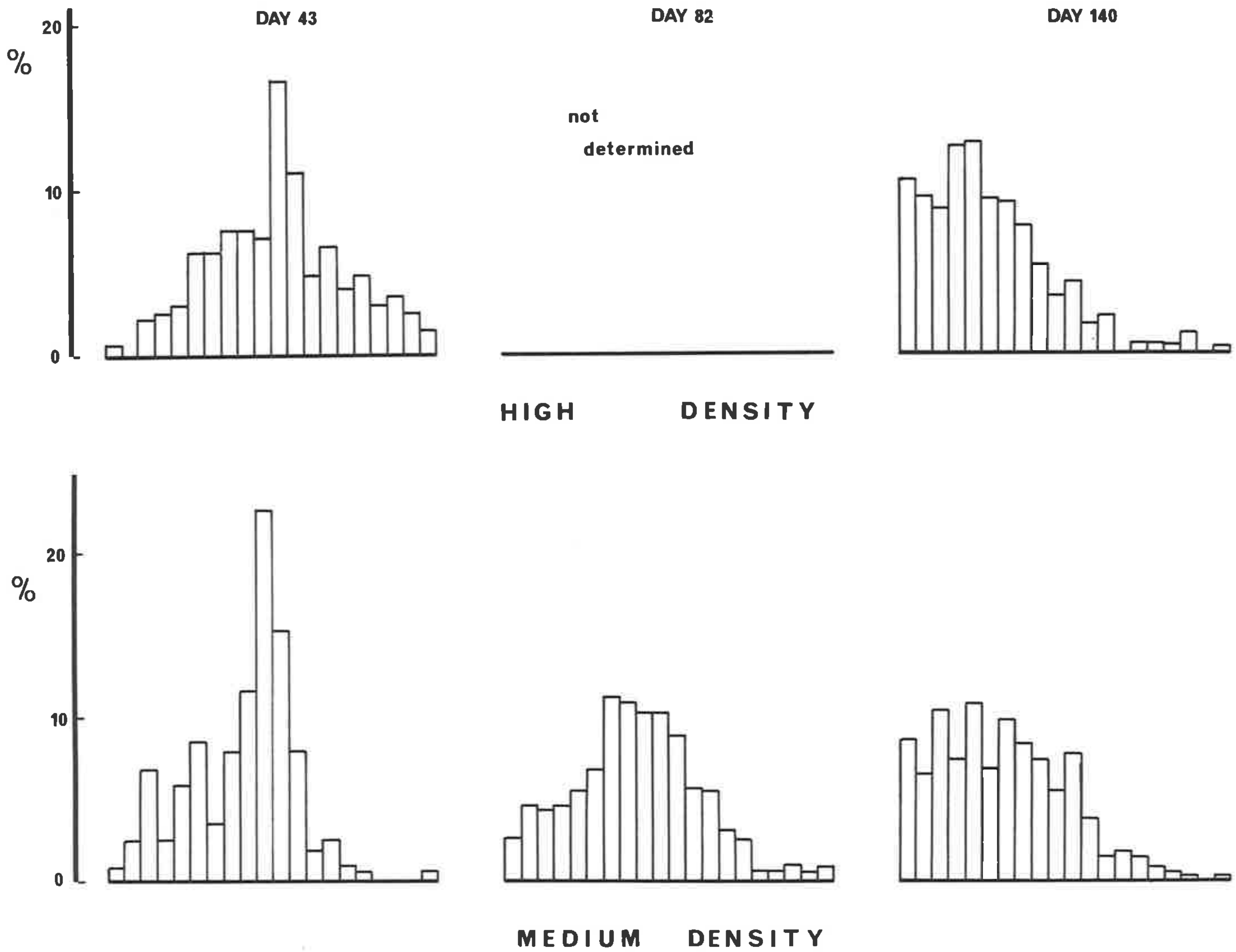


FIG.27: FREQUENCY DISTRIBUTION OF PLANT WEIGHT OF WHEAT AT DAY 43, 82 AND 140.

Table 20 : Degree of skewness on the frequency distribution of plant weight of wheat - Experiment 2

Treatment	HARVEST 1 (day 30)	2 (day 50)	3 (day 70)	4 (day 95)	5 (day 110)	6 (day 130)	7 (day 140)	8 (day 180)
High density	0.202*	0.472**	0.364**	0.782**	0.779**	0.851**	0.970**	1.095**
Medium density	0.169	0.079	0.264*	0.871**	0.796**	0.830**	0.483**	0.666**

Table 21 : Degree of skewness on the frequency distribution of plant height (length of the longest tiller) of wheat - Experiment 2

Treatment	HARVEST 1 (day 30)	2 (day 50)	3 (day 70)	4 (day 95)	5 (day 110)	6 (day 130)	7 (day 140)	8 (day 180)
High density	-0.003	-0.967**	-0.464**	-2.728**	-1.890**	-2.666**	-1.764**	-2.533**
Medium density	-0.020	-0.534**	-1.613**	-1.555*	-2.163**	-3.198**	-3.013**	-2.516**

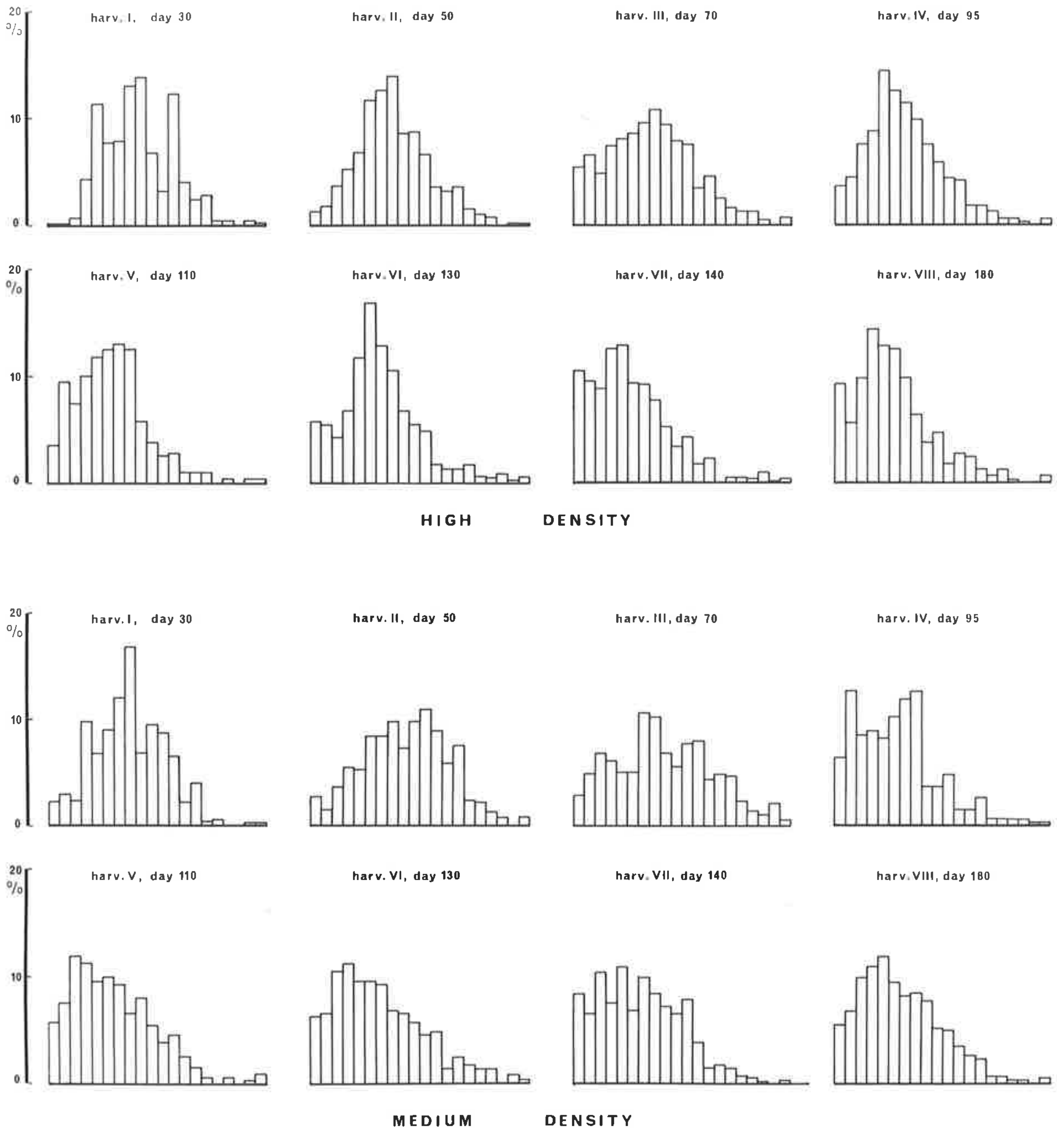


FIG.28: FREQUENCY DISTRIBUTION OF PLANT WEIGHT OF WHEAT AT DIFFERENT STAGES OF GROWTH.

in Table 20 and Figure 28.

At high density, even from the first harvest at day 30, a significantly positive skewness was obtained and the tendency at the later harvests was that their positive skewness became stronger with time. At medium density the first significantly positive skewness was obtained at day 70 (harvest 3), and even though in following harvests, significantly positive skewness was always recorded, there was no tendency for it becoming stronger with time as at high density.

6.2 Plant height (length of the longest tiller)

In Experiment 1, measurements of the length of longest tiller were made at day 50 and day 90 in the permanent quadrats. The frequency distribution of these measurements is illustrated in Figure 29 and their degree of skewness shown in Table 18. Except in the drilled medium density plot at day 50, all treatments had a negatively skewed frequency distribution. At day 90 all the skewnesses were significantly negative.

In the permanent quadrats of Experiment 2, the measurements were done at days 43, 82 and 140 at the medium density, while at high density, as explained earlier, the measurements were done only at days 43 and 140. The frequency distributions of the results are illustrated in Figure 30 and their degree of skewness indicated in Table 19. Without any exception, all the skewnesses were significantly negative. Results from the measurements of the sequential harvests, the frequency distributions are illustrated in Figure 31 with their degree of skewness indicated in Table 21, were also similar, i.e. all the frequency distributions were negatively skewed, and except in harvest 1 (day 30), all the negative skewnesses were highly significant.

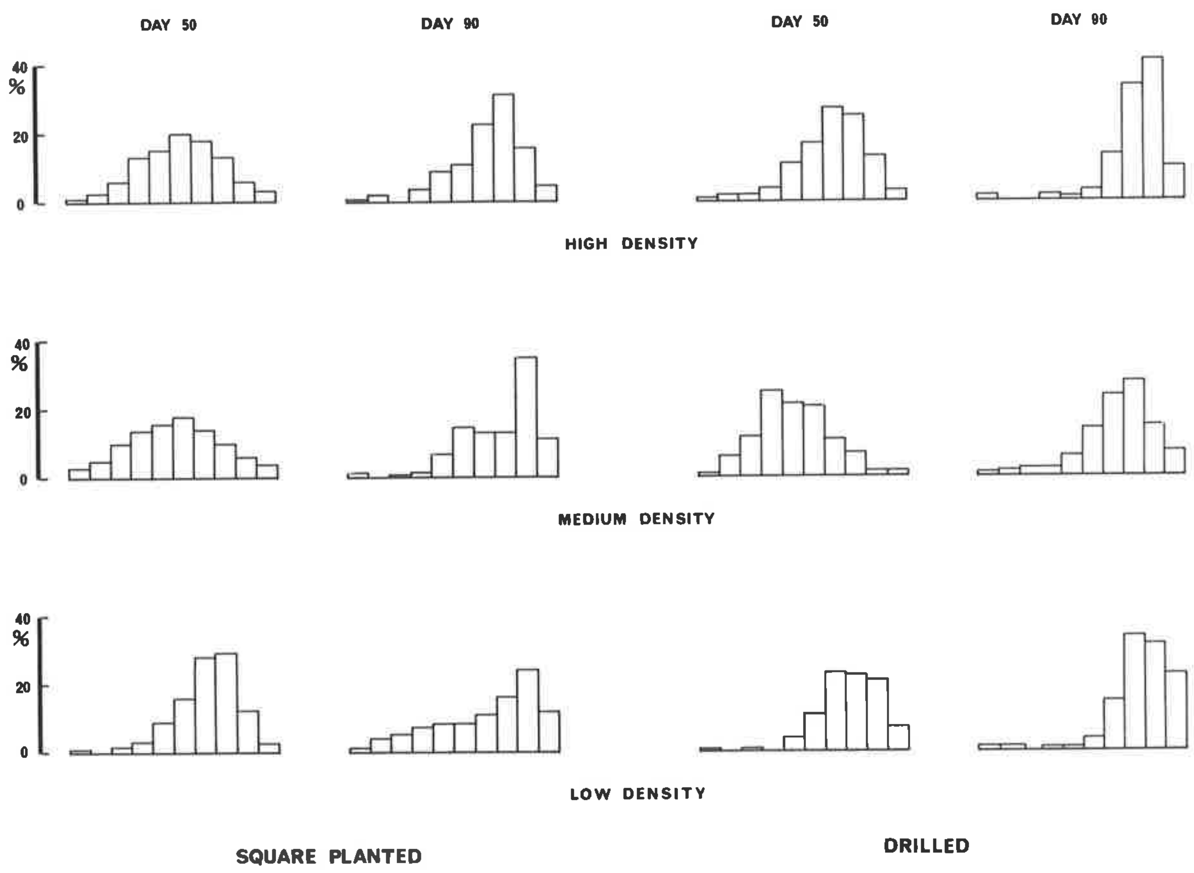


FIG.29: FREQUENCY DISTRIBUTION OF PLANT HEIGHT (LENGTH OF LONGEST TILLER) OF BARLEY AT DAY 50 AND DAY 90.

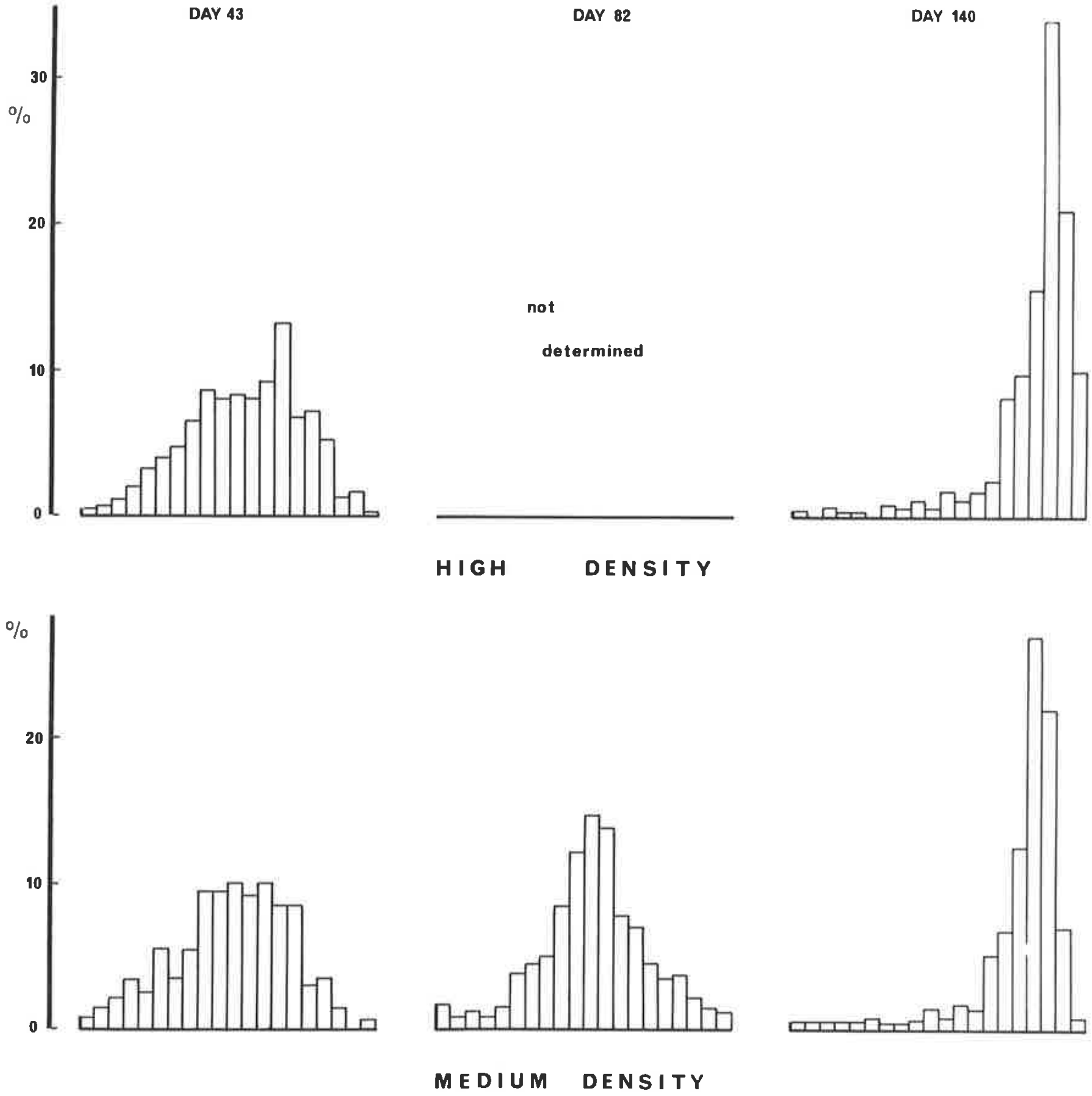


FIG.30: FREQUENCY DISTRIBUTION OF PLANT HEIGHT (LENGTH OF LONGEST TILLER) OF WHEAT AT DAY 43, 82 AND 140.

