GROWTH AND COMPETITION STUDIES WITH SNAP BEANS

(*Phaseolus. vulgaris. L.*)

A Thesis presented in partial fulfilment
of the requirements for a Masterate
in Horticultural Science at
Massey University.

PRAMILA LALLU

1980

ACKNOWLEDGEMENTS

I wish to thank my supervisor Dr. M.A. Nichols for his guidance and encouragement; the staff of the Department of Horticulture for their help; the staff of the library for help with reference material; the D.S.I.R. and Arthur Yates Company for financial assistance, also my friends who helped me with this project, and my sister Domenti for typing the thesis.

TABLE OF CONTENTS

CHAPTER THREE: Experiment 1

CHAPTER FOUR: Experiment 2

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Overseas work suggests that substantial yield increases can occur when the density is increased and the rectangularity is changed to unity. Two trials were carried out to examine some effects of growing snap beans at four densities.

The $\overline{\mathrm{R.G.R.}}$ fell with time until pod swell where it showed a slight increase and then fell again. The $\overline{\mathrm{N.A.R.}}$ followed a similar pattern whereas the $\overline{\mathrm{L.A.R.}}$ increased and then fell earlier than either the $\overline{\mathrm{N.A.R.}}$ or the $\overline{\mathrm{R.G.R.}}$, indicating the dependence of the R.G.R. on the $\overline{\mathrm{N.A.R.}}$ The $\overline{\mathrm{L.A.R.}}$ appears to be dependent on the $\overline{\mathrm{L.W.R.}}$ component rather than the $\overline{\mathrm{S.L.A.}}$ component.

Fertilizer had no effect on the $\overline{\mathrm{R.G.R.}}$ or the $\overline{\mathrm{N.A.R.}}$ As the level of fertilizer increases, the S.L.A. decreases and the $\overline{\mathrm{L.W.R.}}$ increases, indicating that more leaves are produced and the leaves are 'thicker'. Both the L.W.R. and the $\overline{\mathrm{L.A.R.}}$ are maintained at a higher level with increasing amounts of fertilizer.

As density increases, the $\overline{\mathrm{R.G.R.}}$, $\overline{\mathrm{N.A.R.}}$ and $\overline{\mathrm{L.W.R.}}$ fall whereas the $\overline{\mathrm{L.A.R.}}$, $\overline{\mathrm{S.L.A.}}$ and $\overline{\mathrm{L.A.I.}}$ all increase. This shows that at the higher densities, more leaves are produced but they are less efficient at producing and/or utilizing assimilates.

As density increases, the maturity of the beans tend to be delayed, yield/plant at high density is decreased through fewer flowers/plant, higher flower and pod abortion rate and a lower bean weight, all probably due to the lower N.A.R. There is also a

negative correlation between the number of pods and pod size.

The reciprricol yield density relationships showed fertilizer to have no effect on the A and B parameters for either total plant dry matter or bean dry matter. The allometric log plant weight to log bean weight showed the ratio of beans to total plant weight decreases with increasing density.

Fertilizer had no effect on the yield of beans. Density was also shown to have no effect on the yield of beans when the yields were compared at the same seed length. When yields were compared at the same chronological time, density did have an effect. The mean mature bean yield was 13.95 tonnes/ha but the mean harvestable yield was 18.6 tonnes/ha.

INTRODUCTION

1518 ha of snap beans (Phaseolus vulgaris L.) were grown in New Zealand in 1978. 1416 ha of these were grown for processing; 67 % for quick freezing and 33% for canning. The average yield of snap beans in 1978 was 7.98 t/ha. 21% of the frozen snap beans were exported to 22 countries with Australia importing 50% of the exported beans. The area of beans grown for processing has almost doubled between 1971 and 1977 as has the gross yield, but the yield per ha has shown little change over this period. (Anon, 1978).

Horticulture has moved towards systems of high yield and intensive production. The rapid increases in the cost of production must be met by more efficient production and higher yields. The scarcity of good land close to processing factories, with an abundant supply of water, tends to put a premium on high productivity per unit area. According to Bleasdale (1969), this is one incentive for having a comprehensive knowledge of the yield-density relationships of vegetable crops and to use the knowledge to devise highly productive cultural systems.

Overseas work has suggested that yields may be increased significantly by reducing the rectangularity and increasing the plant population (Jones, 1967, Mack and Hatch, 1968). A parabolic relationship between pod yield and density is apparent. The density at which maximum yield occurs will vary with the environment, cultural practices and cultivar. The time taken for the crop to mature, which varies with density, irrigation practices, and other factors, must be taken into consideration when comparing yield differences.

Often there is an interactive effect between density and fertilizer, and between fertilizer and other cultural and environmental factors; for example, as plant density increases, a greater amount of fertilizer is required to produce the maximum yield (Lang, Pendleton and Duncan, 1956). This factor, combined with the effect of soil type on fertilizer response, has made the interpretation of fertilizer trial results difficult.

Growth analysis is a technique that may be used to gain an insight into the physiological basis for yield differences using relative growth rates, net assimilation rates. leaf area ratios, specific leaf areas and leaf weight ratios. Yield differences may also be analysed morphologically using the number of pods m^2 and the mean weight per bean.

The aim of the project was to attempt to relate yield differences due to density and fertilizer to physiological and morphological changes.

CHAPTER ONE

REVIEW OF THE LITERATURE

1. Snap Bean Physiology

1.1 Introduction

Snap beans are known as green beans, French beans, and dwarf beans. Present day snap bean varieties have been developed from types which originate from Central America. This is reflected in the requirement of the crop for a warm, frost free climate for effective growth. Snap beans will not grow below 10°C and, between 10°C and 15°C, flowering is delayed. Snap beans require well drained, moisture retentive, light soils with a pH of around 6.5. Heavy acid soils generally produce poor yields. The seeds are usually sown into rows 60 to 90 cm apart with a 3 - 4 cm spacing within the row, resulting in a density of about 40 plants m^{-2}.

Weeds must be effectively controlled in snap bean crop. Williams, Crabtree, Mack and Derby-Lawes (1973), found that yields were reduced by up to 36% by ineffective weed control. They also found that as plant spacing decreased, the crop had to be kept weed free for a progressively shorter period of time. This is because the crop achieved total canopy cover sooner as spacing was decreased and this choked out small weeds. Weeds will alter the effective density and rectangularity and affect the crop through competition, the effects of which will be discussed later.

Snap beans suffer from a wide range of pathogens. Gane, King and Gent (1975) recommend a 5 year rotation to reduce pathogen build-up in the soil. Closer spacings may provide an ideal environment for pathogens. Nichols (1974), found that <u>Sclerotinia sclerotiorum</u> was more prevalent at closer spacings than at wider spacings. A comprehensive spray programme is essential to prevent the establishment of pathogens.

1.2 Seed aspects

Snap bean seed is expensive and it can be difficult to achieve the desired plant stand. The seed is very easily damaged and can be readily attacked by soil borne pathogens through damaged tissue, although careful handling and dusting with a fungicide will help to prevent this. Barriga (1961) found an inverse relationship between the percentage injury and the moisture content, showing the need to handle dry seed carefully. Most of the damage was in the form of transverse cotyledon cracking. All the food reserves of the bean seed are contained in the cotyledons. If the cotyledons are damage or severed from the radical and plumule, then the emerging plants are small and usually do not reach the pod bearing stage. Damage may also result in a loss in vigour, the degree of which may be ascertained by using the electrical conductivity test of Matthews and Bradnock (1968). Seeds of low vigour should not be planted.

Dickson, Duczmal and Shannon (1973) found that there was a positive relationship between the rate of imbibition and transverse cotyledon cracking. This relationship was very strong with very dry seed. Thus, irrigation after sowing would have to be carefully controlled. Poor irrigation can also lead to soil capping and, as beans have epigeal germination, soils that are lumpy or capped can either prevent emergence or damage the cotyledons. Thus, to achieve a good plant stand snap beans should be sown into a well drained, moisture retentive, light soil.

1.3 Fertilizer use

Shoemaker (1947) reported that on most soils, beans were relatively light feeders, although increased yields did result from the addition of fertilizer. Although beans are legumes, they will respond to nitrogen application (Gane, et al., 1975; Edge, Mughogha and Ayonoadu, 1975). Smittle (1976) found that bean plants grown in soil with too much water, or soil that is too free draining, will also respond to nitrogen application. Nodules may occasionally be found on bean roots but they do not appear to be effective in fixing atomospheric nitrogen. Effective strains of *Rhizobium phaseoli* are not usually present in the soil, or if they are, they are short lived.

The increased revenue resulting from the increase in yield from higher fertilizer application must be weighed against the cost of the fertilizer. Also, as the rate of fertilizer application increases, the yield also increases but the proportion of beans to total weight will decrease (Nichols, 1974).

1.4 Harvesting

The harvesting of snap beans for processing is a highly mechanised operation. Crops must be of uniform high quality, with no suggestion of overmaturity in the form of objectionable string, fibre or hard seed. With mechanical single pick harvesting, it is not possible to reject old pods and it is important that as high a proportion of the pods possible are in the acceptable size and maturity range. That is, a highly determinate crop is required with a very low spread of maturity.

The pods must also be able to withstand harvesting damage. Hoffman (1971) found that machine harvesting damaged all pods although the extent of the damage differed with the cultivar. The pods should be able to be easily detached from the plant to minimise damage. Williamson and Smittle (1976) found that although an increased reel speed resulted in more efficient pod removal, it also increased damage. Pod detachment force is positively related to damage.

1.5 Quality

The assessment of snap bean quality has posed problems. Optimum quality occurs before maximum yield has been achieved (Gane et., al; 1975). That is, maximum yield occurs when the crop is overmature.

Several methods of quality assessment have been devised. Quality in snap beans is related to the amount of fibre present in the pods, the greater the amount of fibre, the lower the quality. Direct measurement of the amount of fibre is tedious and cannot be carried out in the field. According to Gane et al. (1975), there are three stages in the maturation of beans. In stage one there is a rapid increase in pod length with relatively slow seed development. Stage two, during which optimum maturity occurs, consists of the enlargement of the pod and a more rapid enlargement of the seed. The final stage involves lignification, senescence and the drying of the pod, and the drying and hardening of the seed.