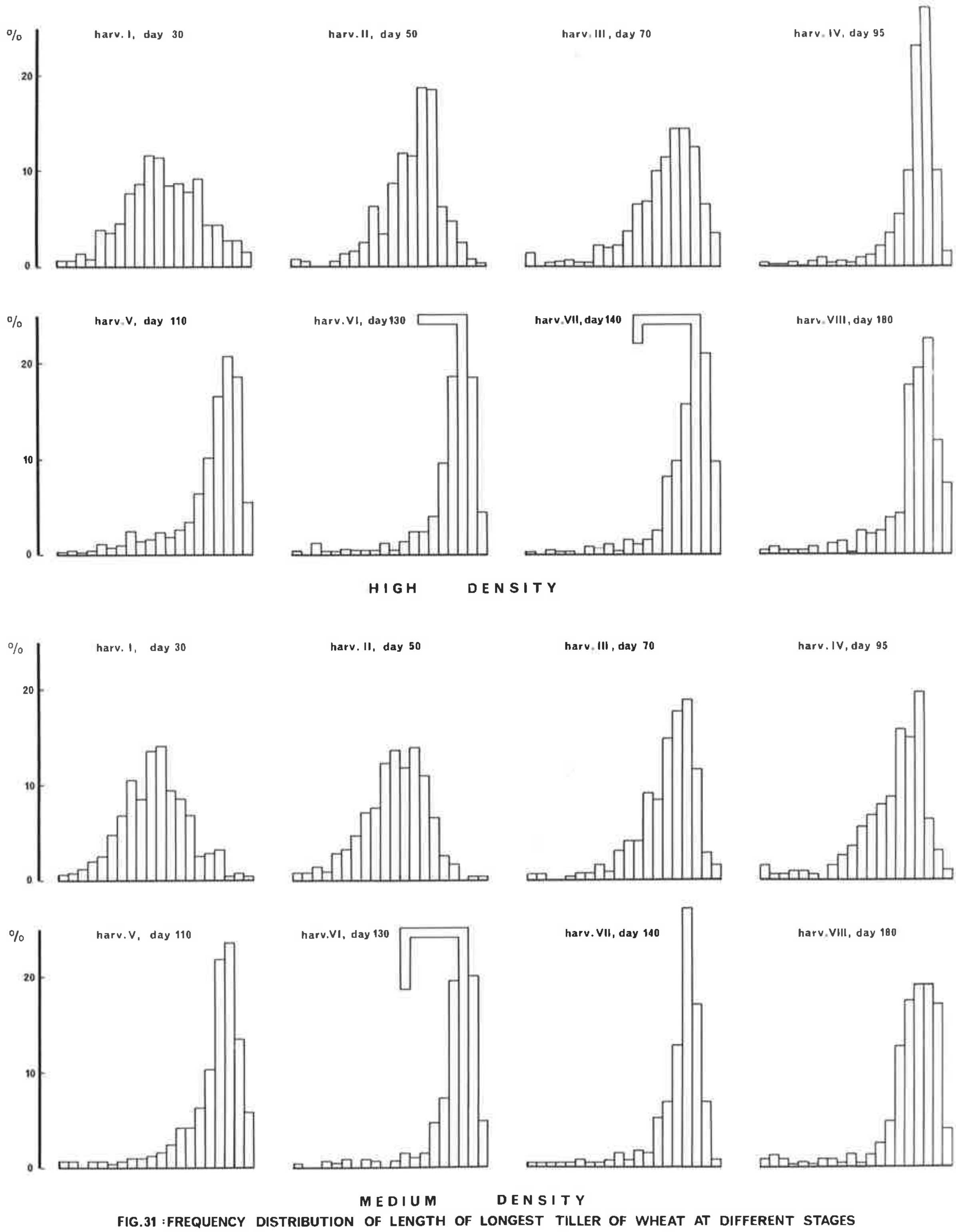


FIG.31 : FREQUENCY DISTRIBUTION OF LENGTH OF LONGEST TILLER OF WHEAT AT DIFFERENT STAGES OF GROWTH.

The patterns of skewness of frequency distributions of plant height (length of longest tiller) were similar; in almost every case their skewness became significantly negative around day 50. Density and plant arrangement did not change this pattern. In other words, most of the plants tended to grow almost as tall as the tallest plant.

6.3 Number of tillers per plant

In the permanent quadrats of Experiment 1, the counting of number of tillers per plant was done at days 50 and 90, with the results illustrated in Figure 32 and Table 18. The general trends are that the skewness of the frequency distributions were significantly positive with an exception at the drilled low density plot which was normal at both dates, as was also the square planted medium density plot.

In Experiment 2, similar results were obtained both from the permanent quadrats and from the sequential harvests, i.e. the skewness of the frequency distributions were significantly positive (Figure 33 and Table 19 for permanent quadrats and Figure 34 and Table 22 for sequential harvests). In Figure 33 frequency distributions of the number of productive tillers (ear producing tillers) per plant are illustrated also, whereas in Figure 34 are the frequency distributions of total and green tiller per plant for harvest 1 to harvest 7. For harvest 8 the frequency distributions of reproductive tillers are also shown.

The general patterns of the frequency distribution of number of tillers per plant were similar to that of individual plant weight (with an exception in the square planted plot of Experiment 1), i.e. they were mainly positively skewed. It is not surprising that the number of tillers per plant is indicative of the individual plant weight. More about tillering pattern will be discussed in the following section.

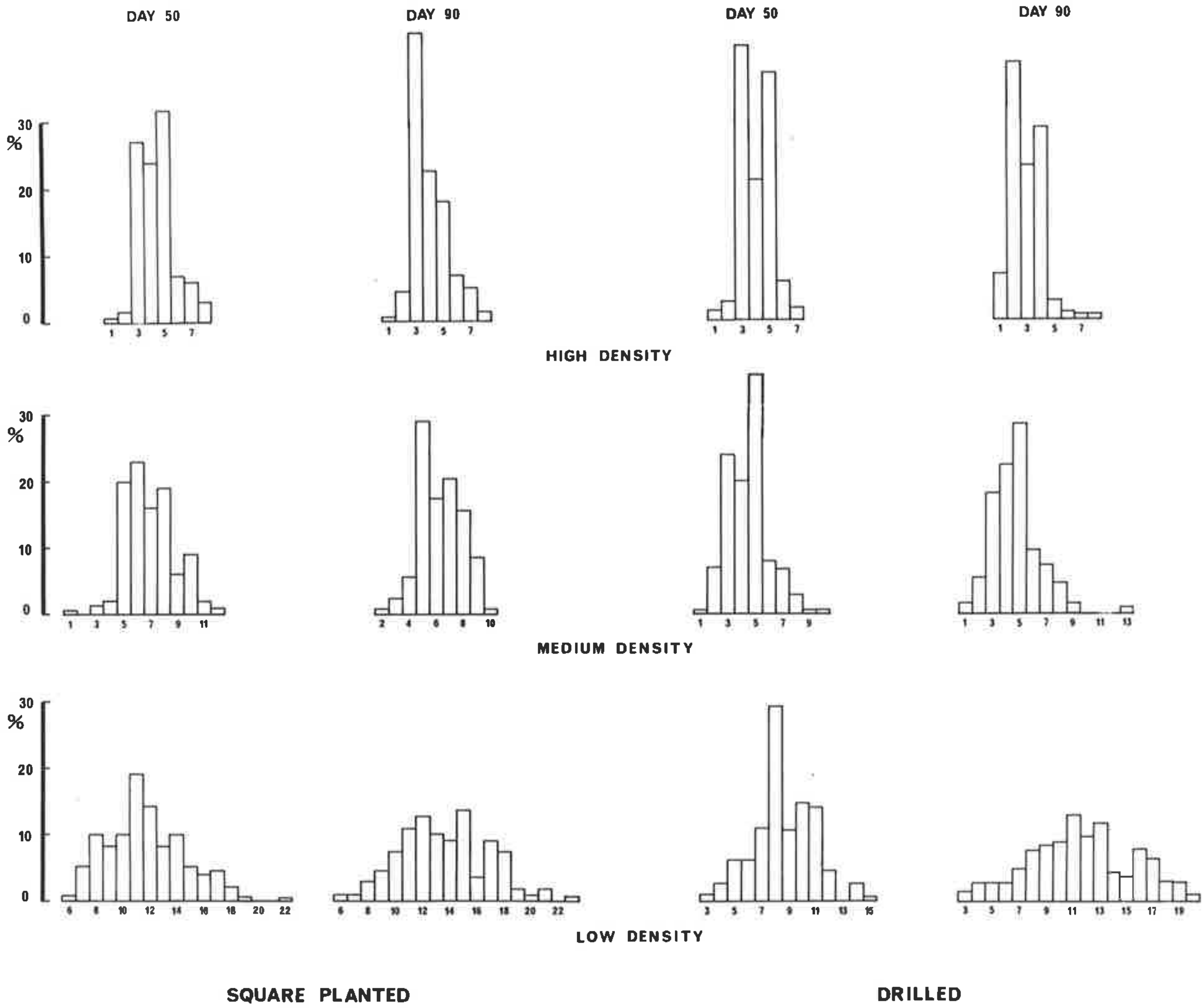


FIG.32: FREQUENCY DISTRIBUTION OF TILLER NUMBER PER PLANT OF BARLEY AT DAY 50 AND DAY 90.

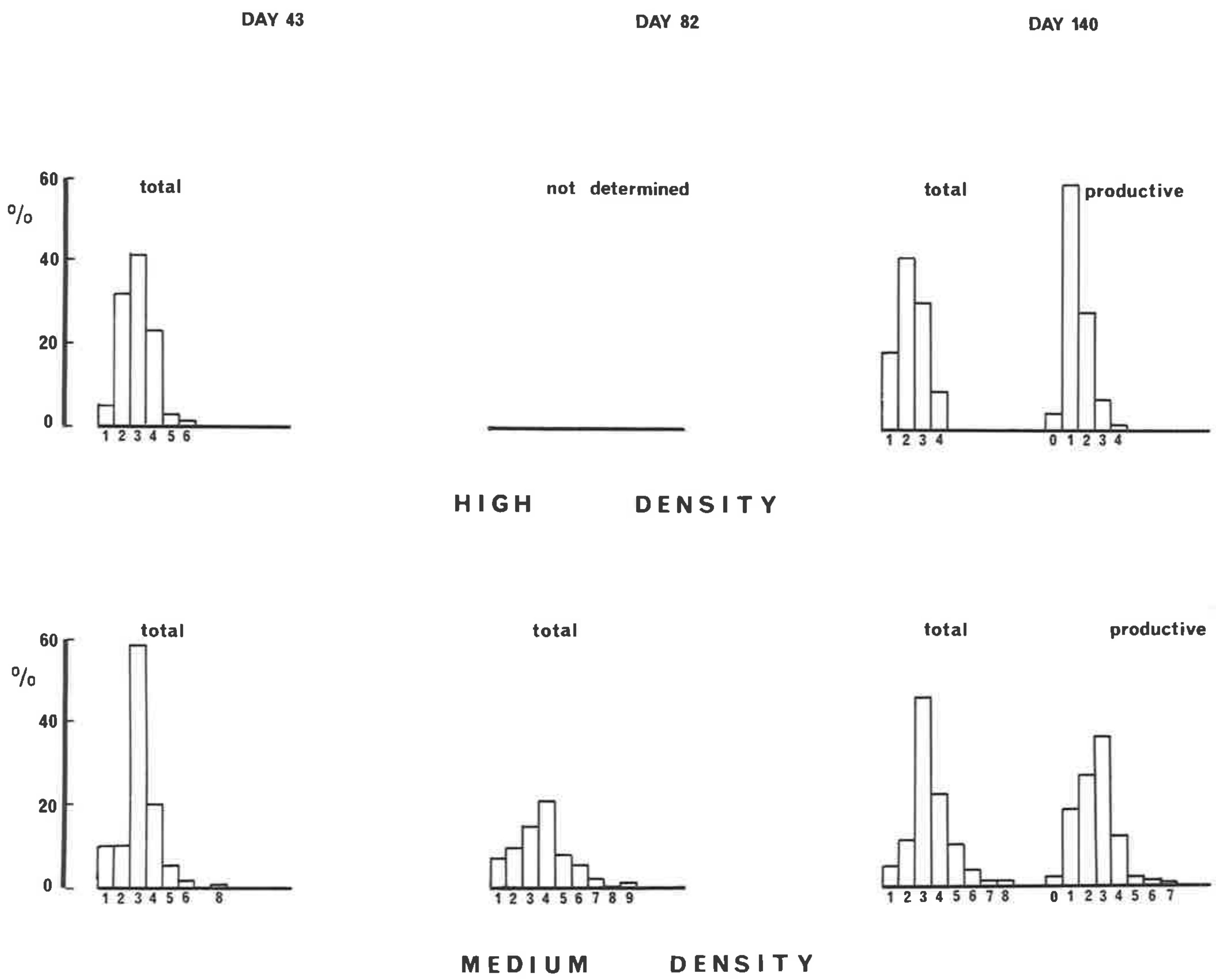


FIG.33: FREQUENCY DISTRIBUTION OF TILLER NUMBER PER PLANT OF WHEAT AT DAYS 43, 82 AND 140.

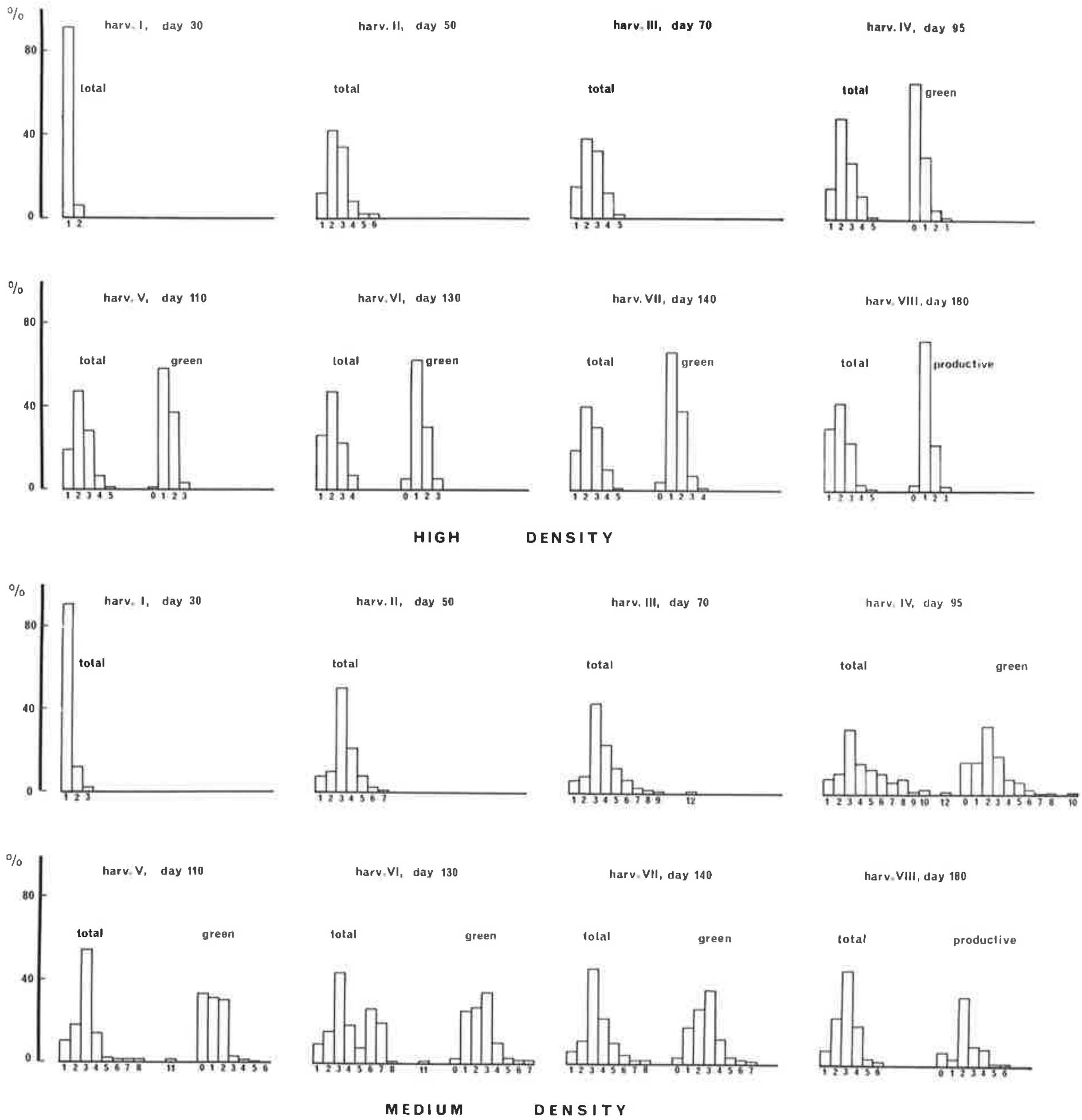


FIG.34: FREQUENCY DISTRIBUTION OF TILLER NUMBER (TOTAL AND GREEN) PER PLANT OF WHEAT AT DIFFERENT STAGES OF GROWTH.

Table 22 : Degree of skewness of the frequency distribution of number of tillers per plant of wheat (from the quadrats for sequential harvest of Experiment 2).

Treatment	HARVEST							
	1 (day 30)	2 (day 50)	3 (day 70)	4 (day 95)	5 (day 110)	6 (day 130)	7 (day 140)	8 (day 180)
High density[1]:								
plant number	421	485	181	515	435	448	471	426
skewness	5.260**	0.532**	0.387*	0.392**	0.278*	0.469**	0.489**	0.208*
Medium density[2]:								
plant number	400	216	378	297	485	414	331	456
skewness	2.580**	0.677**	1.065**	0.798**	0.551**	0.855**	-0.184	0.669**

1. High density → r_s = -0.601: N.S.

2. Medium density → r_s = -0.524: N.S.

7. Light penetration

The light intensity was measured above and within the canopy. Light penetration within the crop canopy itself is already well publicised (Brougham, 1958a; Puckridge and Donald, 1967), but the point examined in this study was the variability of light penetration as affected by plant density and arrangement. In Experiment 1, of five replicates in each treatment, one was randomly selected for these measurements. Figure 35 shows the light intensity adjacent to each individual plant at day 39. The minimum and maximum values and also their means and standard deviations are shown in Table 23.

At day 39, for high density light interception by plant leaves in the square planted plot was far more efficient than in the drilled plot of the same density. Its mean light interception was 91% in comparison to only 76% in the drilled plot,probably because there was more unintercepted light between the drilled rows. This difference tended to be less conspicuous in the lower density. It is obvious from Figure 35 and from Table 23, that at all densities, the variability of light penetration adjacent to each individual plant is higher in drilled plots (with mean row distance of 17.7 cm) than in square planted plots. Within the drilled plot there is no significant difference in the variabilities between densities despite great differences in light penetration. On the square planted plot the variability is least in the high density and becomes greater as the density decreases.

At day 88, because of lodging, measurement of light distribution could only be done at low and medium densities of the drilled plots, and at low density of the square planted plot. Both at half plant height and at ground level (Table 24 and Figure 36), the variability

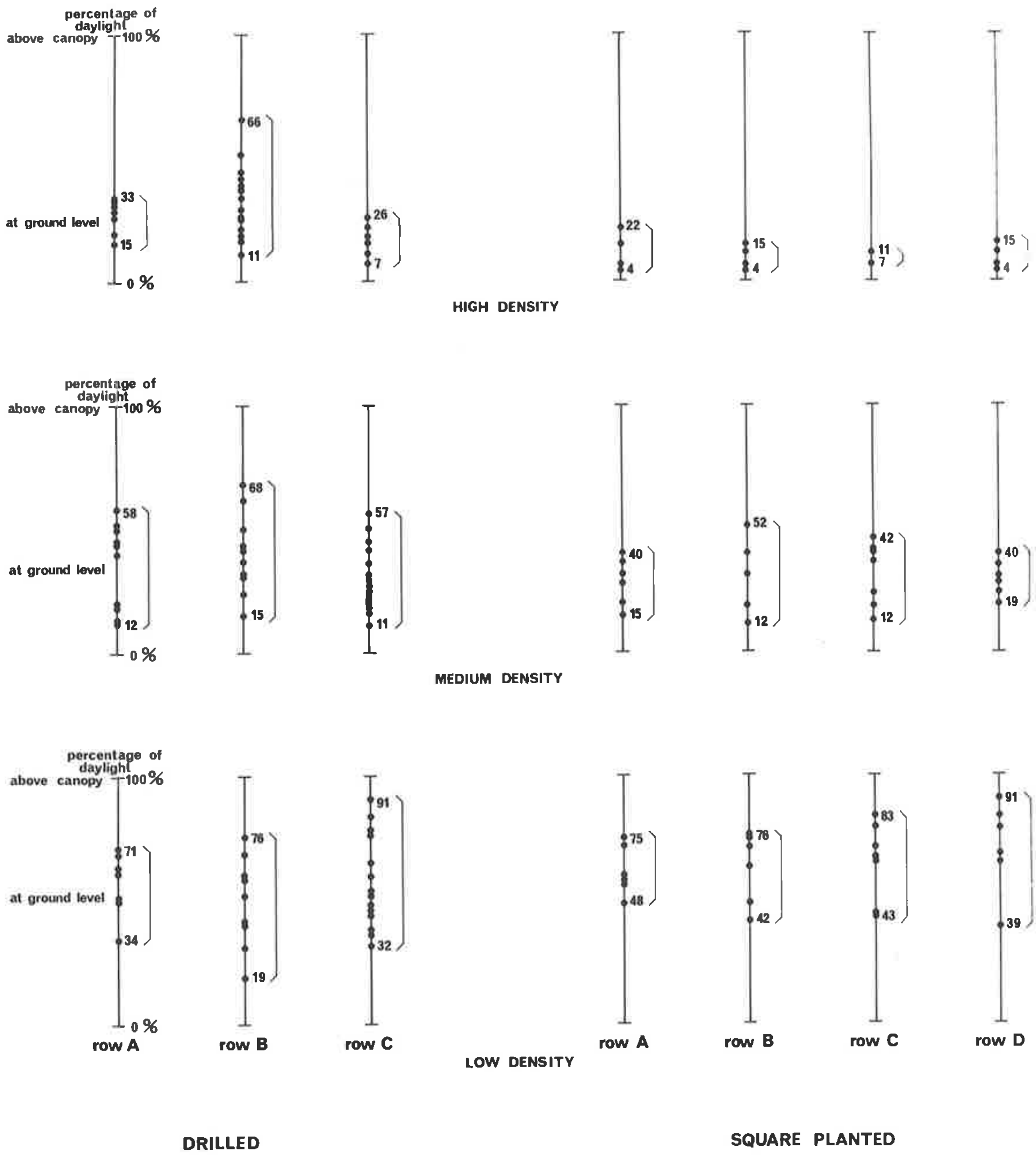


FIG.35: VARIABILITY OF LIGHT PENETRATION TO GROUND LEVEL ADJACENT TO EACH INDIVIDUAL PLANT AT DAY 39. EXPERIMENT 1.