1.5. 1 Seed length

Seed length is one parameter that has been widely used in quality assessment. It is positively related to the fibre content of the pod and is ascertained by measuring, in millimetres, the total length of ten seeds, each being the largest seed from the largest pod from a ten plant sample (Gane et al, 1975). Bean cultivars do not have the same seed length for optimum quality as for large seeded cultivars it is between 80 mm and 100 mm and for large seeded cultivars it is between 100 mm and 120 mm. At the lower end of both ranges, the beans are frozen whilst beans from the higher end of the ranges are canned. Canned beans require a higher amount of fibre to retain their structure after processing than do frozen beans. Dehydrated beans require an even greater amount of fibre to retain their structure so even more mature beans are needed for dehydration.

1.5. 2 Seed weight

Seed weight is another parameter used in quality assessment in the United States. Samples are obtained in a similar manner as for seed length. The weight of the seed is expressed as a percentage of the total pod weight.

1.5. 3 Sieve size

The size of the pod is often used as a parameter for measuring snap bean quality. There are six size grades. (Table 1.1)

Table 1.1: Sieve size gradings. (From Asgrow Seed Co., 1977)

Sieve size grade	Pass through	Retained on
1	4.76 mm	5.76 mm
2	5.76 mm	7.34 mm
3	7.34 mm	8.34 mm
4	8.34 mm	9.53 mm
5	9.53 mm	9.93 mm
6	10.92 mm or larger	

Sieve size is used in conjunction with seed length. Within each size grade there are maximum seed lengths for optimum quality. (See table 1.2)

1.5. 4 Seed index

Robinson, Wilson, Mayer, Atkin and Hand (1964) found that if seed length, seed weight or sieve size was used alone in quality assessment, then this resulted in processed beans with excessive seed and/or fibre. Silbernagel and Drake (1978) derived a formula that uses all three quality parameters called seed index.

$$\text{Seed index} = \left(\frac{\text{seed weight}}{\text{total pod weight x 100}}\right) \text{ x length of 10 seeds} \quad \text{---1}$$

Seed index values for various sieve size grades are shown in table 1.2. Silbernagel and Drake (1978) found that the seed index shows better correlation with the amount of fibre than did seed length, seed weight or sieve size.

Table 1.2: Seed length, sieve sizes, % seed weight and seed indicies for various size grades.

		Maximum 10 seed length (mm)			Maximum seed index values		
		sieve size			sieve size		
Grade	maximum % seed weight	4	5	6	4	5	6
Extra fancy	4	80	90	100	320	360	400
Fancy	8	90	100	110	720	800	880
Extra Standard	12	100	110	120	1200	1320	1440
Standard	16	110	120	130	1760	1920	2080
Standard	24.9	120	130	140	2988	3237	3486

1.5.5 Laboratory method

The most accurate method of determining the fibre content is a laboratory technique in which 100 g of de-seeded pods are ground in water for 5 minutes. The pulp is then washed through a 30 mesh monel wire screen. The retained material is dried and then weighed, with the amount of fibre being expressed as a percentage (Silbernagel and Drake, 1978). Although this method is accurate, it is also time consuming and cannot be carried out in the field. It is often used to calibrate the other quality assessment methods.

1.5. 6 Physiology

Kemp, Krogman and Hobbs (1974) found that high temperatures and dry soil conditions were correlated with a high pod fibre content, with water stress having a greater effect than temperature. Littman (1974 a, 1974 b) found that the fibre content of pods increased at a faster rate at high temperatures. Based on the Queensland grading system, he found that three days storage at 27°C resulted in a change from grade A to grade B. With storage at 13°C, the change from grade A to grade B took six days, whilst there was no change in grade with storage at 3°C. Therefore, it is important to process the beans as soon as possible after harvesting to maintain quality.

1.6 Flowering

Snap beans generally produce 4 to 6 trifoliate leaved nodes, ending in a terminal inflorescence. There are usually 2 vegetative buds in the axil of each main stem leaf. Usually only one of the buds will form a lateral branch. Each lateral branch will grow out from the alternate side of the mainstem to the one below it. From the cotyledonary and primary leaf nodes, 2 lateral branches may appear. Each lateral branch has a varying number of nodes, with a trifoliate leaf at each node. Flower shoots are situated in the axil of each stem and subtending trifoliate leaf, and at the end of each lateral branch (see figure 1.1).

The sequence of flower opening is described by Wivutvonvana and Mack (1974). (See figure 1.1). The first flower buds to open are the lowermost on the terminal inflorescence, followed by the