Table 23: Light penetration to ground level, expressed as percentage of day light at day 39. The light intensity was measured at the base of each plant.

Treatment	Number of observations	Light intensity at plant base (percent of daylight)			
		Mean	Standard deviation	Minimum	Maximum
Drilled:					
High density	33	24	13	7	66
Medium density	43	32	15	7	68
Low density	41	54	16	19	91
Square planted:					
High density	28	9	4	4	22
Medium density	28	30	10	12	52
Low density	28	65	14	39	91

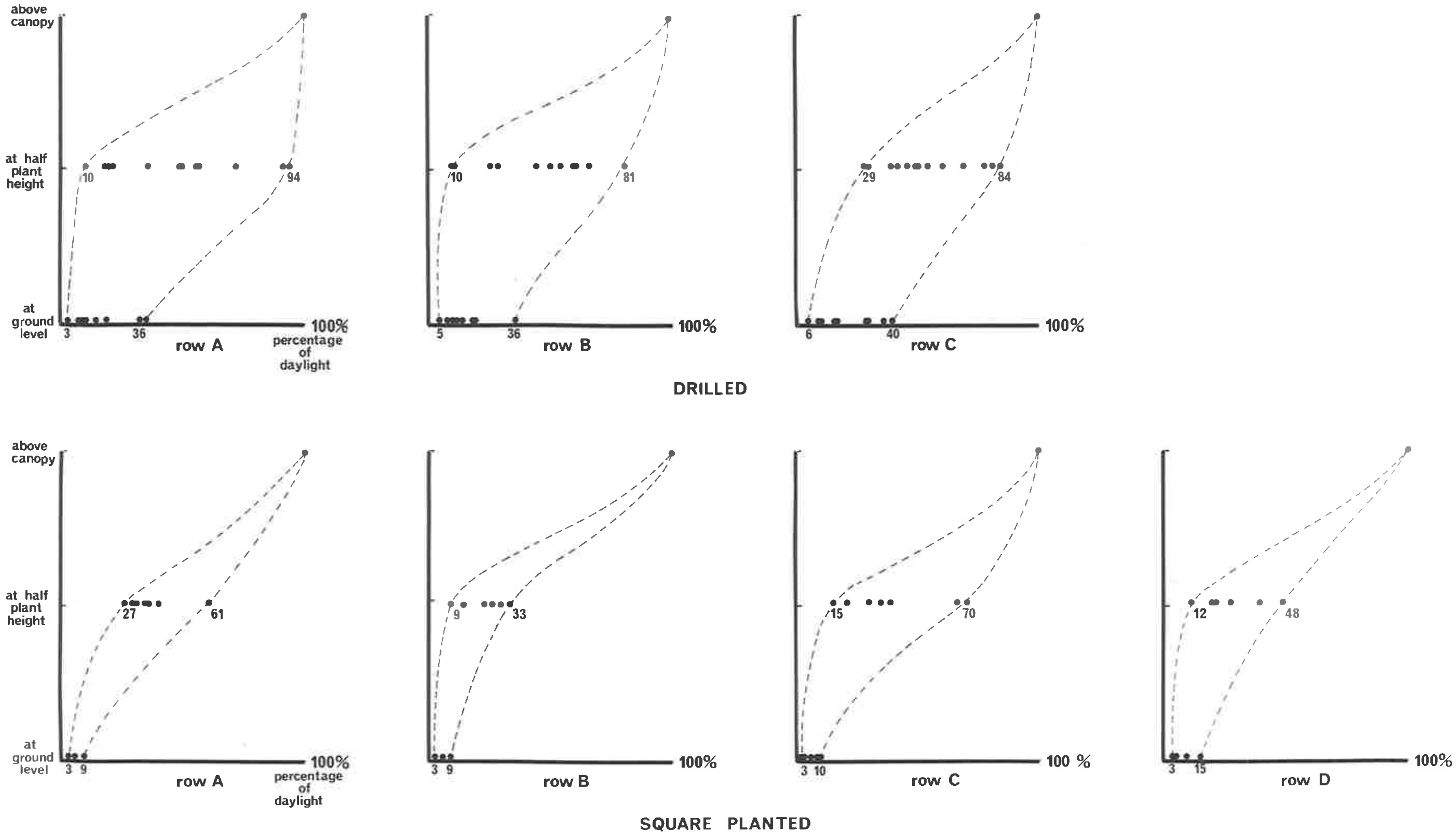


FIG.36: VARIABILITY OF LIGHT PENETRATION ADJACENT TO EACH INDIVIDUAL PLANT AT DAY 88, IN LOW DENSITY PLOTS MEASURED IN QUADRAT NO.1 OF THE DRILLED PLOT AND IN QUADRAT NO.3 OF THE SQUARE PLANTED PLOT. BOTH QUADRATS ARE RANDOMLY CHOSEN. (FOR OTHER QUADRATS SEE TABLE 2)

Table 24/25: Mean and variability of light profile of each plant in the quadrat expressed as percentage of daylight at day 88 (early dough stage).

	Mean no.of plants per replicate	Replicates 1		2		3		4		5		Replicates Mean	Std.dev. of the replicates mean
		Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.		
Drilled, medium density	40												
at half plant height		36	23	27	15	36	21	42	23	36	16	35.4	19.96
at ground level		4	5	5	2	8	5	14	11	10	7	8.2	6.7
Drilled, low density	26												
at half plant height		49	23	60	18	53	22	39	18	43	23	48.8	20.8
at ground level		15	10	18	14	18	15	16	12	16	16	16.6	15.3
Square planted, low dnsty.	22												
at half plant height		44	22	40	20	33	15	55	25	58	17	46.0	19.6
at ground level		16	14	10	5	7	3	19	12	18	10	14.0	9.4

of light penetration adjacent to each individual plant again is *usually* greater in the drilled plots than in the square planted plots. In Table 24 the values of mean and standard deviations for each replicate are given. At this stage of growth, density (medium density in comparison to low density in drilled plots) seems to have no effect on the variability of light penetration at half plant height, but at ground level greater variability was found in the low density. In the drilled plots more light was intercepted at medium density than at low density. Square arrangement, on the average, only slightly increased light interception.

In Experiment 2, light measurements above and within canopy were made at day 92, 110 and 130, and the results are presented in Figure 37. It indicates that there is no significant difference in horizontal variability of light distribution between high density and medium density.

The conclusions from both experiments were that the effect of plant density on the variability of light distribution seems to depend on the plant arrangement, i.e. in square arrangement at day 39 the variability became less as density increases, but in row spacing (drilled plot), density had no effect. By day 88, in drilled plots density affected only the variability of light penetration at ground level, but not at half plant height, while at random spacing density had no effect on the variability of light distribution at any stage of growth.

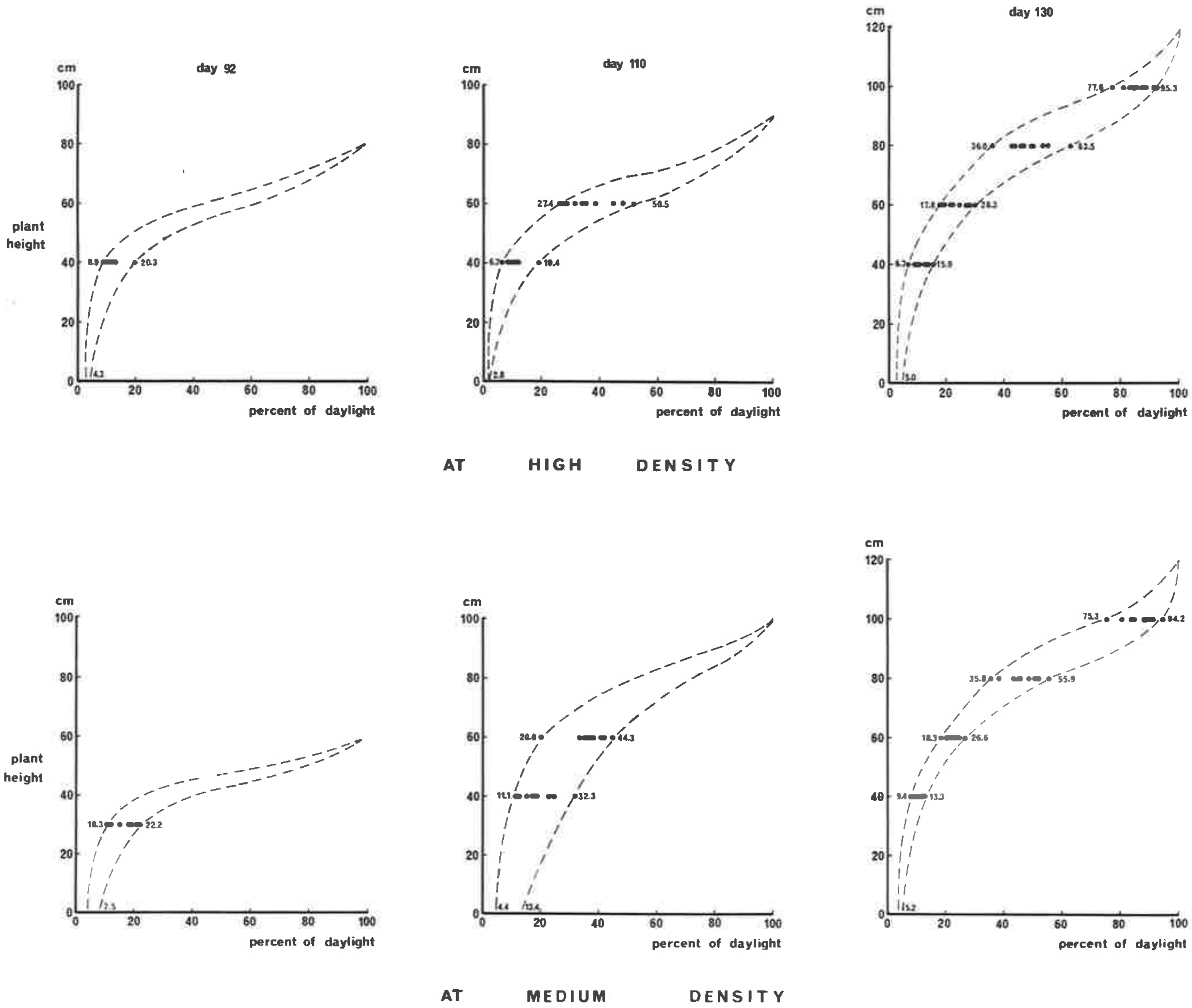


FIG.37: VARIABILITY OF LIGHT PENETRATION AMONG QUADRAT'S STRIPS AT DAYS 92, 110, AND 130
EXPERIMENT 2.

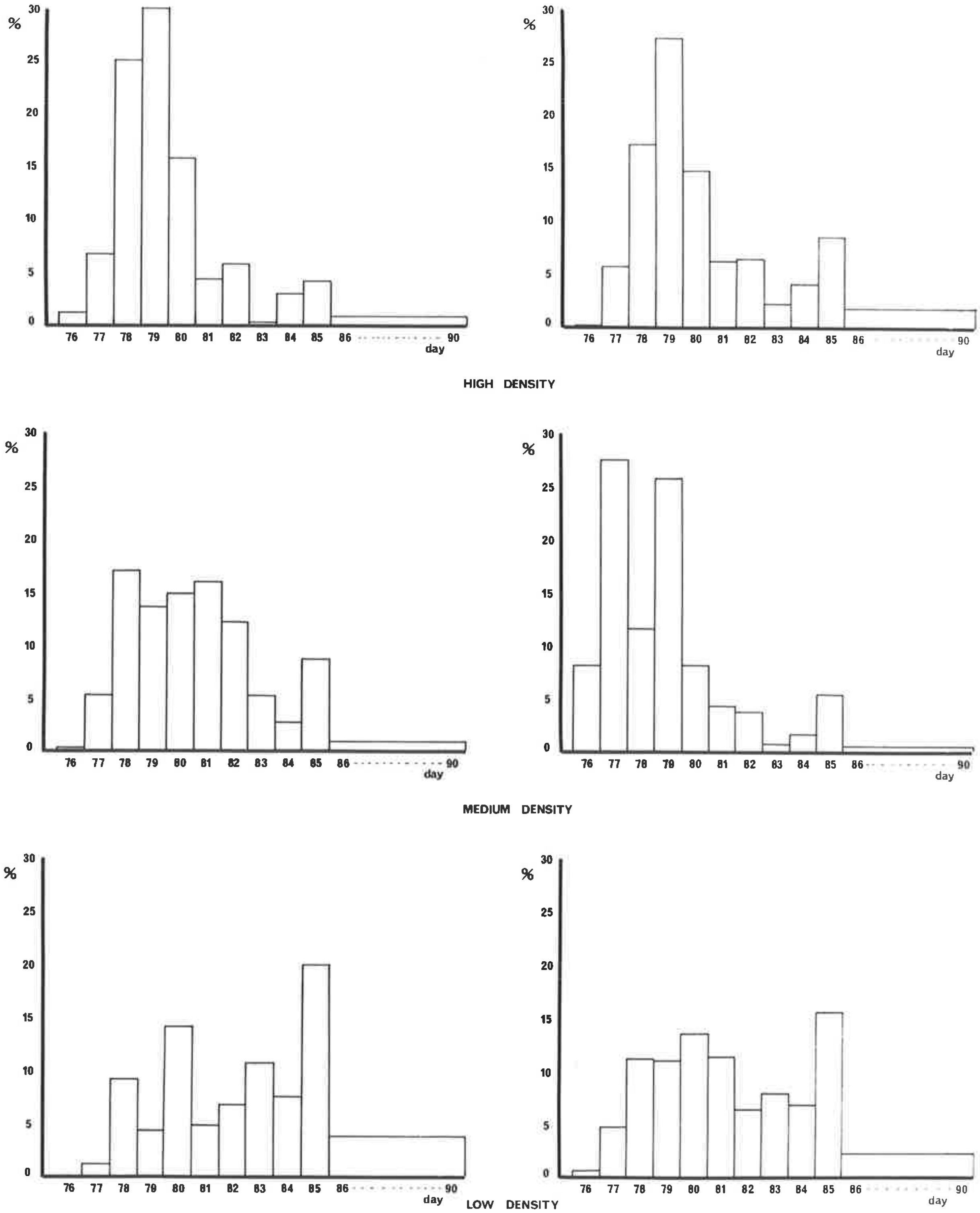
8. Ear emergence

8.1 Results

In Experiment 1, the date of ear emergence of each fertile tiller within the permanent quadrats was recorded. The ear was classed as emerging when its awn was protruding from the leaf sheath. Ears started to emerge at day 76 and the daily recordings were done for a period of 10 days. A few ears emerged during the subsequent 5 day period from day 86 to day 90. The mean percentages of ear emergence per day in each treatment are shown in Figure 38. Skewness of the frequency distributions of ear emergence within each treatment was:

low density		medium density		high density	
drilled	square planted	drilled	square planted	drilled	square planted
0.361	-0.383	-0.019	1.081**	1.054**	1.015**

Except at medium density, the patterns of ear emergence were similar in the drilled and square planted plots. At high density the drilled and square planted plots have the same modal day, i.e. at day 79, and most of the ears (70.7% in drilled plots and 59.1% in square planted plots) emerged in 3 days (days 78, 79 and 80). At low density both plots also have the same modal day (day 85), but the ear emergence was spread out more evenly over the ten day period. At medium density, in the drilled plot, the ear emergence tended to be evenly spread over the ten day period whereas in the square planted plot most of the ears (65%) emerged in 3 days (days 77, 78 and 79).



DRILLED SQUARE PLANTED

FIG.38: MEAN PERCENTAGE OF EAR EMERGENCE IN EACH TREATMENT (Mean per day).

9. Mean and variability of characters of individual plants

9.1 Experiment 1.

9.1.1 Results from the permanent quadrats

As mentioned previously, individual plant weights were measured at days 70 and 90, and the length of the longest tiller and number of tillers per plant at days 50 and 90. At day 90 recordings were also made of number of ears per plant, ear weight per plant, number of spikelets per plant, and leaf and green stem area per plant. Their means and coefficients of variation are given in Table 15 of the appendix, and graphical illustrations are given in Figures 39 and 40.