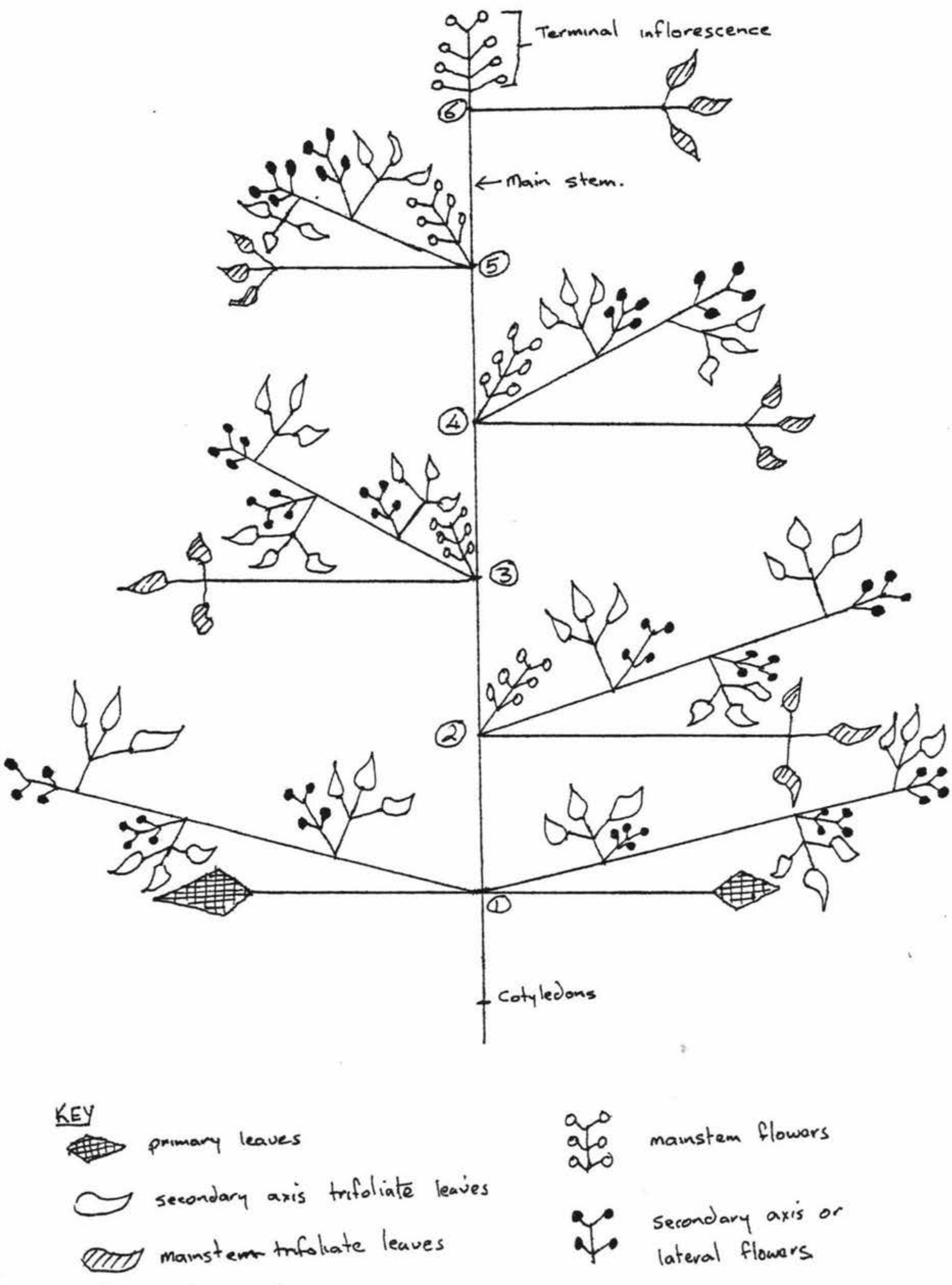

FIG 1.1: Morphology of a plant grown at a wide spacing. (20cm x 20 cm).

middle buds on the terminal inflorescence and the mainstem buds. the rest of the flower buds open last, that is, the uppermost on the terminal inflorescence and those on the lateral branches. According to Jones (1967), flowering can last from one week to several weeks.

Temperature has an effect on flowering. Smith and Pryor (1962) found that plants in bloom during high temperatures had a decreased flower set and the number of beans per pod also decreased in dry beans. Mack and Singh (1969) found that temperatures in excess of 35°C resulted in a 42% decline in yield. Bean plants were subjected to 5 days at 35°C two days after the first bloom appeared. The 42% reduction in yield was due to decreased percentage flower set <u>and</u> a decreased number of pods per plant. No reduction in flower set <u>or</u> pods per plant occured if the high temperature treatment was given seven days after the first bloom appeared. Padda and Munger (1969) noted that low temperatures, below 15°C, only delayed flowering but did not prevent it altogether. The flower primordia were present but did not open at the normal rate. Fisher and Weaver (1974) found that high night temperatures of around 27°C promoted good flower opening but caused a decrease in pods set. They also found that humidity reading of greater than 80% increased flower set and pod retention probably by promoting good pollen germination.

Snap beans are very sensitive to water stress, especially over the flowering period. Stoker (1974) found that the greatest yield reduction due to water stress occured when the water stress was applied over the flowering period. The yield reduction was in the form of fewer pods per plant and fewer seeds per pod.

This may be linked to the temperature effect as, in both cases, the reduction may be due to poor pollen germination.

1.7 Photosynthesis

In beans, the majority of the photosynthates are produced in the leaves. Crookston, O'Toole and Ozbun (1974 b) found, using the dry bean variety "Redkote", that the pod was not an important source dry matter for the seed. However, they did find that the pod was very efficient in re-fixing CO_2 evolved from respiration.

Crookston, O'Toole, Lee, Ozbun and Wallace (1974 a) found that exposure to one night of cold temperatures of less than 5°C led to a decrease in the photosynthetic rate if the roots were chilled as well as the aerial portion of the plant. The cold temperature causes an increase in the resistance to water uptake, which put the whole plant into a water stressed state. This caused the closure of the stomata and, hence, increased the resistance to CO_2 uptake and the subsequent decrease in the photosynthetic rate. Water stress prior to flowering can cause a 53% decrease in pod weight (Dubetz and Mahalle, 1969).