Plant weights decreased with increasing density with the exception of the drilled-medium-density plot at day 70; and the effect was stronger at later stage of growth (day 90). Length of the longest tiller, on the contrary, had a tendency to increase with increasing density, especially between low and high density. (The density effect on length of longest tiller was significant, with a mean length of 78.4, 84.3 and 85.9 cm for low, medium and high density respectively, and an L.S.D. (.05) of 6.3). Number of tillers per plant, both at days 50 and 90, decreased with increasing density, but the difference between medium and high density drilled plots was not significant. The effect of density on number of ears per plant, ear weight per plant, number of spikelets per plant and leaf and green stem area per plant was basically similar, i.e. they decreased with increasing density. Only in ear weight per plant, was there a significant interaction between density and arrangement. At day 90, the effect of density on number of ears per plant, number of spikelets per plant and leaf and green stem area per plant was significant with mean values at each density and L.S.D. as follows:

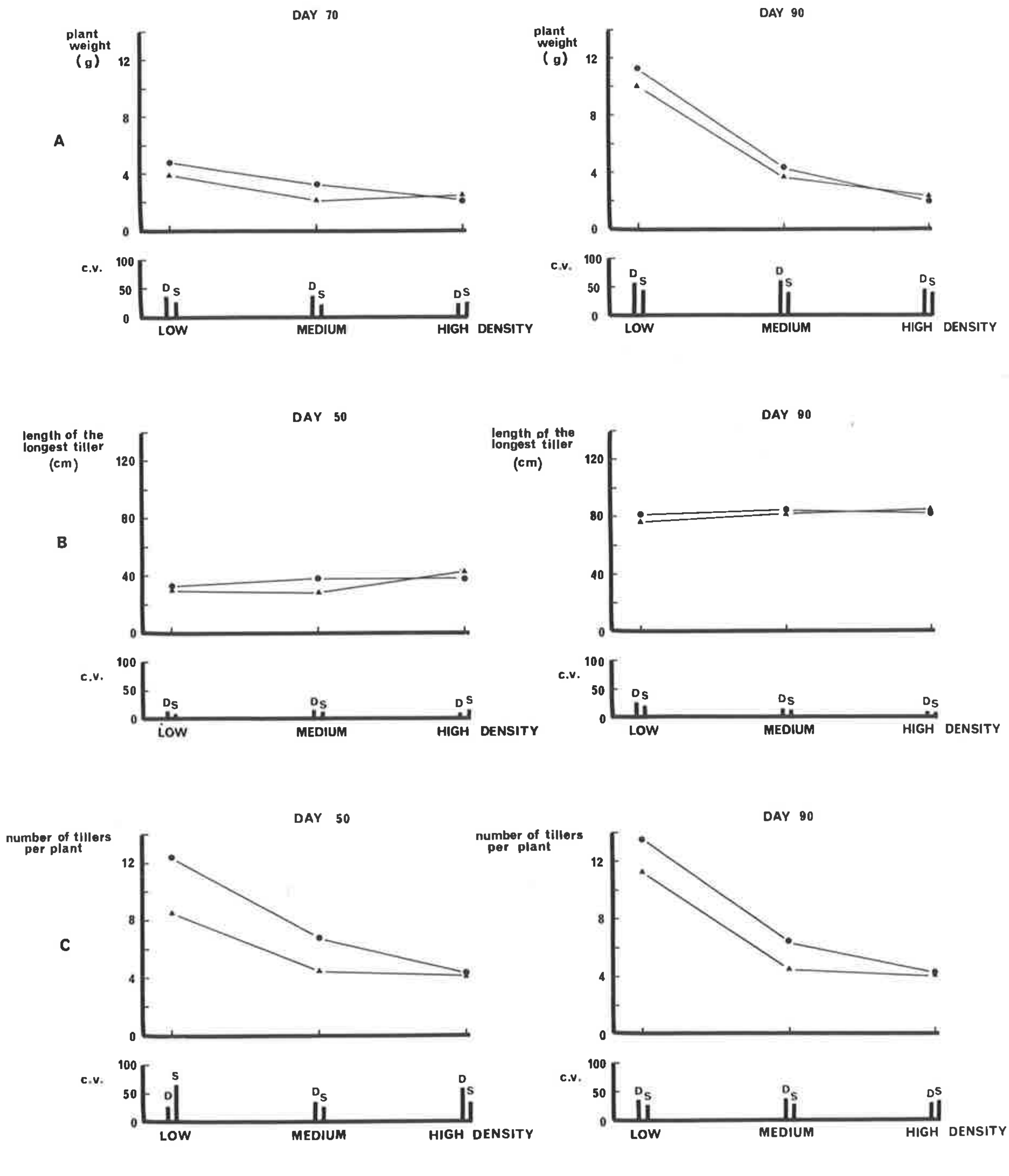


FIG. 39: MEANS AND COEFFICIENTS OF VARIATION OF INDIVIDUAL PLANT CHARACTERS: (A) PLANT WEIGHT, (B) LENGTH OF LONGEST TILLER AND (C) NUMBER OF TILLERS PER PLANT AS AFFECTED BY TREATMENT AND TIME

▲ ——— ▲ (D) : DRILLED

● ——— ● (S) : SQUARE PLANTED

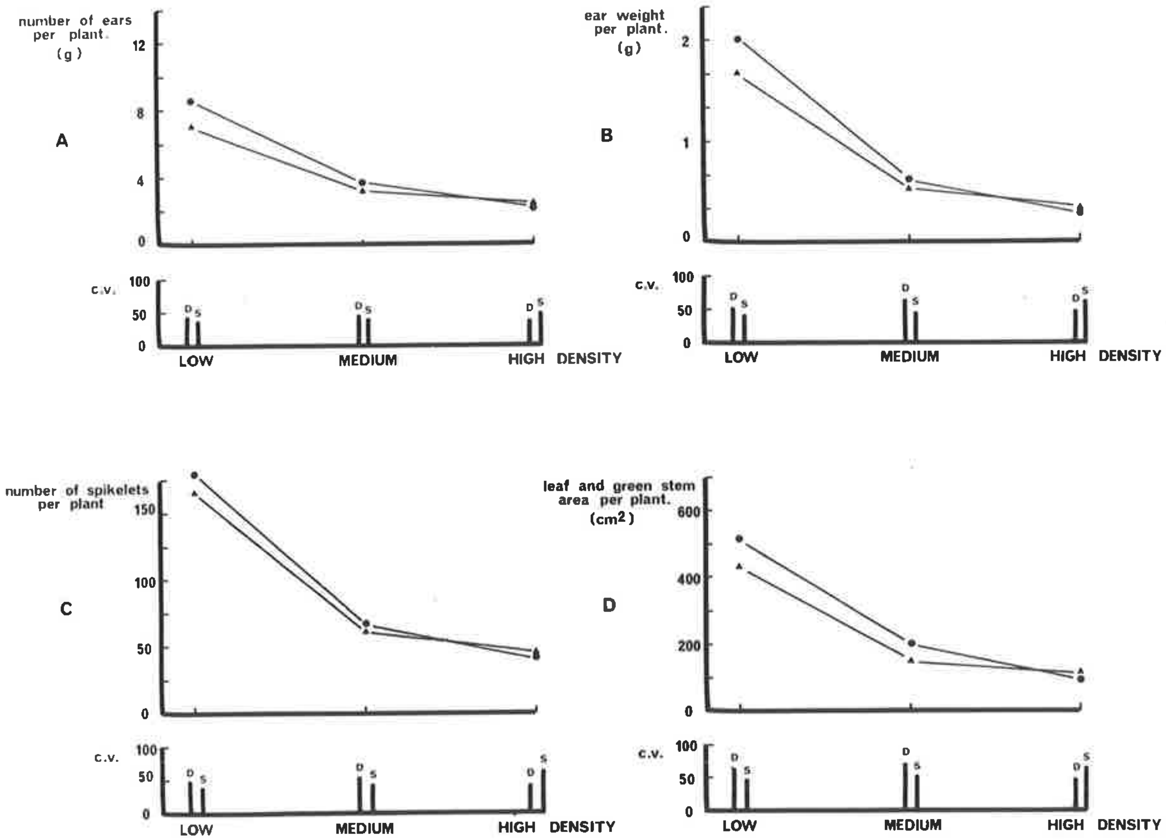


FIG. 40: MEANS AND COEFFICIENTS OF VARIATION OF:
(A) NUMBER OF EARS PER PLANT
(B) EAR WEIGHT PER PLANT
(C) NUMBER OF SPIKELETS PER PLANT
(D) LEAF AND GREEN STEM AREA PER PLANT

	Density			
	Low	Medium	High	L.S.D.(.05)
Number of ears/plant	7.8	3.4	2.6	0.7
Number of spikelets/plant	171	64	43	16
Leaf and green stem area per plant	474	164	103	67

The effect of plant arrangement (drilled *vs* square planted) on plant weight was that, in the low and medium density plots, plant weight was greater with square planting (Figure 39 and Table 15 of the appendix). The low and medium density plants in the square planted plots also tended to be taller than plants from the drilled plots. In the square planted plots there were consistently more tillers per plant than in the drilled plots (Figure 39), but the more abundant tillers per plant apparently caused stronger competition between tillers resulting in a lower tiller weight as follows:

	D.L.	Sq.L.	D.M.	Sq.M.	D.H.	Sq.H.
At day 70*(g/tiller)	0.40	0.37	0.48	0.49	0.64	0.51
At day 90 (g/tiller)	0.89	0.83	0.75	0.67	0.60	0.49

(* The number of tillers at day 70, used for the derivation of these tiller weights, were obtained by interpolating the similar values at day 50 and day 90.)

There was also a lower percentage of fertile tillers in the square planted plots, as follows:

	D.L.	Sq.L.	D.M.	Sq.M.	D.H.	Sq.H.
At day 90	63	63	68	59	69	62

Even though the percentage of fertile tillers was generally lower in the square planted plots, the ears at low and medium density were bigger and also there were more spikelets per plant and a trend of more leaf per plant. At high density, with interplant competition intense in both arrangements, the plant weight, tiller number, ear size and spikelet number were similar.

The effect of treatment on the variability of plant characters is shown by their coefficients of variation (Figures 39 and 40). At low and medium density the variability of plant characters (with the single exception of number of tillers per plant at low density) was always greater in the drilled plots than in the square planted plots. At high density similar effects were found on individual plant weight and length of the longest tiller at day 90, and on number of tillers per plant at day 50, while on other plant characters (number of ears, ear weight and number of spikelets) the effect was reversed, i.e. variability in the drilled plots was lower than in the square planted plots.

The overall picture of the results is that plant size decreased with increasing density, and that regular spacing (square planted) was more favourable for plant growth than less regular spacing (drilled). In comparison with the plants in the drilled plots, plants in the square planted plots at low and medium density were heavier (with more tillers per plant but due to stronger mutual competition the weights per tiller were less), they tended to have more leaf, and although they had a lower percentage of ear producing tillers they had more ears per plant and the ears were heavier, and the number of spikelets per plant was also greater.

At high density, interplant competition was equally intense in both drilled and square planted plots and the plants were generally similar in both situations.

9.1.2 Results from the grain sample quadrats

As explained earlier, no grain data were obtained from the drilled low density plot. Means and coefficients of variation of plant weight, length of the longest tiller, number of tillers per plant, grain weight per plant and number of grains per plant are given in Table 26.

Except in length of the longest tiller, the mean values of each character indicate similar trends, i.e. they decreased with increasing density. Because of the absence of drilled low density plots, the experiment was analysed as having 5 treatments. The treatment interactions for individual plant weight, grain weight per plant and number of grain per plant were highly significant and their L.S.D. (.05) were 1.83, 1.44 and 31.6 respectively. There is no significant difference between medium and high density at both square planted and drilled plots, and also there is no significant difference between square planted and drilled plots at medium and high density.

9.2 Experiment 2.

9.2.1 Results from quadrats for sequential harvest

There were eight sequential harvest including one from the permanent quadrat (harvest 7 at day 140). Three characters were recorded from each plant, i.e. weight, length of longest tiller and number of tillers per plant, and their means and coefficients of variation are illustrated in Figure 41, and their figures are presented in Table 17 of the appendix.

After day 30 individual plant weights at medium density were significantly greater (approximately double) than at high density. The length of the longest tiller also increased with time, and in

Table 26: Means and coefficients of variation of plant weight, length of the longest tiller, number of tillers, grain weight and number of grain per plant of barley from the grain sample quadrats.

Plant Character	Square planted low density		Square planted medium density		Square planted high density		Drilled Medium density		Drilled low density	
	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %
1. Plant weight	19.59	48	4.59	35	3.03	39	5.57	50	4.19	49
2. Plant height (length of longest tiller)	84.1	17	82.2	9	84.6	8	82.7	13	83.0	11
3. Number of tillers per plant	11.1	40	3.3	28	2.2	35	3.4	37	2.9	40
4. Grain weight per plant	7.98	53	1.94	42	1.34	45	2.51	50	1.87	51
5. Number of grains per plant	18.0	45	47	32	32	36	53	45	44	48

No grain sample quadrat was available for the drilled, low density plot.

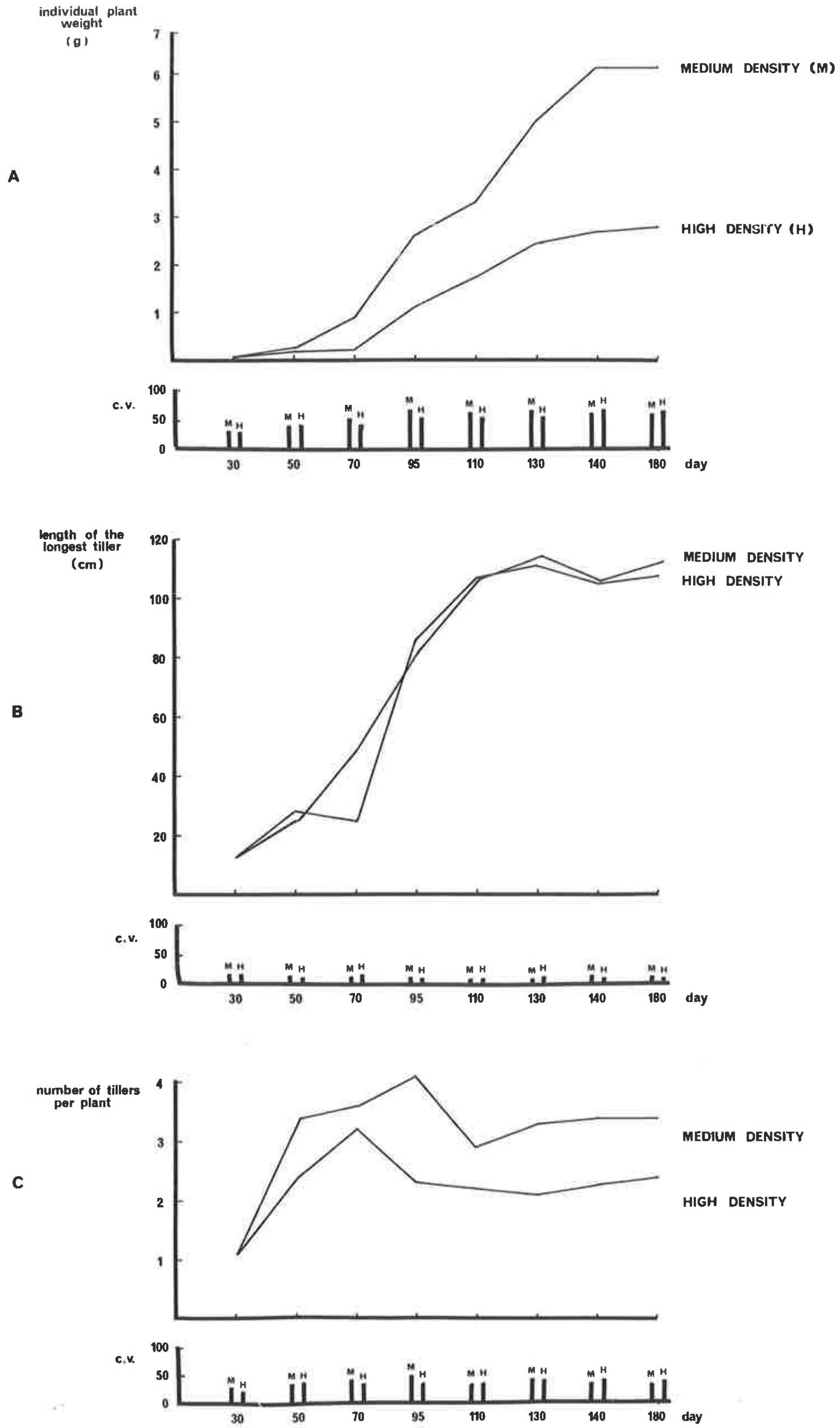


FIG.41: INDIVIDUAL PLANT WEIGHT (A), LENGTH OF THE LONGEST TILLER(B) AND NUMBER OF TILLERS PER PLANT(C) OF WHEAT AT DIFFERENT STAGES OF GROWTH.

general differences between densities were not significant.

The number of tillers per plant increased rapidly with time in the first stages of growth (from day 30 to day 70 at high density, and from day 30 to day 95 at medium density) then decreased, levelling off at the last growth stages (approximately after jointing stage).

The effect of density on the coefficient of variation was not consistent, but in most cases it was greater at medium density. The coefficient of variation of plant weight tended to increase with time, while the coefficient of variation of length of the longest tiller and number of tillers per plant were relatively constant during all stages of growth.

For harvests 2-7, sub-samples of a tenth of the number of plants within the quadrats (plant number 10, number 20, number 30...etc.) were taken to measure the green area of each plant (leaf area plus green stem area for harvests 2-5, and also green ear area for harvests 6 and 7. The results are presented in Table 27. Green area per plant increased with time in the earlier stages of growth, reached a maximum at day 95 in medium density (late tillering stage) and at day 110 in high density (jointing stage), and then decreased. Density effects were marked at day 70 (advanced tillering stage), from then on the plant green area at medium density approximately doubled the plant green area at high density. This is also clearly reflected on the individual plant weight (see Figure 41A). There was a tendency for the variability of individual plant green area, as expressed by the coefficient of variation, to increase with time and this tendency was stronger at medium density.

Table 27: Individual plant green area (leaf area + green stem area in harvests 1 to 5 together with green ear area in harvests 6 and 7) of wheat at different stages of growth.

	At high density			At medium density		
	Number of plants	Mean	C.V. %	Number of plants	Mean	C.V. %
At day 50 (harvest 2)	48	53.0[1]	41.9	40	55.8	35.7
At day 70 (harvest 3)	48	128.1	49.5	37	243.2	44.9
At day 95 (harvest 4)	50	141.0	51.5	29	352.4	57.5
At day 110 (harvest 5)	43	208.1	49.1	47	351.7	55.8
At day 130 (harvest 6)	45	155.5	49.1	39	300.6	56.8
At day 140 (harvest 7)	45	110.0	57.3	35	233.7	66.7

1 Non-significant difference between treatments in harvest 2 (day 50) and highly significant difference in all the following harvests.

At harvest 8 (day 180) recordings were also made on the number of spikelets, number of grains and grain weight per plant, and the results are shown in Table 28. The mean values were affected strongly by density, at medium density they almost doubled the mean values at high density. Variability of these characters seems not to be strongly affected by density in this experiment.

9.2.2 Results from the permanent quadrats

Repeated measurements on the same plants were done at days 43, 82 and 140, except that as explained earlier, data from the high density plot at day 82 was not available. The quadrats were harvested at day 140 (dough stage).

At day 43 the mean plant weight and length of longest tiller was greater at high density, but at day 140 the mean plant weight was definitely greater at medium density, while the difference of the length of longest tiller seems to be insignificant (Table 29). There was no significant difference between tiller number per plant at high and medium density at day 43, but at day 140 the mean tiller number per plant was 2.3 at high density while at medium density it was 3.4. The variability length of the longest tiller was consistently greater at medium density, while the variability of plant weight and number of tillers per plant changed with time, i.e. at day 43 it was greater at medium density and the reverse was found at day 140.

Table 28: Variability of number of spikelets, number of grains and grain weight per plant of wheat at harvest 8 (day 180).

	Maximum*	Mean	C.V.(%)
Number of spikelets at:			
high density	52	15.86	55.5
medium density	96	30.03	55.5
Number of grains at:			
high density	146	30.98	71.4
medium density	203	57.46	67.7
Grain weight at:			
high density	4.98	0.864	78.6
medium density	6.07	1.511	73.1

* In all instances the minimum value was zero, since some plants produced no ears.