The photosynthetic capacity of the leaves can be approached in terms of the source-sink theories of Warren - Wilson (1972), which state that the rate of assimilation per plant is equal to the leaf area per plant multiplied by the rate of assimilation per unit leaf area. The second term is the net assimilation rate (N.A.R.) used also in growth analysis. Thus, theoretically if either the leaf area or the N.A.R. increase then the photosynthetic capacity of the plant should also increase. Wallace and Munger (1965) noted that the higher yielding cultivars of beans tended to have a larger leaf area but this was not always true. Wallace, Peet and Ozbun (1976) also found that a high N.A.R. is not always associated with a high yield. There appears to be a negative correlation between leaf area and N.A.R. As the leaf area increases, the lower leaves become shaded, cause the level of photosynthesis in those leaves to decrease through competition for light and level of respiration to increase. Thus, the overall N.A.R. will decrease as the N.A.R. is the difference between photosynthesis and respiration.

Crookston, Treharne, Ludford and Ozbun (1975) demonstrated the effect of shading on beans by growing bean plants at 2 light intensities, 22,000 lux and 3,200 lux, and found that at the lower light intensity there were fewer leaves, decreased leaf area, and thickness, and a 38% decrease in the N.A.R. Treharne, Ozbun, O'Toole, Crookston and Peet (1973) found the net CO_2 exchange rates, photorespiration and enzyme activity all increase with increasing light intensity, up to light saturation.

The arrangement of the leaves can also affect the N.A.R. Watson and Wits (1959) noted that cultivated beets have more erect leaves than wild beet and, that this allows for greater light penetration into the canopy, resulting in a greater effective leaf area and also a greater N.A.R. Wallace (1973) reported an unique method of leaf orientation in beans. He found that the pulvinule was receptive to light. Light impinging on the top of pulvinule caused it to bend upwards, which caused the leaflets to orientate themselves parallel to the light source. Thus, while the sun is overhead, the upper leaves allow a greater penetration of light into the canopy. However, when the light impinges on the side of the pulvinule, it twists so that the leaflets point downwards and so are perpendicular to the light source. In this case, that is, early morning and late afternoon, the outer leaves make maximum use of the available light and allow very little light penetration into the canopy.

Increasing the photosynthetic efficiency alone may not result in an increase in yield (Evans, 1975), the extra assimilated produced may not be partitioned into economic yield, that is, bean pods. The various sinks, for example, pods, stems, leaves, roots etc., have different strengths. If present, the pods are the strongest sinks and will attract a major portion of the assimilates produced. Yield increases due to an increase in the photosynthetic capacity of a plant would occur if yield was being limited by the supply of assimilates. One cannot generalise as to whether it is the supply of assimilates of the partitioning of it into useful sinks is limiting yield (Evans, 1975), because of the ability of plants to adapt to different environmental conditions. Work reviewed by Neales and Incoll (1968) demonstrated that leaves appear not to be operating at their full capacity, that is, under normal field conditions the capacity for storage could be limiting yield. Also the N.A.R. of plants is not constant as shown by Moorby (1968) with potatoes. He found that the N.A.R. may rise and the proportion of assimilates exported may increase as soon as tubers are initiated.

Photosynthesis during the storage phase, that is, pod swell in beans, is an important yield determinant. Photosynthesis prior to the storage phase determines the size of the storage system (Evans, 1975) as well as the capacity for assimilate production, that is, leaf area. However, once the flowers are set, it is desireable for vegetative growth to cease and for the majority of the assimilates to be diverted into pod growth. Wallace et.al., (1976) have screened many bean varieties to determine their harvest indicies. They define harvest index as the economic yield divided by the biological yield. Their aim is to breed cultivars with a high photosynthetic capacity early in the life of the plant and a high capacity for pod storage after flowering.

2. Plant spacing

2.1 Introduction

According to Bleasdale (1973), the spacing of plants within a crop determines more than any other single factor the resources available to each plant and whether these resources are fully utilised. Spacing can influence not only yield but also quality and earliness.

Plant spacing consists of 2 components,

(a) Plant density - the number of plants per unit area, and

(b) Plant arrangement - the spatial distribution of these plants.

2.2 Plant density

It can be shown that as plant density increases, the yield from each plant will decrease but the yield per unit area will increase, up to a point. Holliday (1960 a) proposed 2 yield-density relationships.

(a) An asymptotic relationship where yield rises to a maximum with increasing density and the remains constant at higher density, and

(b) a parabolic relationship where yield rises to a maximum with increasing density and the decreases with further increasing density.

Holliday (1960b) found that total crop dry matter always follows an asymptotic relationship. This has been shown not to be true in all cases, as a fall off in total crop dry matter may occur at high densities (Bleasdale, 1966). In most cases, the asymptotic relationship between density and total dry matter is valid, although the whole plant is rarely marketed. Usually only a part of the plant is marketed or harvested, for example, bean pods, corn cobs, potato tubers etc.