Table 29: Measurements in the permanent quadrat of wheat

	Day 43		Day 82[1]		Day 140	
	Mean	C.V.(%)	Mean	C.V.(%)	Mean	C.V.(%)
Plant weight[2]:						
Medium density	0.15	40.0	2.80	38.9	6.13	61.0
High density	0.21	28.6	-	-	2.66	68.8
Plant height (length of longest tiller):						
Medium density	18.1	19.1	68.1	11.5	105.9	17.3
High density	25.7	14.6	-	-	104.9	13.2
Tiller number per plant:						
Medium density	3.1	34.0	3.5	45.3	3.4	36.0
High density	2.8	31.0	-	-	2.3	40.0

1. At day 82 measurement cannot be made on high density without disturbing plant micro-environment.

2. Plant weight at day 43 and 82 was estimated by the 'matching tiller' method and 'plant cylinder' method respectively.

10. The effect of neighbours

10.1 Weight distribution charts

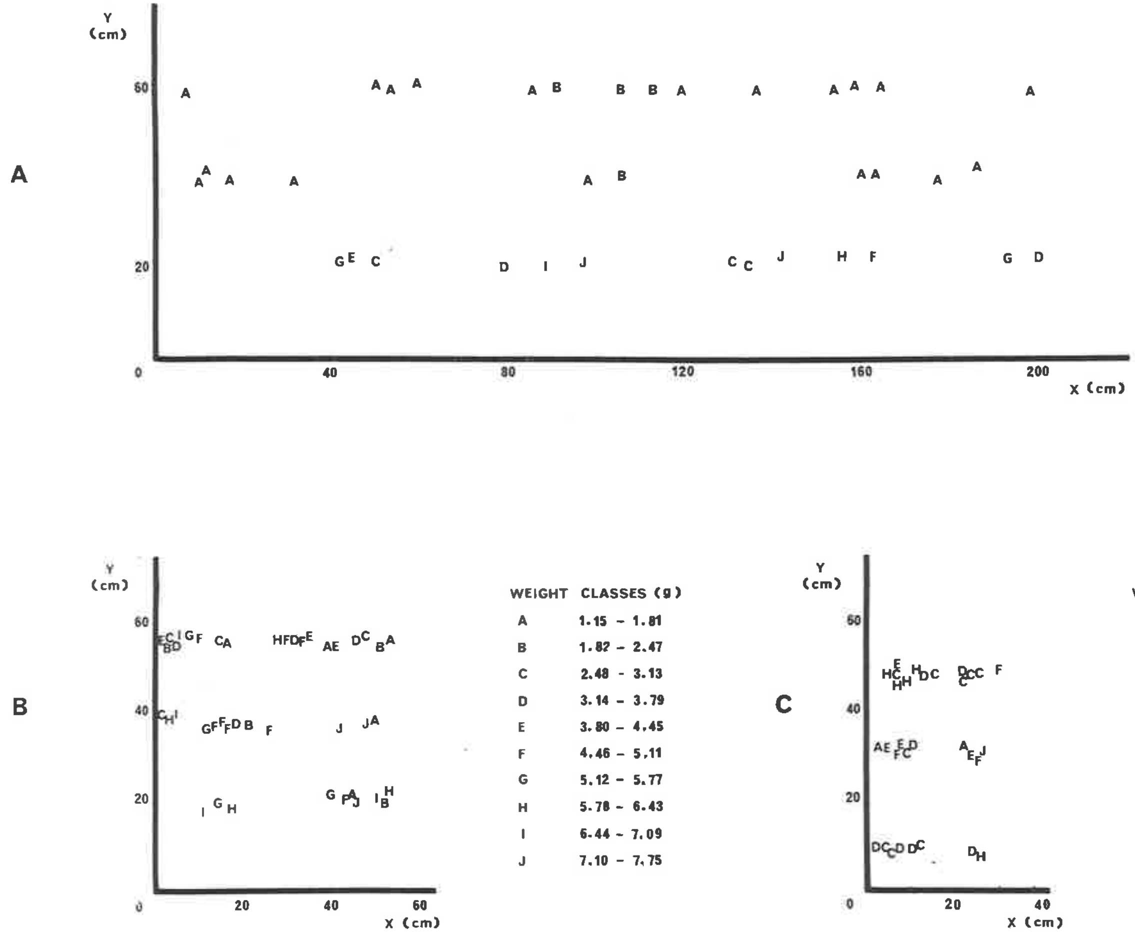
In both Experiment 1 and Experiment 2 the positions of all plants within the quadrats were recorded by measuring their coordinates from common base lines, X- and Y-axes. Plant weights within each quadrat were grouped into 10 weight classes and given a symbol for each class: A, B, C, D, E, F, G, H, I or J from the smallest (A) to the greatest (J) weight class.

In Figures 42 to 46 the weight class of each plant is plotted on its actual position. From Experiment 1, only one quadrat from each treatment is presented (Figures 42 and 43), while from Experiment 2 results from harvests 6, 7 and 8 at both densities are given (Figures 44 to 46).

By visual examination of weight classes of plants in their actual positions, the general effect of neighbours was rather hard to detect. As expected, there were cases where the isolated individuals became larger plants, but to a surprising degree, there were also cases where isolated individuals were smaller plants. No consistent pattern was apparent between density of aggregates of individual plants within the community and individual plant weight. In the following section the effect of neighbours on individual plant weight will be examined more closely.

10.2 Analysis on the effect of neighbours

As mentioned earlier, the effect of neighbours on each plant is basically believed to be a function of distance and size of neighbouring plants. This effect which puts a certain pressure for



A — WEIGHT CLASSES (g)

A	0.08 – 2.12
B	2.13 – 4.15
C	4.16 – 6.19
D	6.20 – 8.23
E	8.24 – 10.26
F	10.27 – 12.30
G	12.31 – 14.34
H	14.35 – 16.38
I	16.39 – 18.41
J	18.42 – 20.45

B — WEIGHT CLASSES (g)

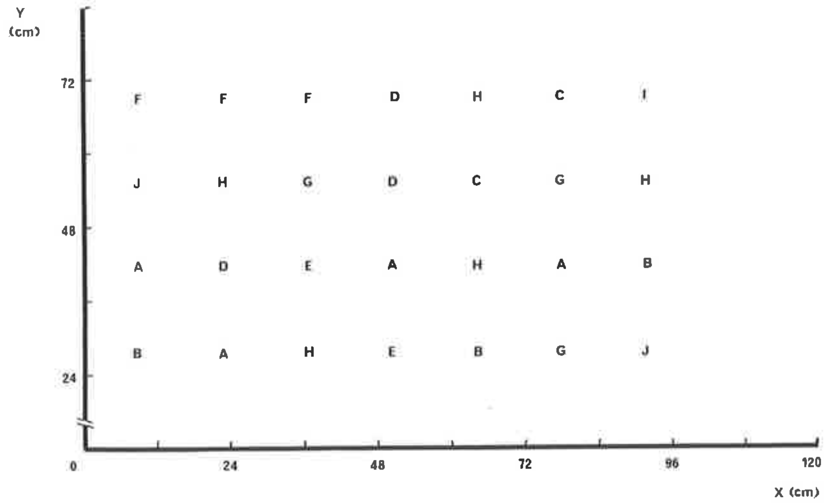
A	1.15 – 1.81
B	1.82 – 2.47
C	2.48 – 3.13
D	3.14 – 3.79
E	3.80 – 4.45
F	4.46 – 5.11
G	5.12 – 5.77
H	5.78 – 6.43
I	6.44 – 7.09
J	7.10 – 7.75

C — WEIGHT CLASSES (g)

A	0.82 – 1.24
B	1.25 – 1.67
C	1.68 – 2.09
D	2.10 – 2.51
E	2.52 – 2.93
F	2.94 – 3.35
G	3.36 – 3.77
H	3.78 – 4.19
I	4.20 – 4.61
J	4.62 – 5.03

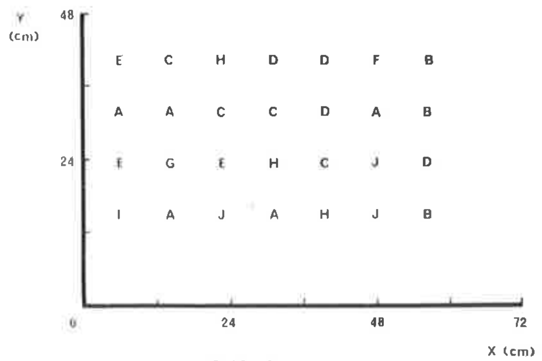
FIG. 42: ACTUAL POSITIONS AND WEIGHT CLASSES OF EACH INDIVIDUAL PLANT WITHIN ONE QUADRAT OF DRILLED PLOTS. A: LOW, B: MEDIUM, C: HIGH DENSITY.

A



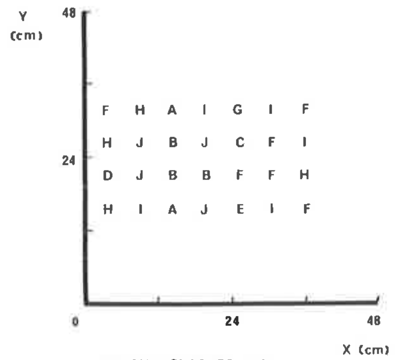
WEIGHT CLASSES (g)	
A	2·97 – 4·78
B	4·79 – 6·58
C	6·59 – 8·39
D	8·40 – 10·19
E	10·20 – 12·0
F	12·1 – 13·81
G	13·82 – 15·61
H	15·62 – 17·42
I	17·43 – 19·23
J	19·24 – 21·03

B



WEIGHT CLASSES (g)	
A	1.63 – 2.14
B	2.15 – 2.66
C	2.67 – 3.18
D	3.19 – 3.69
E	3.70 – 4.21
F	4.22 – 4.73
G	4.74 – 5.24
H	5.25 – 5.76
I	5.77 – 6.28
J	6.29 – 6.79

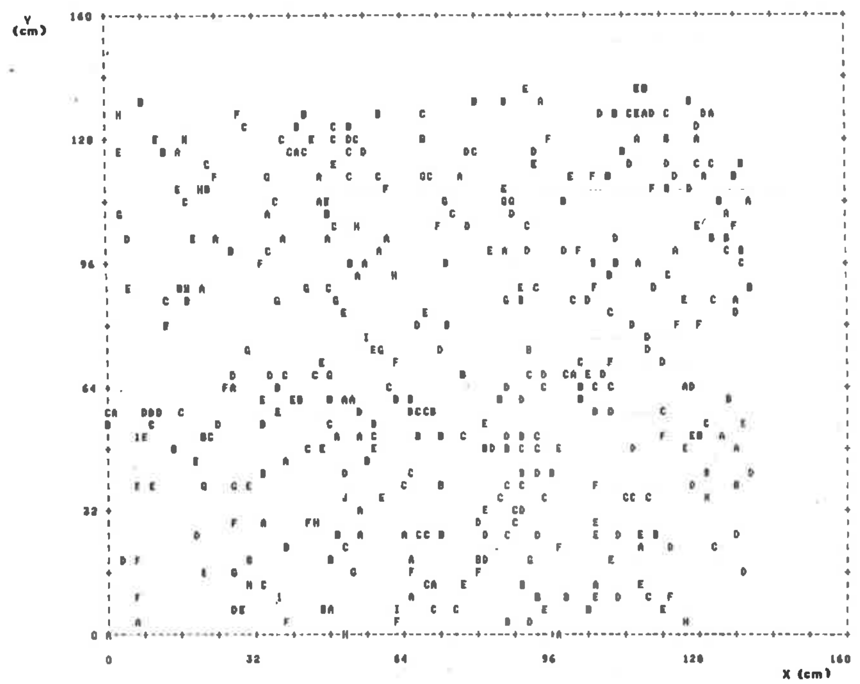
C



WEIGHT CLASSES (g)	
A	0.53 – 0,77
B	0.78 – 1.01
C	1.02 – 1.26
D	1.27 – 1.50
E	1.51 – 1.74
F	1.75 – 1.98
G	1.99 – 2.22
H	2.23 – 2.47
I	2.48 – 2.71
J	2.72 – 2.95

FIG. 43: ACTUAL POSITIONS AND WEIGHT CLASSES OF EACH INDIVIDUAL PLANT WITHIN ONE QUADRAT OF SQUARE PLANTED PLOTS. A: LOW, B: MEDIUM, C: HIGH DENSITY.

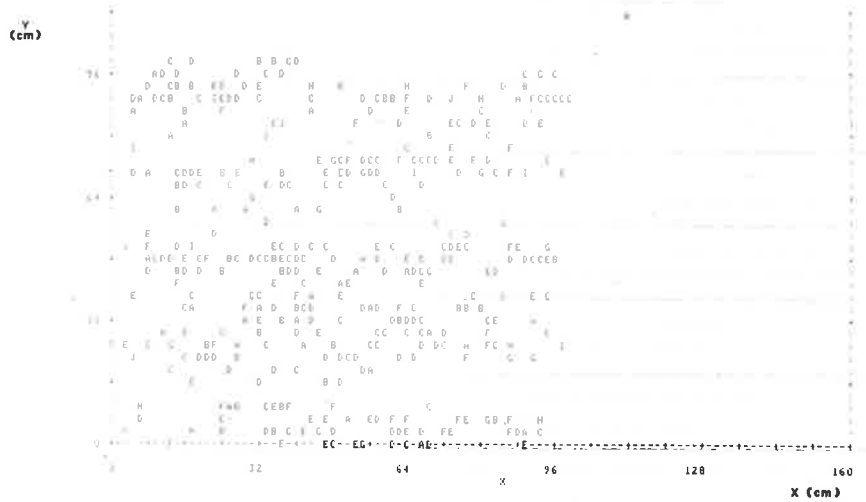
A



WEIGHT CLASSES (g)

A	0	– 1·67
B	1·68	– 3·35
C	3·36	– 5·02
D	5·03	– 6·70
E	6·71	– 8·37
F	8·3	– 10·05
G	10·06	– 11·72
H	11·73	– 13·40
I	13·41	– 15·07
J	15·08	– 16·74

B

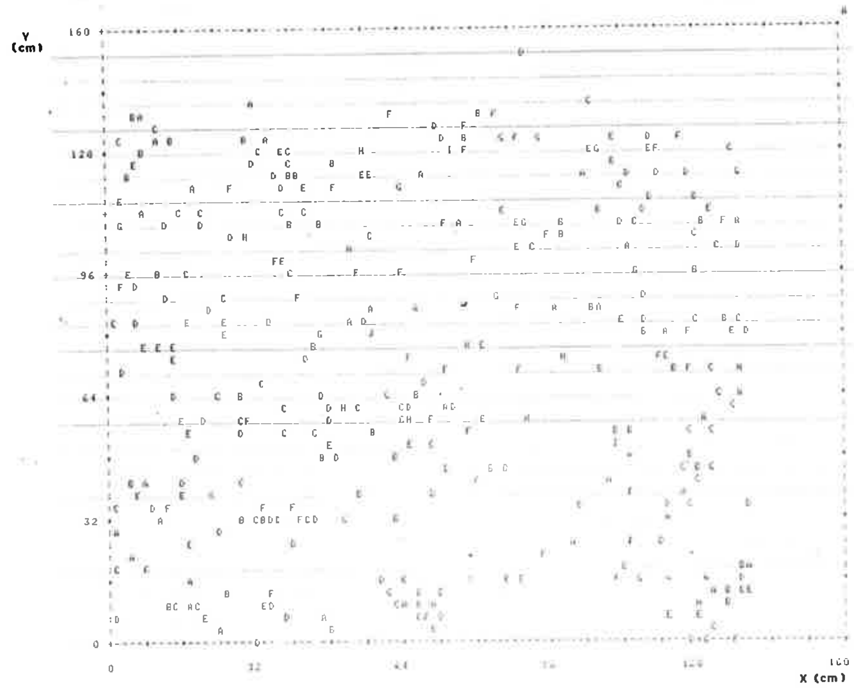


WEIGHT CLASSES (g)

A	0	– 0·75
B	0·76	– 1·50
C	1·51	– 2·25
D	2·26	– 3·00
E	3·01	– 3·75
F	3·76	– 4·50
G	4·51	– 5·25
H	5·26	– 6·00
I	6·01	– 6·75
J	6·76	– 7·50

FIG. 44: ACTUAL POSITIONS AND WEIGHT CLASSES OF EACH INDIVIDUAL PLANT WITHIN ONE QUADRAT OF HARVEST 6 (DAY 130). A: MEDIUM, B: HIGH DENSITY.

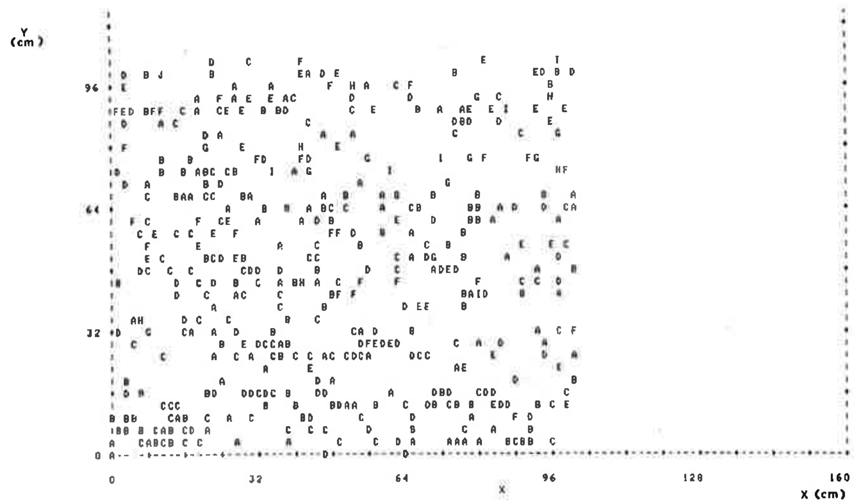
A



WEIGHT CLASSES (g)

A	0	– 1.93
B	1.94	– 3.86
C	3.87	– 5.79
D	5.80	– 7.72
E	7.73	– 9.65
F	9.66	– 11.58
G	11.59	– 13.51
H	13.52	– 15.44
I	15.45	– 17.37
J	17.38	– 19.30

B



WEIGHT CLASSES (g)

A	0	– 1.00
B	1.01	– 2.00
C	2.01	– 3.01
D	3.02	– 4.01
E	4.02	– 5.01
F	5.02	– 6.02
G	6.03	– 7.02
H	7.03	– 8.02
I	8.03	– 9.03
J	9.04	– 10.03

FIG.45: ACTUAL POSITIONS AND WEIGHT CLASSES OF EACH INDIVIDUAL PLANT WITHIN ONE QUADRAT OF HARVEST 7 (DAY 140). A : MEDIUM, B : HIGH DENSITY.