Experimental results have supported the suggestion of Holliday (1960 b) that reproductive forms of yield always follows a parabolic pattern with density. Certain forms of vegetative yield also follow this parabolic relationship, for example, the sprout yield of Brussel sprouts and the root yield of red beet.

2.3 Plant arrangement

Plant arrangement can be divided into 3 components

(a) Rectangularity,

(b) Orientation of the rows, and

(c) The regularity of spacing within the rows.

Rectangularity is the ratio of the distance between the rows to the distance in the row. Experiments have shown that at any given density, beans planted on a square pattern, that is, a rectangularity of 1, will have a greater yield than beans planted on a non-square pattern (Jones, 1967, Mack and Hatch, 1968).

Loomis and Williams (1969) have suggested orientating rows in a N - S direction, rather than in a E - W direction, will result in a greater amount of photosynthesis due to better light utilization. However, this may be nullified by local conditions such as the direction of the prevailing wind or the slope of the land. Also, if the crop is planted with a rectangularity of 1, then orientation of the 'rows' would not have an effect on yield.

Spacing in the row is more difficult to control than spacing between the rows. Irregular spacing in the rows can reduce the potential yield and lead to an unevenly maturing crop that would be unsuitable for once-over machine harvesting.

2.4 Competition

The reduction in yield per plant as density increases is due to competition for light, soil nutrients, soil moisture and occasionally CO_2 in the air and O_2 in the soil. Competition begins when the immediate supply of one essential factor is exceeded by the demands of the crop (Donald, 1963).

Competition for light which occurs when on plant shades itself or its neighbour, is present in most crops except in the case of very widely spaced crops or newly emerged crops. There is very little that can be done to overcome competition for light except by altering plant arrangement and leaf orientation.

Generally, applications of fertilizer will increase yields at all densities. Lang, Pendleton and Duncan (1956) found grain yield of maize increased with applications of nitrogen at all densities, and that the higher the plant density, the greater was the increase. Also, the greater the application of nitrogen, the higher was the density at which maximum yield occured.

Work carried out by Salter (1961) demonstrated the interaction between plant density and soil moisture. Cauliflowers were grown at 4 densities with and without irrigation and showed an increase in total yield with increasing density, regardless of irrigation. However, the highest marketable yields were from the higher densities that received irrigation, due to a much higher level of quality. With the non-irrigated plots, marketable yield decreased as density increased.

2.5 Effects of density on the plant

As plant density increases the yield per plant will decrease although yield per unit area will increase, up to a point, as shown by Jones (1967) with snap beans, Fery and Janick (1970, 1971) with tomatoes and Mack (1972) with sweet corn. Competition for the various growth requirements limits the size of each plant as density increases. In snap beans, this is manifest in the suppression of lateral branches at high density (Jones, 1967), thus, reducing the number of pods per plant. With onions, as density increases, the bulb size decrease, thus reducing yield per plant.

Bleasdale and Thompson (1966) have demonstrated that when some form of size grading is practised, the yield-density relationship is always parabolic. With vegetative structures, the size of each economic unit will decrease with increasing density. With reproductive structures, the size of each economic unit may decrease with increasing density and/ or there may be fewer economic units per plant (Jones, 1967, Fery and Janick, 1970, 1971, Mack, 1972).

Bleasdale (1973) states that horticulturalists are looking for uniformity within a crop. With once-over harvesting, a very low spread of maturity is required (Jones, 1967) as it is usually not possible to reject overmature portions of the crop. It is possible to obtain an evenly maturing snap bean crop by planting at a higher density. This restricts lateral development so that only mainstem flowers develop. (c.f. figures 1.1 and 1.2). This will reduce the flowering period to less than one week and reduce the spread of maturity. Fery and Janick (1970) found similar results with tomatoes.

Density can also have an effect on the time to optimum maturity. Thomas (1966) found that Brussel sprouts grown at a high density mature later than sprouts grown at a low density. Bleasdale (1969) found similar result with cabbages. With onions, however, a high density will result in the earlier maturity of the bulbs. Fery and Janick (1970) found this to be the case with