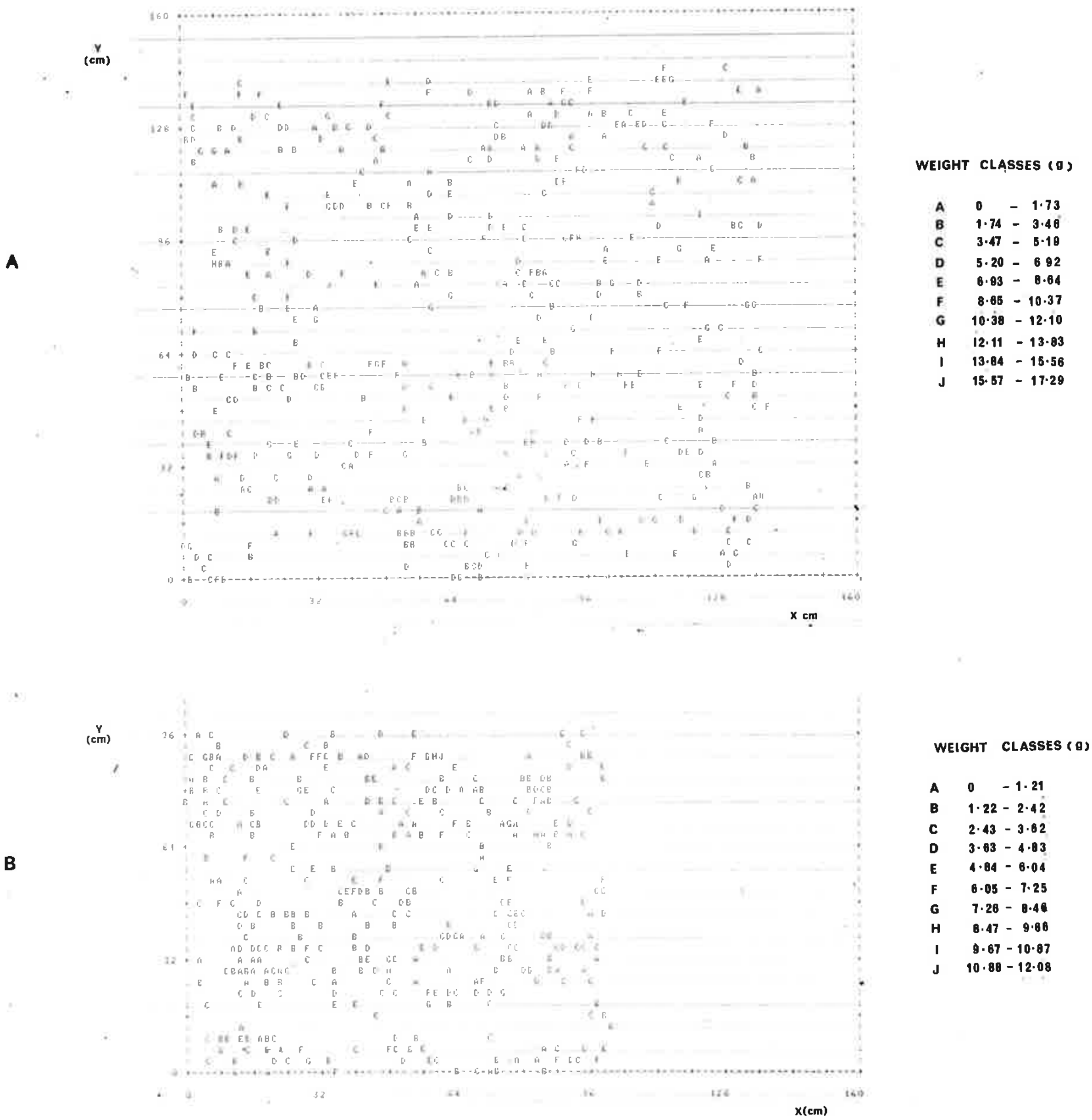


FIG. 46: ACTUAL POSITIONS AND WEIGHT CLASSES OF EACH INDIVIDUAL PLANT WITHIN ONE QUADRAT OF HARVEST 8 (DAY 180). A: MEDIUM, B: HIGH DENSITY.

resources on each plant is called the 'competitive pressure' (z). Since the competitive pressure is a compound effect of all neighbours within certain range, it can be expressed in the form of:

$$z = \Sigma_i \frac{w_{n_i}}{d_{n_i}^{\theta}} \qquad (1)$$

where $w_{n_1}, w_{n_2}, \ldots\ldots w_{n_i}$ are weights of neighbours, and

$d_{n_1}, d_{n_2}, \ldots\ldots d_{n_i}$ are distances of corresponding neighbours,

and θ is a constant. The reason for using a constant as a power of the distance is that distance is not believed to be linearly related to competitive pressure, e.g. if a neighbour at distance p has a contributory effect to the competition pressure q, then if the distance is increased to 2p, the effect may be less than q/2, i.e. $\theta > 1$.

The influence of neighbours around the 'test plant' or 'centre plant' is considered in this equation by putting in the sum of weight of neighbours. If the neighbours are clustered then the total weight of neighbours tends to be smaller, due to stronger competition among themselves, than if they were evenly distributed. This means that the competitive pressure on the test plant is also smaller than if the neighbours are scattered evenly around the centre plant.

The critical point in the competitive pressure equation is to determine the number of neighbours (n_i) which have an effect on a particular plant (test plant or centre plant). A possible solution is by arbitrarily choosing the 'range of influence' of a plant, e.g. 2, 5 or 10 cm radius. All neighbours within this range will be included in the calculation.

In determining the relationship between weight of the 'centre plant' (w) and the competitive pressure (z), the most suitable procedure seemed to be by modification of the reciprocal relationship of Shinozaki and Kira (1956) by replacing factor density (ρ) by the competitive pressure (z). The equation then becomes:

$$\frac{1}{w} = \alpha + \beta z \qquad (2)$$

where α and β are constants. The competitive pressure, z, is considered as better than density since it also incorporates the distance of neighbours from the 'centre plant'. This relationship can be fitted by minimising

$$\Sigma \; [\log w + \log(\alpha + \beta z)]^2 \qquad (3)$$

with respect to α, β and θ.

This analysis was first tried on the data from Experiment 1. It was found that the number of plants available within each quadrat was too small and that there were not enough 'centre plants' with surrounding neighbours within the quadrat for testing and fitting the relationships. In Experiment 2, there were hundreds of individuals in each quadrat which could be used as 'centre plants' with known neighbours.

There are two main steps involved in the analysis. First, the estimation of the values of α and β with a certain value of θ (at first inserted as $\theta = 2$), and then fitting the relationship by minimising by iterative steps (3).

Results of these analyses on harvest 1 (day 30), harvest 6 (day 130) and harvest 8 (day 180) of Experiment 2 are presented in Table 30. In general the results indicate an extremely low value of β in comparison to α. This means that the effect of local density on individual plant size is relatively very small in comparison with the effect of community density. This was also tested by looking at the correlation between the size of individual plants and the number of neighbours within certain range. Again there was no correlation.

Table 30: The values of α, β and θ which fit the data in equations: (1) $z = \Sigma_i \frac{w_{n_i}}{d_{n_i}^{\theta}}$ and (2) $\frac{1}{w} = \alpha + \beta z$.

Harvest	Treatment	Range* (cm)	α	β	θ
1	Medium density	10	33.225	0.000	0.781
6	Medium density	10	0.213	0.003	0.571
	Medium density	5	0.249	0.002	0.670
	High density	5	0.527	0.000	1.524
	High density	2	0.524	0.000	1.763
8	Medium density	10	0.244	0.000016	6.979
	Medium density	5	0.248	0.000006	7.762

* Radius of circle around the individual test plants within which all plants are regarded as neighbours of the test plant in Equation (1).

FINAL DISCUSSION AND CONCLUSIONS

These studies were made with the realization that knowledge of individual plant performance within crop communities, especially in cereals, is still inadequate. The main objectives of the studies reported in this thesis were:

(i) to add to our knowledge on the ecology of individual plants within a crop community, e.g. the effect of date of seedling emergence on the performance of individual plants, or the effect of density and plant arrangement on ear emergence;

(ii) to re-examine some of the phenomena reported in earlier studies on individual plant performance, e.g. the nature of the frequency distributions of individual plant weight and other plant characters, the presence of dominance and suppressed individuals within a crop community, and the role they play in contributing to the total crop yield;

(iii) to examine the mutual effects of neighbours.

Several aspects of the results have already been discussed fully, e.g. the methods of weight estimation, and no further discussion of these is considered necessary.

In the first experiment, carried out in 1972, two plant arrangements (square planted, or drilled rows) were used with three densities, but due to the lateness of the season the barley variety Clipper was used instead of wheat. The second field experiment carried out in 1973 was especially intended to look at the effect of neighbours as well as to complement the first experiment, and was based on random spacing. The wheat variety Halberd was used in this experiment. There were many interesting results obtained and some of them warrant further discussion.

1. The effect of date of seedling emergence on plant performance in the field.

Most of the work examining this subject has been done in a more uniform soil environment and this stimulated curiosity to know how those findings would apply under field conditions. In controlled environments, time of seedling emergence has a strong effect on plant performance. In subterranean clover with a population density of 4400 plants/m^2, a delay of five days in emergence was sufficient to induce in most cases 50% reduction in final weight of the late plants (Black and Wilkinson, 1963). Earlier work by Black (1956) indicated that different depths of sowing, leading to different times of emergence, could effect the early vegetative growth of subterranean clover plants.

In certain environments, especially at high density with plants which are sensitive to shading, the earlier emerged seedlings could easily dominate the neighbours, yet the significance in agricultural production of this effect of a slight advantage of one plant over another is not fully explored.

In a field environment many factors, e.g. different depths of sowing, the formation of hard crust of top soil layer on local sites due to heavy rain followed by a dry period (a common occurrence on some types of soil like the red brown earth at the Waite Institute), local dryness or water logging, and also other factors inherent within the seeds including genetical factors, could lead to different times of seedling emergence. In experiment 1, depth of sowing was probably a principal contributor to the differences in time of seedling emergence from 2 to 7 days within each treatment.

In correlating the date of seedling emergence and individual plant weight at days 70 and 90, both significantly negative and significantly positive correlations were obtained, but mainly the former with a clear tendency for the earlier emerged plants to remain larger. The irregularity of the results was probably due to the fact that in the field environment there are many factors which could either strengthen or weaken the effect of time of seedling emergence. Proximity of neighbours, favourability of local environment for early vegetative growth, and to a certain extent genetical factors, could either reduce or enhance the advantage of early emerging seedlings.

In this study it was found that in 30 quadrats examined at day 70, 25 showed negative correlation of dry weight with the day of emergence. Of those that were significantly negative, the regression indicated that a plant emerging on the first day of emergence would have a strong competitive advantage over that emerging several days later, and the advantage was far stronger at low density, i.e. 550 mg, 261 mg and 155 mg respectively at low, medium and high density (advantage in plant weight at day 70 per day earlier in emergence). A question which then arises is whether there is any compensating effect, i.e. whether the higher dry weight of the larger plants which emerged earlier compensated for the lower dry weights of smaller plants which emerged later. In other words, was the total yield the same as if the plants had all emerged on the same day? This is probably so if the results obtained in many experiments with species mixtures apply also to individual plants in pure cultures.

2. Plant dominance

The phenomenon of dominant and suppressed plants within a crop community is clearly demonstrated in this study. In the square planted barley plots, the degree of plant dominance indicated by the difference between relative growth rate (R-G-R) of the largest plants (top decile group) and the smallest plants (bottom decile group), was influenced by density. As was illustrated in the right hand section of Figure 25, plant dominance in the square planted plots decreased with increasing density. The probable explanation is that in the square planted crop communities, plant interaction started earlier at high density than at lower density, with a consequence that absolute size discrepancies had not become as great as in the lower density. From then on there was less chance for the larger plants to dominate their smaller neighbours because they themselves suffered a depressing effect from their other neighbours. In the lower density by the time plant interaction started, the greater size discrepancy between individuals allowed the larger plants to continue to suppress their neighbours without suffering too much from the general level of competition. This is possibly the first account of the phenomenon of plant dominance being influenced by density in a field crop situation, and it may have some significance in plant breeding practice. For example, in segregating populations, the more competitive plants are likely to gain progressively greater dominance over their neighbours, and this might contribute to misleading evaluation of genotypes.

In the drilled plots the effect of density on plant dominance was not very conspicuous, and this could be due to the fact that in the drilled crop community the irregularity of spacing within the row, which could increase considerably the size discrepancy, was offset by the presence of more space between the rows. In other words the more closely clustered plants within the rows all had access to the resources between the rows, with a final result of lesser size discrepancies in comparison to the square planted community. In the drilled low density community the result was not convincing due to virus disease incidence ('barley yellow dwarf'), but based upon the trend in the high and medium density, the degree of dominance (Figure 25) was not strongly influenced by density.

The dates of examination of the randomly spaced plant communities of wheat in experiment 2 were separated by too great an interval (days 43-82-140) to make a satisfactory R-G-R analysis. Instead, the absolute and relative increases of plant weight were examined. Greater absolute increase in weight by larger plants could be used as an indicator for plant dominance, but a more stringent test is by examining the weight increase relative to its weight in the first observation.

Based upon the relative increase in plant weight the degree of plant dominance (expressed as the difference between the relative increase in plant weight between the top decile group and bottom decile group) in a randomly spaced crop community of wheat appear to be higher at higher density, but the fact that mean plant weight at day 43 was greater at high density (0.100 g) than at medium density (0.043 g) has to be considered. If the result obtained at medium density is considered anomalous, and the calculation of the relative increase in plant weight based upon the same mean plant weight for medium and high density (e.g. using a mean weight of 0.100 g for day 43), then the degree of dominance at medium density was stronger than at high density.

Apparently the degree of plant dominance within a crop community is determined by mean discrepancies of plants and mean plant distances; and the mean discrepancies of plant weights in turn appear to be a function of plant arrangement (increasing with increasing irregularity) and density, governing the time before plant interaction starts.

3. Frequency distribution of individual plant weight and other plant characters.

3.1 Individual plant weight.

The three types of plant arrangement used, i.e. square planted and drilled in experiment 1, and randomly spaced in experiment 2, had an increasing degree of irregularity. The overall picture of the degree of skewness of the frequency distribution of plant weight for time of sampling and plant arrangement are:

	Significantly negative	Normal (Non-significantly negative or positive)	Significantly positive
Square planted			
day 70	0	3/3*	0
day 90	2/3	1/3	0
Drilled			
day 70	0	2/3	1/3
day 90	0	1/3	2/3
Random spacing			
day 43	0	2/2	0
day 82	0	0	1/1
day 140	0	0	2/2

(* Right hand figure of pair is number of samples examined; left hand figure is number of samples designated by heading of column.)

All the results point to the fact that irregularity of plant spacing had a stronger influence on the skewness than density. Increasing density tended to shift the degree of skewness from negative to normal (non-significantly negative or non-significantly positive), or from normal to positive, and this last mentioned phenomenon conforms with the results obtained by Koyama and Kira (1956) and Obeid *et al.*

(1967). Time had the tendency to move the skewness from non-significant to significant, either to the negative side as in the equidistant spacing (square planted), or to the positive side as in the row (drilled) and random spacing, and these results are also in accord with the results from earlier workers.

Most of the earlier work in this field gave no numberical values on the degree of skewness of the frequency distribution of plant weight which makes comparison difficult. The conclusions drawn by Koyama and Kira (1956) were mainly based on right triangular or right rectangular arrangement and linear spacing. The importance of obtaining 100% establishment may be overlooked, and in regular spacing this is the crucial factor determining the irregularity of plant arrangement. One or two missing plants could change the arrangement from regular to irregular. Possibly the inconsistent trend in the results from the right triangular arrangement and linear spacing was due to different percentages of establishment.

As indicated earlier irregularity of plant spacing has a stronger influence on the skewness than does density. In regular spacing, increasing density reduces the mean values, but the frequency distribution of the values is still similar, i.e. close to normal. In irregular spacing, increasing density again reduces the mean values, while the frequency distribution itself is at least as skewed as in the low density.

3.2 Plant height (length of the longest tiller) and number of tillers per plant.

The skewness of the frequency distributions of plant height (length of the longest tiller) was consistently negative, which means that most of the plants tended to grow almost as tall as the tallest plant, and neither plant arrangement nor density changed this pattern. This indicated that in cereals in general and specifically in barley and wheat, elongation growth is more consistent than other main plant characters like total weight or number of tillers per plant. In isolation plants utilize solar radiation more effectively by forming more leaves and tillers, but the length of tillers is still not far different from those in high density environments.

Under population pressure plants tend to extend themselves vertically as a reaction against the pressure of competition for light. Due to lack of light, a shorter plant under population pressure can hardly survive, unless it extends to reach the top of the canopy. This will eliminate the possibility of obtaining very small values for length of the longest tiller.

The skewness of the frequency distributions of tiller number per plant were almost consistently positive. Tiller number per plant has usually a strong correlation with plant weight, and it is not surprising that the pattern of frequency distribution is also similar.

4. Ear emergence

Apparently the pattern of ear emergence was mainly influenced by plant density, i.e. at high density most of the ear emerged earlier. At high density each plant has fewer tillers than at lower densities (see Table 15 of the appendix) and approximately 50% of the tillers observed were main stems and first tillers. According to Cannel (1969) ears of the main stem and first tiller of barley plant emerge earlier, so that the reason that most of the ears at high density emerge earlier is that most of them probably were main stems and first tillers.

At low density, the number of tillers per plant in both drilled and square planted plots was much higher, i.e. 11.2 and 13.6 respectively compared with 3.9 and 4.0 for high density. Main stems and first tillers formed relatively smaller portions (approximately 18% and 15% respectively) of the total tillers at low density, and this is probably the reason for the more even spread of ear emergence.

The effect of density on ear emergence obtained in this study is rather similar to the findings in dwarf French bean, i.e. at low density flowering continued for several weeks while at high density the flowering was compressed into 7-10 days. However, in this study of barley, at high density even though there was a strong concentration of ear emergence in the third, fourth and fifth days of the 10 day period, the period of ear emergence was not compressed into a shorter time.

5. Light penetration.

The main feature examined in this study was the variability of light penetration as affected by plant density and arrangement. In experiment 1 light penetration was examined at day 39 and 88 adjacent to each individual plant, but at day 88 due to lodging measurement could only be done at low and medium densities of the drilled plots, and at low density of the square planted plot. In experiment 2 there were too many plants for individual measurements and light measurements were done at ten locations within each quadrat at day 92, 110 and 130.

In the square planted plots of experiment 1, light interception at day 39 was more efficient than in the drilled plots. Greater light interception and more uniform supply of light to each plant undoubtedly indicates the reason for higher yields with square planting when water and nutrients are non-limiting.

Variation in light pattern at day 39 can be viewed both as a reflection of unequal growth of plants (due for example to day of seedling emergence) and as a factor influencing subsequent differences in growth.

6. Means and variability of plant characters.

6.1 Experiment 1.

Length of the longest tiller was the only value increased with increasing density, and the probable reason for this has been discussed earlier in reviewing its frequency distribution. All other characters examined had the general trend of decreasing with increasing density, and this is a well established phenomenon which needs no further discussion.

The effect of plant arrangement (square planted *vs* drilled) was clear cut at low and medium density, with an advantage of square planted over drilled. This is probably due to the more efficient light interception in the square planted plots. At high density due to a very intense competition between individuals, the way the plants were arranged made no difference. The last mentioned phenomenon might have some implication in crop production, i.e. with the progressive trend to higher crop densities, plant arrangement may matter less.

At low and medium densities variability of plant characters generally was greater in the drilled plots. This is probably due to greater size discrepancies between individuals caused by a higher degree of irregularity in spacing. One of the factors which undoubtedly played an important role in determining size discrepancies was light. The variability of light penetration adjacent to each individual plant at day 39 was higher in the drilled plots than in the square planted plots. At high density the reverse situation was found, i.e. the variability was generally greater in the square planted plots. Apparently the very intense competition between plants within the row did not allow size discrepancies to develop to a greater extent.

6.2 Experiment 2.

In this experiment both repeated measurements on the same plants in one quadrat and sequential harvests on other quadrats were done.

Means of individual plant weight, length of the longest tiller and number of tillers per plant recorded in the eight sequential harvests, followed the expected pattern as was illustrated in Figure 41.

The effect of density on mean green stem area per plant was not significant between densities at day 50 but from then on it became highly significant, which indicated that up to day 50 competition for light was not yet operating, and only gradually intensified afterwards. At day 70 the plant green area at medium density was already approximately double that at high density, and maintained that ratio until the last measurement at day 140.

The effect of density on number of spikelets, number of grains and grain weight per plant followed closely the yield-density relationship, i.e. by doubling the density, the values for spikelet and grain number were reduced to approximately half.

7. The effect of neighbours.

Many accounts have already been made on the relationship between plant density and crop yield, and a review on this was made by Wiley and Heath (1969). As mentioned earlier, few workers based their consideration on the performance of the individual plant, e.g. Mitscherlich (1919, quoted from Wiley and Heath, 1969) and Shinozaki and Kira (1955), and even then they assumed equal growth by all plants.

Other workers looked at crop performance by examining the effect of neighbours on the performance of individual plants. These works gave a strong background for this study.

Hozumi *et al.* (1955) and Yoda *et al.* (1957) confirmed that plant interaction may extend beyond the nearest neighbours, but their studies were only concerned with interaction in a single direction, i.e. along a row. The question which then arises is, that in knowing that plant interaction is not limited to a single direction but occurs between each plant and all its surrounding plants, how to examine this 'multiple direction' interaction. Mead (1966 and 1968) studied the multiple direction interaction between plants and their neighbours by polygon analysis for a random arrangement, and by correlating a plant's weight with the mean weight of its neighbours for a regular hexagonal arrangement. In both instances the analysis took account only of the effect of the nearest surrounding neighbours. Surprisingly the first analysis, which looked very attractive, accounted for only 20% (largest mean proportion) of the variation in plant yield attributable to polygon variation. In his second analysis Mead obtained inconsistent results and suggested that they were due to the fact that the model only calculated the degree of competition between a plant and its six neighbours. This reasoning probably could be applied to the first type of analysis (polygon analysis) as well.

The next logical step is to try to examine the interaction between each plant and all its surrounding neighbours within a certain range. In this context the concept of 'range of interaction' or 'range of influence' is introduced. Each plant within a crop community has an area, assumed circular, within which all plants have influence on the 'centre plant'. The radius of the circular area is the range of interaction. The sum of influence of each neighbour within the range is called 'competitive pressure' which is expressed in equation (1) (page 160), and the relation between competitive pressure and weight of each individual plant is stated in a reciprocal equation modified from Shinozaki and Kira (1956),

$$\text{i.e.} \qquad 1/w = \alpha + \beta z$$

$$\text{where} \qquad z = \Sigma \frac{w_{n_i}}{d^{\theta}_{n_i}} .$$

The most important result obtained in this experiment was that using different ranges of interaction (i.e. distance within which plants are classed as neighbours), the first constant (α) in equation (2) was invariably much greater than the second constant (β). This indicates that average weight-density relationships for the crop communities are apparently not applicable for aggregates of individual plants within the community. If the value of β is relatively very small in comparison with α then the product of β and z is also very small, and will not influence the value of $1/w$. This obviously implies that the effect of neighbours within certain range is dominated or concealed by the general community performance. This result is similar to the consideration by Pielou (1962) in using plant to neighbour distances for the detection of competition. He pointed out that the distribution of inter-neighbour distances will differ in a random population compared with a population where there are aggregates of plants within which competition is particularly intense. In a way this discrepancy could be ascribed to the effect of competition. But unless certain precautions are taken, i.e. by excluding the very high variates (excluding very distant plants) and only including the small variates above certain minimum value (excluding very near to the centre plants), there might be no observable discrepancy. The sample with extreme values excluded is termed a truncated sample even though failure to observe the discrepancy does not imply that competition is not occurring.

A suggestion that could be given for future work to detect the effect of competitive pressure by surrounding neighbours within a certain range on individual plant weight is to eliminate the effect of community performance by using an isolated aggregate. For example, by planting isolated groups of plants with a varying number of plants within a certain range from the centre plant, the patterns of distribution around the centre plant also varied. To a limited extent this sort of work had been done by Sakai (1957) in examining the characters of central plants surrounded by 1 to 6 competing plants of another cultivar with stronger competitive ability. He only used one pattern of plant arrangement (hexagonal), and the different competitive pressure exerted by the surrounding neighbours is due to the different numbers of plants with stronger competitive ability around the centre plant.

Another point which needs closer attention is that under field conditions, there are many other factors beside distance of surrounding neighbours which may have a strong influence on the size of the individual plant. This point can be illustrated by comparing the variability (coefficient of variation) of individual plant weight in the square planted plots and drilled plots of experiment 1 (from Table 15 of the appendix) as follows:

		C.V. (%) of individual plant weight			
		low density	medium density	high density	mean
day 70 :	square planted*	27	23	23	24
	drilled	34	39	22	32
day 90 :	square planted	44	39	40	41
	drilled	57	60	45	54

(* Disposition of neighbours is constant in square planting)

At day 70 the variability of individual plant weight which could be ascribed to the irregularity of neighbour distances was the difference between mean C.V. in square planted (24%) and drilled plots (32%). At day 90 the consequent figures were 41% and 54%. This in fact points out that the variability due to factors other than distances of neighbours is much stronger than that due to neighbours. Factors which could play an important role among others are date of seedling emergence as indicated earlier in this study, and local difference in physical and chemical environments. Under irregular spacing, in the southern hemisphere, the concentration of neighbours on the northern side of the test plant could have more detrimental effect than on the south. To examine the effect of neighbours these factors should be accounted for, either by adding more parameters in the relationship, one for each of those factors, or by reducing the effect of those factors to a minimum by making the study under more controlled environments.

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APPENDIX

Table 1 : Meteorological data of the Waite Agricultural Research Institute - 1972

Month	Mean daily air temperature (°C) Max.	Min.	Ave.	Rainfall (mm)	Evaporation (mm)	Hours of bright sun-shine per day	Solar radiation Meg.j/m²/day	Wind velocity at 1.25 m height (km/day) Max.	Min.	Ave.
January	26.6	15.9	21.2	36.3	207.0	8.57	25.64	239.5	61.0	129.5
February	28.2	18.2	23.2	29.0	223.5	8.66	23.60	184.6	78.9	127.7
March	24.4	14.2	19.3	0.3	194.7	9.51	22.59	201.0	74.0	115.8
April	23.1	14.4	18.8	53.2	135.5	6.81	14.89	217.4	54.6	116.9
May	19.7	11.5	15.6	18.1	88.2	5.39	10.77	181.4	37.5	89.1
June	16.7	8.1	12.4	29.9	71.6	5.20	9.64	293.7	49.9	106.7
July	14.0	8.6	11.3	116.7	52.5	2.28	6.86	254.6	48.6	136.1
August	15.2	8.7	12.0	88.3	64.7	4.05	10.17	247.8	32.3	132.8
September	18.8	10.5	14.6	42.2	130.6	7.13	17.45	260.2	61.6	129.6
October	20.8	11.3	16.1	39.5	155.8	7.50	21.76	248.5	64.5	134.2
November	23.5	12.6	18.1	21.8	203.2	9.56	28.00	213.7	66.0	127.9
December	26.8	15.4	21.1	31.6	255.1	9.63	28.4	206.6	51.7	119.1

Table 2 : Meteorological data of the Waite Agricultural Research Institute - 1973

Month	Mean daily air temperature (°C)			Rainfall (mm)	Evaporation (mm)	Hours of bright sun-shine per day	Solar radiation Meg.j/m^2/day	Wind velocity at 1.25 m height (km/day)		
	Max.	Min.	Ave.					Max.	Min.	Ave.
January	29.9	19.0	24.4	34.1	260.1	8.13	25.2	248.3	84.5	133.6
February	27.4	17.7	22.6	53.1	199.5	9.16	24.0	219.0	43.9	119.6
March	24.5	15.9	20.1	34.5	176.7	6.99	18.57	173.6	55.7	114.9
April	22.5	14.7	18.6	91.1	131.3	5.77	13.27	168.2	59.9	122.2
May	19.0	11.8	15.4	77.8	79.4	4.81	9.63	226.8	24.8	108.8
June	13.8	7.8	10.8	105.6	41.0	3.21	7.08	185.6	44.4	93.7
July	15.8	9.1	12.5	123.3	61.0	4.63	8.91	217.1	46.2	126.1
August	15.9	9.4	12.7	65.0	67.8	4.63	10.35	253.0	59.4	125.6
September	18.1	11.0	14.6	92.5	101.4	4.90	13.37	289.5	55.4	158.3
October	21.1	12.7	16.9	78.8	128.4	6.65	19.32	217.9	70.7	122.9
November	23.0	12.8	17.9	36.3	145.6	7.60	23.1	243.7	63.1	109.8
December	26.8	16.9	21.9	44.6	215.5	8.16	25.77	279.1	80.9	137.1

Table 3 : Meteorological data of Waite Agricultural Research Institute - 48 years average (1925 - 1973)

Month	Rainfall (mm)	Days with rain ≥ 1mm	Evaporation (mm)	Mean relative humidity at 0900 (%)	Hours of bright sun-shine per day	Solar radiation Meg.j/m^2/day*
January	23.0	3.2	242.9	48.2	9.14	26.99
February	27.5	3.2	202.4	52.0	8.71	24.01
March	20.6	3.2	176.1	53.1	7.64	19.35
April	57.0	7.6	112.4	60.8	5.58	13.01
May	81.5	10.5	63.8	68.8	4.07	8.77
June	74.9	11.0	48.0	73.8	3.34	7.35
July	84.9	13.5	46.9	75.8	3.14	7.22
August	74.1	12.8	64.8	72.1	4.36	10.37
September	60.5	10.0	98.0	64.2	5.60	14.74
October	51.7	8.7	148.4	58.7	6.63	20.16
November	39.5	5.7	180.9	53.7	7.72	23.68
December	31.0	4.8	214.5	50.7	8.30	25.88

* Mean 1959-1973

Table 4 : Number of days per month with light, moderate, strong and very strong wind during the 1972 season (upper figure), and 1973 season (lower figure)

Wind type	Days per month							
	May	June	July	August	September	October	November	December
0 - 24 km/hour : light	19	18	12	14	16	9	5	13
	17	20	13	17	14	13	15	10
24 - 31 km/hour : moderate	10	8	9	7	8	14	19	15
	11	7	10	9	8	14	10	11
31 - 40 km/hour : strong	2	2	8	10	3	3	6	3
	3	3	8	4	6	3	2	7
> 40 km/hour : very strong	-	2	2	-	3	5	1	-
	-	-	-	1	2	1	3	3

Table 5 : The weight of the standard tillers used for plant weight estimation in each treatment in the 'matched tiller' method

High Density				Medium Density				Low Density			
Square planted		Drilled		Square planted		Drilled		Square planted		Drilled	
Standard grade	Weight	Standard grade	Weight	Standard grade	Weight	Standard grade	Weight	Standard grade	Weight	Standard grade	Weight
I 1	0.01	I 1	0.02	I 1	0.03	I 1	0.08	I 1	0.01	I 1	0.01
2	0.08	2	0.04	2	0.10	2	0.12	2	0.01	2	0.02
3	0.12	II 1	0.01	II 1	0.11	II 1	0.23	3	0.02	3	0.07
II 1	0.30	2	0.51	2	0.15	2	0.39	4	0.08	II 1	0.10
2	0.36	III 1	0.64	3	0.32	3	0.56	5	0.09	2	0.21
III 1	0.12	2	1.12	4	0.39	III 1	0.50	6	0.11	3	0.46
2	0.48	IV 1	0.86	III 1	0.06	2	0.82	II 1	0.03	III 1	0.40
3	1.30	2	1.01	2	0.22	3	1.13	2	0.12	2	0.69
IV 1	1.58	V 1	1.00	3	0.32	IV 1	1.29	3	0.18	3	1.15
2	1.89	2	1.87	4	1.41	2	1.72	4	0.29	IV 1	0.74
V 1	0.77			IV 1	0.88	V 1	1.22	5	0.67	2	1.62
2	2.46			2	3.21	2	3.40	III 1	0.32		
VI 1	1.16			V 1	1.20	VI 1	2.20	2	0.79		
2	3.47			2	3.28			3	1.46		
VII 1	3.83			VI 1	1.51			IV 1	0.18		
				2	2.10			2	0.53		
				3	4.40			V 1	1.18		
								2	1.87		
								VI 1	2.50		
								2	3.80		

Table 6 : The estimated weights by the 'matched tiller' method and the actual fresh weight (g).

Plant number	Estimated weight Observer A	Observer B	Observer C	Actual fresh weight
1	6.6	12.7	7.3	11.3
2	7.4	8.7	6.1	8.5
3	5.1	8.3	4.8	5.9
4	3.3	3.1	2.1	3.0
5	1.2	1.0	1.3	1.3
6	5.8	10.8	9.2	9.7
7	7.5	6.4	3.2	5.3
8	9.1	9.1	7.0	7.7
9	7.3	8.6	4.0	8.7
10	4.4	9.0	4.7	10.9
11	20.1	12.3	9.4	15.1
12	5.3	3.7	3.4	5.7
13	7.1	6.0	4.3	7.5
14	15.0	8.0	5.7	12.5
15	11.2	16.4	7.6	14.3
16	14.8	10.6	7.4	13.2
17	6.5	12.2	5.2	11.4
18	4.5	8.1	3.1	7.7
19	10.2	11.4	7.1	12.0
20	7.7	11.8	7.2	11.4
21	8.9	11.8	7.7	14.0
22	5.3	11.8	4.2	8.8
23	7.3	12.7	8.8	11.3
24	12.9	12.9	6.5	11.7
25	8.1	9.1	7.2	11.4
26	14.0	16.7	16.4	18.6
27	8.7	11.5	10.2	12.2
28	8.7	12.6	10.2	13.5
29	5.8	9.7	6.0	9.4
Mean	8.3	9.9	6.5	10.1
Stand. Dev.	4.0	3.5	3.0	3.7

Mean number of tiller per plant was 5.3

Table 7 : The estimated weights by the 'plant cylinder' method and the actual fresh weights (g)

Plant number	Estimated weight*			Actual fresh weight
	Observer A	Observer B	Observer C	
1	12.2	12.8	10.0	11.3
2	11.2	10.7	8.6	8.5
3	7.7	8.3	7.4	5.9
4	6.0	6.3	5.6	3.0
5	2.9	3.4	2.2	1.3
6	9.4	10.6	9.7	9.7
7	6.9	8.2	7.7	5.3
8	8.3	8.6	8.6	7.7
9	9.0	8.6	8.8	8.7
10	10.6	10.8	12.0	10.9
11	12.6	13.4	12.5	15.1
12	6.9	7.3	7.4	5.7
13	8.3	8.7	8.8	7.5
14	11.6	12.1	11.9	12.5
15	13.7	12.3	10.1	14.3
16	10.3	11.4	11.3	13.2
17	11.3	10.4	11.5	11.4
18	12.3	9.0	9.3	7.7
19	13.0	11.0	10.6	12.0
20	11.2	8.4	13.7	11.5
21	11.3	11.3	15.2	14.0
22	9.1	9.5	9.6	8.8
23	11.7	10.3	11.5	11.3
24	10.6	11.2	11.3	11.7
25	11.9	11.1	11.7	11.4
26	15.9	19.0	15.7	18.6
27	10.6	12.8	12.4	12.2
28	11.7	10.8	13.3	13.5
29	9.7	10.4	10.3	9.4
Mean	10.3	9.9	10.3	10.1
Stand. Dev.	2.6	3.2	2.8	3.7

* Each figure is the product of length and circumference of plant cylinder multiplied by a constant (for observer A: 0.095, for observer B: 0.080, for observer C: 0.076).

Table 8 : Testing the hypothesis that replicate's r's (correlation between date of seedling emergence and individual plant weight) are from the same population (r's at day 70)

Treatment	n	n-3	r	Z	(n-3)Z	$(n-3)Z^2$	Corrected Z	
I	26	23	-0.35	-0.365	-8.395	3.064	-0.370	
(Drilled,	31	28	-0.30	-0.310	-8.680	2.691	-0.314	χ^2= 2.663
high	30	27	-0.10	-0.100	-2.700	0.270	-0.104	P = 0.625
density)	21	18	-0.46	-0.497	-8.946	4.446	-0.503	H_o accepted
	21	18	-0.13	-0.131	-2.358	0.309	-0.137	
	129	119			-31.079	10.780		Z = -0.265
					$\bar{Z}_W$ = -0.261			r = -0.259**
					$\bar{r}$ = -0.255			
II	39	36	-0.19	-0.192	-6.912	1.327		
(Drilled,	30	27	-0.46	-0.497	-13.419	6.705		χ^2= 3.478
medium	39	36	-0.45	-0.485	-17.460	8.468		P = 0.487
density)	24	21	0.10	0.100	2.100	0.210		H_o rejected
	36	33	-0.29	-0.299	-9.867	2.950		
		153			-49.758	19.660		

The same tests were made on the other treatments and also on the r's values at day 90. The results are:

	Treatment	χ^2	P	Results
Day 70:	Drilled, Low density	7.538	0.112	H_o rejected
	Square planted, High density	9.298	0.100	H_o rejected
	Square planted, Medium density	5.381	0.250	H_o rejected
	Square planted, Low density	1.939	0.753	H_o accepted r = -0.293**
Day 90:	Drilled, High density	10.380	0.037	H_o rejected
	Drilled, Medium density	8.733	0.075	H_o rejected
	Drilled, Low density	12.796	0.025	H_o rejected
	Square planted, High density	2.198	0.700	H_o accepted r = -0.125
	Square planted, Medium density	13.027	0.012	H_o rejected
	Square planted, Low density	8.910	0.066	H_o rejected

Table 9 : Regression of weight at day 90 on weight at day 70 in each replicate

Treatment	Replicate	Regression equation	R	Standard deviation
Drilled: high density	1	y = -1.108 + 1.439x	0.816**	0.606
	2	y = -1.593 + 1.390x	0.749**	0.170
	3	y = -0.053 + 0.924x	0.621**	0.781
	4	y = -1.960 + 1.789x	0.840**	0.658
	5	y = -1.110 + 1.400x	0.844**	0.467
Drilled: medium density	1	y = -2.093 + 2.115x	0.858**	0.922
	2	y = -1.564 + 2.333x	0.875**	0.813
	3	y = -1.567 + 3.068x	0.830**	1.332
	4	y = -2.551 + 3.130x	0.933**	0.629
	5	y = -2.144 + 2.771x	0.909	0.980
Drilled: low density	1	y = -1.857 + 2.874x	0.842**	2.133
	2	y = 6.732 + 1.663x	0.364	4.470
	3	y = 0.866 + 3.205x	0.805**	2.463
	4	y = 2.551 + 2.400x	0.447*	4.233
	5	y = -5.551 + 3.916x	0.890**	2.515
Square planted: high density	1	y = 0.255 + 0.783x	0.459*	0.647
	2	y = -0.048 + 0.931x	0.682**	0.545
	3	y = -0.828 + 1.360x	0.825**	0.478
	4	y = -1.889 + 1.702x	0.845**	0.424
	5	y = -1.507 + 1.713x	0.945	0.319
Square planted: medium density	1	y = -2.973 + 2.189x	0.947**	0.514
	2	y = -2.772 + 2.148x	0.912**	0.658
	3	y = -1.695 + 1.819x	0.855**	0.862
	4	y = -1.681 + 1.915x	0.882**	0.945
	5	y = -3.650 + 2.356x	0.879	0.729
Square planted: low density	1	y = -2.415 + 3.136x	0.693**	3.195
	2	y = -5.439 + 3.549x	0.876**	1.835
	3	y = -2.343 + 2.982x	0.862**	1.581
	4	y = -8.068 + 4.123x	0.820**	3.468
	5	y = -3.966 + 2.990x	0.928**	1.644

Table 10A: Values of T for comparison of individual slopes and displacements

Treatment		Slopes	Displacements
Drilled, high density on 117 DF			
Replicate	Replicate		
1	4	-1.01	-0.13
1	2	0.17	3.27**
1	3	1.78	0.89
1	5	0.11	0.46
1	2	1.15	3.21**
4	3	2.53*	0.97
4	5	0.95	0.55
2	3	1.62	-2.42*
2	5	-0.03	-2.61*
3	5	-1.32	-0.38
Drilled, medium density on 176 DF			
Replicate	Replicate		
1	2	-0.60	-5.19***
1	5	-2.20*	-7.21***
1	3	-2.89**	-7.88***
1	4	-2.21*	-5.66***
2	5	-1.27	-1.69
2	3	-1.97*	-4.86***
2	4	-1.62	-2.08*
5	3	-0.96	-3.88***
5	4	-0.80	-0.77
3	4	-0.13	2.76**
Drilled, low density on 96 DF			
Replicate	Replicate		
2	4	-0.69	1.49
2	3	-1.30	-0.28
2	1	-1.16	3.56***
2	5	-2.21*	3.01**
4	3	-0.71	-1.73
4	1	-0.46	2.46*
4	5	-1.56	1.83
3	1	0.30	3.64***
3	5	-0.65	3.09**
1	5	-1.11	-0.54

Table 10B: Values of T for comparison of individual slopes and displacements

Treatment			Slopes	Displacements
Square planted, high density on 124 DF				
	Replicate	Replicate		
	1	5	-3.18**	-1.15
	1	3	-1.94*	-0.72
	1	2	-0.51	-0.21
	1	4	-2.52*	-0.94
	5	3	1.34	0.42
	5	2	3.06**	0.96
	5	4	0.03	0.15
	3	2	1.64	0.53
	3	4	-1.00	-0.23
	2	4	-2.30*	-0.75
Square planted, medium density on 124 DF				
	Replicate	Replicate		
	1	4	1.63	-1.84
	1	2	1.29	-0.27
	1	3	-0.29	-0.18
	1	5	0.10	0.96
	4	2	0.31	1.47
	4	3	1.36	1.74
	4	5	1.53	2.91**
	2	3	1.04	0.10
	2	5	1.21	1.16
	3	5	0.36	1.17
Square planted, low density on 90 DF				
	Replicate	Replicate		
	2	4	-0.69	-0.05
	2	3	0.72	-0.02
	2	1	0.52	-1.15
	2	5	0.82	2.00*
	4	3	1.39	0.03
	4	1	1.20	-0.95
	4	5	1.58	1.78
	3	1	-0.20	-1.15
	3	5	-0.01	2.08*
	1	5	0.22	3.22**

Table 11 : Degree of skewness of the frequency distribution of individual plant weight (estimated weight) of barley at day 70 - Experiment 1.