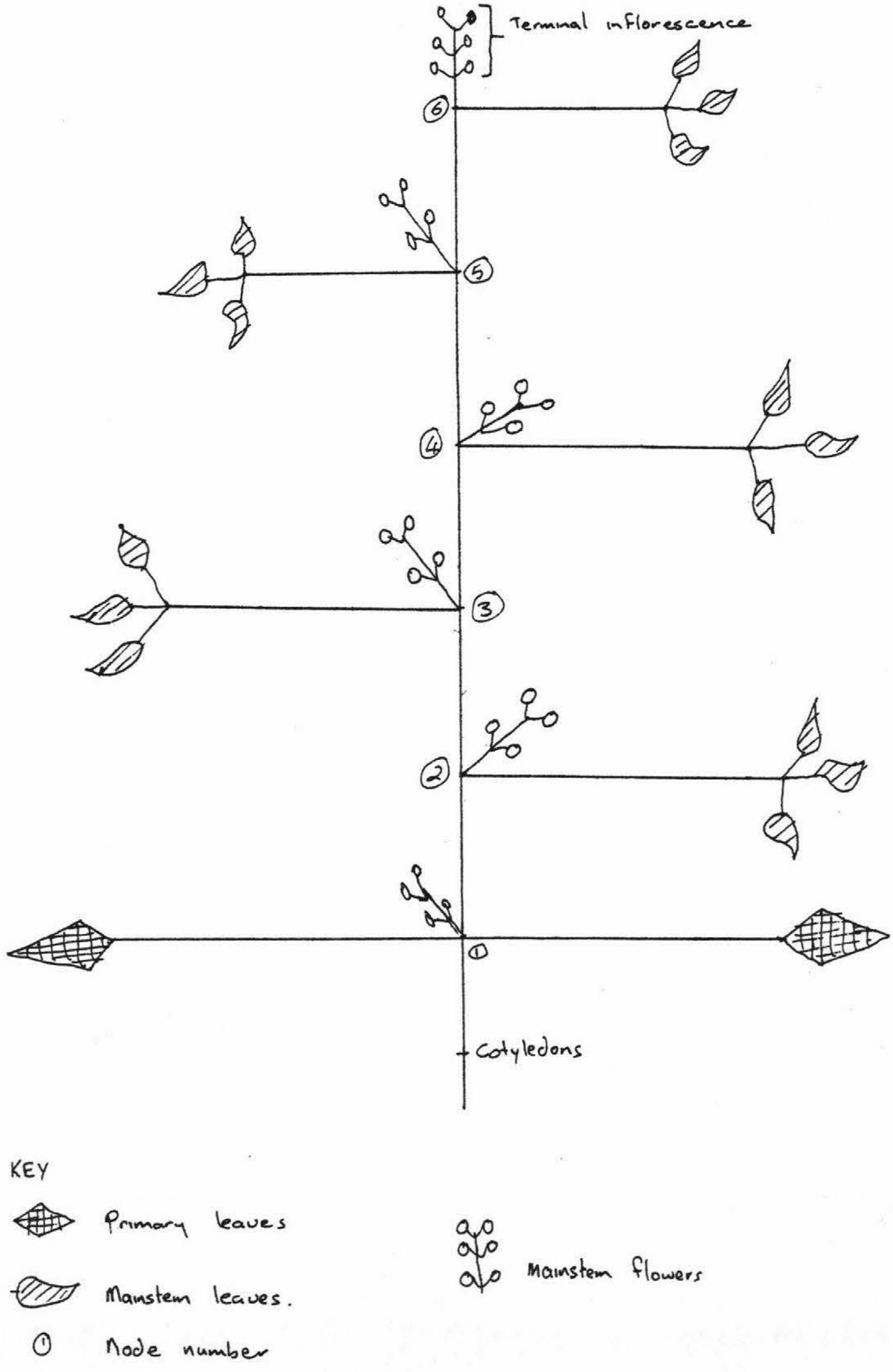

FIG. 1.2: Morphology of a plant grown at a close spacing (5cm x 5cm)

tomatoes also.

2.6 Plant density and competition models

Mathematical equations have been developed to help in the analysis and interpretation of plant density experiments. Shinozaki and Kira (1956) related density and plant yield by equation 2.

$$\frac{1}{w} = A\rho + B \qquad \text{\_\_\_\_2}$$

Where w is the mean weight per plant at density ρ. A and B are constants. Inherent in the model is an asymptotic yield-density relationship.

$\frac{1}{A}$ is considered the measure of the yield potential of the environment

that is, as $\rho \longrightarrow \infty$; then $w\rho \longrightarrow \frac{1}{A}$

$\frac{1}{B}$ is considered the genetic potential of the plant growing free of competition, that is, as $\rho \longrightarrow 0$, $w \longrightarrow \frac{1}{B}$

This model adequately describes the relationship for the whole plant. However, this model does not apply to a plant part, which has a parabolic relationship with density. Thus, Bleasdale and Nelder (1960) modified equation 2 and derived equation 3.

$$w^{-\theta} = A\rho^{\phi} + B \qquad \text{\_\_\_\_3}$$

Where θ and ϕ are constants as are A and B. W and ρ are the same as in equation 2. With experience, Bleasdale and Thompson (1966) found that it was reasonable to assume that

ϕ was one, thus, equation 3 becomes,

$$w^{-\theta} = A\rho + B \qquad 4$$

This equation can be applied to the whole plant, in which case $\theta = 1$ and, thus, equation 4 reverts to equation 2, or, it can be applied to a plant part, in which case $\theta < 1$. Bleasdale (1967) found a simple method to calculate θ based on allometry. The total weight (W_T) and the weight of the plant part (W_p) at 2 densities are required for use in equation 5.

$$\log_{10} W_T = \log_{10} K + \theta \log_{10} W_p \qquad 5$$

Both K and θ are constant with θ being more important. Jones (1967), Nichols (1974) and Stang (1974) all found θ to be less than unity for a plant part. This indicates that as density increases, a smaller portion of the assimilates is partitioned to the plant part in question, that is, a parabolic yield-density relationship. When θ is equal to unity then the relationship of yield and density would be asymptotic.

These equations have only one variable, density, and the constants will apply to one set of conditions only. Different fertilizer rates or moisture levels, for example, may alter these constants. Bleasdale (1969) states that as only 2 densities need be grown, in order to use these equations, then it is practicable to include plant density as a variable in variety, fertilizer or irrigation trials.

3. Growth Analysis

Growth analysis may be approached in 2 ways,

(a) The component approach, or

(b) The classical approach.