	REPLICATES				
	1	2	3	4	5
Drilled:					
High density	0.107	0.957**	-0.373	0.348	0.241
Medium density	-0.893**	-0.231	0.864**	-0.114	0.809*
Low density	-0.460	-0.343	-0.438	0.115	0.291
Square planted:					
High density	0.056	-0.436	-0.413	0.853*	-0.088
Medium density	-0.964*	-0.916*	-0.446	-0.922*	-0.242
Low density	0.144	0.353	-1.061**	0.640	-0.413

Table 12 : Degree of skewness of the frequency distribution of individual plant weight of barley at day 90 - Experiment 1.

Treatment	REPLICATES									
	1		2		3		4		5	
	No. of plants	Skewness	No. of plants	Skewness	No. of plants	Skewness	No. of plants	Skewness	No. of plants	Skewness
Drilled:										
High density	30	0.341	48	0.979**	38	0.267	29	0.413	31	0.552
Medium density	43	-0.096	37	0.586	43	1.085**	38	0.894**	26	0.846**
Low density	37	0.498	41	0.148	35	0.003	44	0.209	45	0.554
Square planted:										
High density	28	0.052	28	-0.521	27	0.198	22	0.349	28	0.443
Medium density	28	-0.651	26	-0.341	28	-0.092	28	-0.397	27	0.521
Low density	28	-0.056	28	-0.557	27	-0.862*	28	0.767*	28	-0.014

Table 13 : Degree of skewness of the frequency distribution of individual plant height (length of longest tiller) of barley at day 90 - Experiment 1.

	REPLICATES				
	1	2	3	4	5
Drilled:					
High density	-4.974**	-2.076**	-2.623**	-4.683**	-1.174**
Medium density	-1.483**	-3.088**	-5.131**	-1.191**	-1.616**
Low density	-2.831**	-0.863*	-0.827*	-2.674**	-2.921**
Square planted:					
High density	-0.559	-0.349	-0.737*	-1.263**	-4.450**
Medium density	-1.336**	-1.156**	-3.694**	-1.287**	-0.584
Low density	-3.933**	-1.096**	-1.948**	-3.767**	-0.855*

Table 14 : Degree of skewness of the frequency distribution of tiller number of barley at day 90 - Experiment 1.

Treatment	REPLICATES				
	1	2	3	4	5
Drilled:					
High density	-0.519	0.347	0.474	-0.534	0.080
Medium density	0.010	-0.215	0.148	1.063**	0.260
Low density	0.121	-0.455	0.201	-0.049	0.202
Square planted:					
High density	0.657	0.105	1.443**	-0.789*	-0.188
Medium density	0.276	-0.620	-1.091**	-0.776*	0.451
Low density	0.758*	0.124	0.681	0.911*	0.257

Table 15: Means and coefficients of variation of plant characters for each treatment in six barley crop communities - Experiment 1.

Plant Characters	D.L.[1]		D.M.		D.H.		Sq.L.		Sq.M.		Sq.H.		L.S.D. for significant interaction between density and pl arrangement
	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %	
1. Individual plant weight													
at day 70	3.91	33.6	2.16	39.2	2.55	21.8	4.84	27.5	3.22	23.8	2.15	22.7	0.58
at day 90[2]	10.01	56.8	3.54	60.2	2.35	44.7	11.29	44.5	4.23	39.2	1.98	40.4	
	1.041		0.552		0.371		1.110		0.625		0.286		0.075
2. Length of longest tiller													
at day 50	29.2	13.1	27.6	17.4	42.0	8.6	31.3	10.0	39.3	11.4	38.9	13.1	2.9
at day 90	76.2	23.8	82.0	12.6	85.7	9.2	80.7	19.2	86.6	10.2	86.1	8.2	N.S. interaction
3. Number of tillers per plant													
at day 50	8.5	26.5	4.4	33.9	4.2	58.5	12.4	64.8	6.9	27.2	4.4	30.2	0.7
at day 90	11.2	32.9	4.7	36.0	3.9	29.8	13.6	26.3	6.3	26.2	4.0	32.7	
4. Number of ears per plant													
at day 90	7.1	45.2	3.2	45.3	2.7	37.6	8.6	38.7	3.7	39.1	2.5	49.9	N.S. interaction
5. Ears weight per plant													
at day 90	1.67	51.4	0.55	61.6	0.33	49.0	2.02	42.8	0.63	43.6	0.27	61.3	0.19
6. Number of spikelets/plant													
at day 90	164	49.2	61	56.2	45	43.6	178	42.7	67	43.7	42	65.7	N.S. interaction
7. Leaf and green stem area per plant													
at day 90	431	63.8	147	70.6	115	49.5	518	48.6	181	52.1	92	65.3	N.S. interaction

1. D.L., D.M. and D.H. are drilled low, medium and high density. Sq.L., Sq.M. and Sq.H. are square planted low, medium and high density.

2. Two values of means for plant weight at day 90 are actual values (upper figures) and log transformed values (lower figures)

Table 16A: Replicate values for plant characters of barley - Experiment 1.

	D_H (1)					D_M (2)					D_L (3)				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1. Plant weight															
at day 70	2.5	2.6	2.6	2.5	2.6	3.2	3.4	1.5	1.8	2.2	4.0	3.5	4.8	4.1	4.0
at day 90	2.4	1.9	2.6	2.4	2.6	4.4	3.4	2.6	3.4	3.3	9.4	9.9	11.1	11.0	8.3
2. Plant height															
at day 50	41	42	41	41	45	33	28	24	25	26	28	28	30	30	30
at day 90	82	84	83	78	91	88	78	73	80	81	64	73	78	81	65
3. Tiller number/plant															
at day 50	4	4	4	4	4	5	5	4	4	4	8	9	9	9	8
at day 90	4	3	4	4	4	5	5	4	4	4	10	12	12	12	10
4. Number of ears/plant at day 90	2.7	2.2	2.9	2.8	2.8	3.7	3.3	2.6	2.9	3.4	6.4	6.8	8.1	7.4	6.9
5. Ear weight/plant at day 90	0.36	0.25	0.37	0.31	0.35	0.61	0.56	0.43	0.54	0.62	1.42	1.61	2.0	1.76	1.52
6. Number of spikelets/plant at day 90	45	35	48	47	49	76	63	47	56	64	140	157	197	171	155
7. Leaf & green stem area per plant at day 90	109	93	116	131	125	226	190	81	123	117	343	380	559	553	318

Table 16B: Replicate values for plant characters of barley - Experiment 1.

	$H_H(4)$					$H_M(5)$					$H_L(6)$				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1. Plant weight															
at day 70	2.2	2.2	1.9	2.4	2.0	3.5	3.3	3.2	3.0	3.2	5.0	5.4	5.4	4.9	5.0
at day 90	2.0	2.0	1.8	2.2	2.0	4.6	4.2	4.2	4.0	3.7	11.3	12.1	13.5	9.9	9.3
2. Plant height															
at day 50	44	37	35	41	37	41	38	38	39	40	31	30	32	32	31
at day 90	81	88	88	82	78	90	89	78	87	83	75	82	93	68	74
3. Tiller number/plant															
at day 50	6	4	4	4	4	7	7	6	7	7	12	12	12	11	11
at day 90	5	4	4	3	4	6	6	6	6	6	14	13	16	13	12
4. Number of ears/plant at day 90	2.8	2.9	2.6	2.0	2.4	3.3	4.0	3.7	3.7	3.8	8.2	6.9	9.2	10.7	7.8
5. Ear weight/plant at day 90	0.24	0.26	0.32	0.24	0.28	0.68	0.65	0.67	0.58	0.55	2.14	1.94	2.14	2.27	1.6
6. Number of spikelets per plant at day 90	40	49	51	33	37	63	71	66	68	65	173	141	195	225	158
7. Leaf & green stem area per plant at day 90	88	92	117	72	93	249	187	157	180	131	484	531	689	526	358

Table 17: Means and coefficients of variation of individual plant weight, length of the longest tiller, and number of tillers per plant of wheat at different stages of growth.

Plant character	Day 30 (harvest 1)		Day 50 (harvest 2)		Day 70 (harvest 3)		Day 95 (harvest 4)		Day 110 (harvest 5)		Day 130 (harvest 6)		Day 140 (harvest 7)		Day 180 (harvest 8)	
	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %	Mean	C.V. %
1. Individual plant weight*																
at medium density	0.03	33.3	0.22	41.8	0.86	51.5	2.62	66.2	3.31	62.8	5.04	64.3	6.13	61.0	6.13	61.0
at high density	0.03	30.0	0.18	41.7	0.21	42.4	1.12	53.0	1.70	54.8	2.42	55.8	2.66	68.8	2.82	67.5
2. Plant height (length of longest tiller)**																
at medium density	12.6	19.2	25.5	16.0	48.7	12.0	82.3	11.7	106.0	11.0	114.7	10.4	105.9	17.3	112.2	17.3
at high density	12.7	19.1	28.5	14.4	24.7	17.2	86.1	11.8	106.9	11.9	110.8	12.3	104.9	13.2	107.4	15.2
3. Number of tillers/plant***																
at medium density	1.1	30.0	3.4	34.4	3.6	41.1	4.1	48.8	2.9	35.5	3.3	41.8	3.4	36.0	3.4	36.2
at high density	1.1	24.5	2.4	36.7	3.2	34.7	2.3	37.4	2.2	36.8	2.1	40.0	2.3	40.0	2.4	37.9

* Non-significant difference between treatments at harvest 1, significant difference in all following harvests.

** Non-significant difference in harvests 1, 5 and 7, the rest were significantly different.

*** Non-significant difference in harvest 1, the rest were significantly different.

Table 18: Analysis of variance for plant weight of barley at day 70 - Experiment 1.

Variation due to	S.S.	D.F.	M.S.	F.	Prob.
Replicate	0.415	4	0.104	0.541	0.707
Replicate by plant arrangement by density	37.115	25	1.485		
Plant arrangement	1.776	1	1.776	9.27	0.006**
Density	28.355	2	14.177	74	0 ***
Plant arrangement by density	3.155	2	1.577	8.23	0.002**
Residual	3.829	20	0.191		

Table 19: Analysis of variance for log plant weight of barley at day 90 - Experiment 1.

Variation due to	S.S	D.F.	M.S.	F.	Prob.
Replicate	0.009	4	0.002	0.712	0.593
Replicate by plant arrangement by density	2.517	25	0.101		
Plant arrangement	0.004	1	0.004	1.080	0.311
Density	2.412	2	1.206	366	0 ***
Plant arrangement by density	0.036	2	0.018	5.44	0.013*
Residual	0.066	20	0.003		

Table 20: Analysis of variance for plant height (length of longest tiller) of barley at day 50. Experiment 1.

Variation due to	S.S.	D.F.	M.S.	F.	Prob.
Replicate	31.2	4	7.8	1.59	0.215
Replicate by plant arrangement by density	1054.2	25	42.2		
Plant arrangement	100.0	1	100.0	20.5	0.0002***
Density	558.5	2	279.2	56.9	0 ***
Plant arrangement by density	296.9	2	148.4	30.2	0 ***
Residual	98	20	4.9		

Table 21: Analysis of variance for number of tillers per plant of barley at day 50 - Experiment 1.

Variation due to	S.S.	D.F.	M.S.	F.	Prob.
Replicate	1.8	4	0.45	1.55	0.226
Replicate by plant arrangement by density	233.2	25	9.327		
Plant arrangement	28.0	1	28.0	96.6	0 ***
Density	190.1	2	95.0	327.7	0 ***
Plant arrangement by density	9.3	2	4.6	15.9	0.00007***
Residual	5.8	20	0.29		

Table 22: Analysis of variance for plant height (length of longest tiller) of barley at day 90 - Experiment 1.

Variance due to	S.S.	D.F.	M.S.	F.	Prob.
Replicate	66.66	4	16.66	0.365	0.830
Replicate by plant arrangement by density	1490.8	25	59.63		
Plant arrangement	108.3	1	108.3	2.37	0.139
Density	408.8	2	204.4	4.47	0.025*
Plant arrangement by density	60.8	2	30.4	0.666	0.525
Residual	912.93	20	45.65		

Table 23: Analysis of variance for number of tillers per plant of barley at day 90 - Experiment 1.

Variance due to	S.S.	D.F.	M.S.	F.	Prob.
Replicate	3.333	4	0.833	1.13	0.368
Replicate by plant arrangement by density	454.83	25	18.193		
Plant arrangement	14.7	1	14.7	20	0.00023***
Density	419.27	2	209.63	285.9	0 ***
Plant arrangement by density	6.2	2	3.1	4.22	0.0294*
Residual	14.66	20	0.733		

Table 24: Analysis of variance for number of spikelets per plant of barley at day 90 - Experiment 1.

Variation due to	S.S.	D.F.	M.S.	F.	Prob.
Replicate	1163	4	290.8	0.996	0.423
Replicate by plant arrangement by density	100668	25	4026.7		
Plant arrangement	240.8	1	240.8	0.825	0.374
Density	94221	2	47110.6	161.4	0 ***
Plant arrangement by density	370.1	2	185	0.634	0.541
Residual	5836.7	20	291.8		

Table 25: Analysis of variance for leaf and green stem area per plant of barley at day 90 - Experiment 1.

Variation due to	S.S.	D.F.	M.S.	F.	Prob.
Replicate	30455.9	4	7613.9	1.46	0.249
Replicate by plant arrangement by density	916798	25	36671.9		
Plant arrangement	8003.3	1	8003.3	1.54	0.228
Density	790101.6	2	395051	76.1	0 ***
Plant arrangement by density	14962.5	2	7481.2	1.44	0.260
Residual	103730	20	5186.5		

Table 26: Analysis of variance for number of ears per plant of barley at day 90 - Experiment 1.

Variation due to	S.S	D.F.	M.S.	F.	Prob.
Replicate	1.408	4	0.352	0.665	0.623
Replicate by plant arrangement by density	174.495	25	6.980		
Plant arrangement	2.760	1	2.760	5.21	0.033*
Density	158.006	2	79.003	149.3	9 ***
Plant arrangement by density	3.149	2	1.574	2.97	0.074
Residual	10.58	20	0.529		

Table 27: Analysis of variance for ear weight per plant of barley at day 90 - Experiment 1.

Variation due to	S.S.	D.F.	M.S.	F.	Prob.
Replicate	0.101	4	0.025	1.17	0.350
Replicate by plant arrangement by density	14.193	25	0.568		
Plant arrangement	0.114	1	0.114	5.32	0.032*
Density	13.425	2	6.712	313	0 ***
Plant arrangement by density	0.225	2	0.113	5.25	0.015*
Residual	0.429	20	0.021		

Table 28: Means (per replicate and per treatment) of individual plant weight, grain weight per plant and number of grain per plant of barley from the grain sample quadrats - Experiment 1.

	Drilled, medium density			Drilled, high density			Square planted, low density			Square planted, medium density			Square planted, high density			L.S.D. (.05)
	1	2	Mean	1	2	Mean	1	2	Mean	1	2	Mean	1	2	Mean	
Plant weight	6.67	4.48	5.57	4.38	4.01	4.19	19.95	19.23	19.59	4.49	4.69	4.59	3.09	2.98	3.03	1.83
Grain weight/plant	2.92	2.11	2.51	1.95	1.79	1.87	8.09	7.88	7.98	1.86	2.02	1.94	1.35	1.34	1.34	1.44
Number of grain/plant	61.6	44.7	53.1	45.2	42.3	43.7	184.9	174.8	179.8	45.5	49.4	47.4	33.1	31.1	32.1	31.6

Note: 1) Only two replicates per treatment; no data from the drilled, low density plot (explained in text).

2) All the treatment interactions were highly significant.

Table 29: Analysis of variance of individual plant weight of barley taken from grain sample quadrats - Experiment 1.

Variation due to	D.F.	S.S.	M.S.	F.
Replicates	1	1.0176	1.0176	
Treatments	4	378.2961	94.5740	218.14***
Plant arrangements	1	42.0676	42.0676	97.03***
Within plant arrangement	3	336.2285	112.0762	258.51***
Residual	4	1.7342	0.4336	
Total	9	381.0478		

Table 30: Analysis of variance of grain weight per plant of barley - Experiment 1.

Variation due to	D.F.	S.S.	M.S.	F.
Replicates	1	0.1061	0.1061	
Treatments	4	60.2784	15.0696	55.90***
Plant arrangements	1	5.8719	5.8719	21.78**
Within plant arrangement	3	54.4065	18.1355	67.27***
Residual	4	0.2696		
Total	9	60.6541		

Table 31: Analysis of variance of number of grains per plant of barley - Experiment 1.

Variation due to	D.F.	S.S.	M.S.	F
Replicates	1	78.4	78.4	
Treatments	4	29954.0	7488.5	57.96***
Plant arrangements	1	3468.6	3448.6	26.85**
Within plant arrangement	3	26485.4	8828.5	68.33***
Residual	4	129.2		
Total	9	30161.6		