The component approach divides the plant into components of yield. One of the first attempts to analyse yield in terms of antecedent growth was made by Balls and Holton in 1915 on the cotton crop in Egypt (Cited by Watson, 1952). They measured the daily growth in height of the mainstem, the daily rate of flowering and the weekly rate of boll production throughout the latter part of the growing season. The flowering and bolling curves were used to interpret variations in yield produced by differences in spacing, sowing date, water supply, climatic factors and boll worm attack.

Engledow and Wadham (1923) made a census of plant characteristics assumed to affect the yield of cerals, for example, density, grains per ear, ears per plant, weight per grain etc. These results gave a quantitative description of the morphological changes occuring during crop growth but they do not add to the understanding to the physiological causes. Hardwick and Milburn (1967) used a similar method, for peas, in which the final yield for the whole plant is factorised into components, that is, weight per pea, peas per pod, pods per node, and podding nodes per plant. Jones (1967) used a similar technique on snap beans.

The classical approach to growth analysis involves the use of a series of large harvests to follow the growth of a plant. Yield is usually expressed as wieght per unit area of land but Watson (1952) points out that it would be more logical to base the analysis of yield on the weight changes that occur during growth rather than on changes in morphológical characters.

Watson's (1952) aproach to growth analysis involves the calculation of the Relative Growth Rate (R.G.R.), and its components, the Net Assimilation Rate (N.A.R.) and Leaf Area Ratio (L.A.R.). Radford (1967) defines the growth analysis formulae, at an instant of time (t) when

(a) W is a measure of plant material present, and

(b) A is a measure of the size of the assimilatory system as follows:

The relative growth rate is the rate of increase of plant material per unit of material present.

$$\text{i.e.} \quad R.G.R. = \frac{1}{W} \cdot \frac{dw}{dt} \qquad \text{\_\_\_\_ 6}$$

The net assimilation rate is the rate of increase of plant material per unit of assimilatory material

$$\text{i.e.} \quad N.A.R. = \frac{1}{A} \cdot \frac{dw}{dt} \qquad \text{\_\_\_\_ 7}$$

The leaf area ratio is the ratio of the assimilatory material per unit of plant material present

$$\text{i.e.} \quad L.A.R. = \frac{A}{W} \qquad \text{\_\_\_\_ 8}$$

It can be seen that if the N.A.R. is multiplied by the L.A.R., then the product is R.G.R., that is, N.A.R. and L.A.R. are the 2 components of R.G.R. The L.A.R. can be divided into 2 components (Evans and Hughes, 1961)

(a) The specific leaf weight which is the amount of leaf area present per unit of assimilatory material present (W_L)

i.e. S.L.A. $= \frac{A}{W_L}$ ——— 9

and (b) The leaf weight ratio which is the ratio of the assimilatory material to the plant material

i.e. L.W.R. $= \frac{W_L}{W}$ ——— 10

Multiplying the S.L.A. by the L.W.R. will give the L.A.R.

The traditional use of these formulae involves the calculation of mean R.G.R's, N.A.R's, L.A.R.'s, S.L.A.'s and L.W.R.'s over the time periods between harvests using the following formulae:

$$\overline{RGR} = \frac{(\log_e W_2 - \log_e W_1)}{(t_2 - t)} \qquad \text{——— 11}$$

$$\overline{NAR} = \frac{(W_2 - W_1)}{(t_2 - t_1)} \times \frac{(\log_e A_2 - \log_e A_1)}{(A_2 - A_1)} \qquad \text{——— 12}$$

$$\overline{LAR} = \frac{(A_2 - A_1)}{(W_2 - W_1)} \times \frac{(\log_e W_2 - \log_e W_1)}{(\log_e A_2 - \log_e A_1)} \qquad \text{——— 13}$$

$$\overline{SLA} = \frac{(A_2 - A_1)}{(W_{L2} - W_{L1})} \times \frac{(\log_e W_{L2} - \log_e W_{L1})}{(\log_e A_2 - \log_e A_1)} \qquad \text{——— 14}$$

$$\overline{LWR} = \frac{(W_{L2} - W_{L1})}{(W_2 - W_1)} \times \frac{(\log_e W_2 - \log_e W_1)}{(\log_e W_{L2} - \log_e W_{L1})} \qquad \text{——— 15}$$

where W_1 and W_2 are the plant dry weights, A_1 and A_2 are the leaf areas and W_{L1}, and W_{L2} are the leaf dry weights all at times t_1 and t_2 respectively.

Radford (1967) states that it is more important to find out the relationships between W and time. Vernon and Allison fitted 2nd order polynomials to W and A, but the method suffered from a statistical drawback in that progessions of W and A against time seldom show the uniform variability, with increasing time that is required if W and A are subjected to regression analysis.

To overcome the statistical problems, Hughes and Freeman (1967) used polynomial regression to fit curves to logged data:

$$\log_e W = a + bt + ct^2 + dt^3 \qquad \text{\_\_\_\_\_\_} 16$$

$$\log_e A = a^1 + b^1t + c^1t^2 + d^1t^3 \qquad \text{\_\_\_\_\_\_} 17$$

where a, a^1, b, b^1, c, c^1, d and d^1 are constants. Using these equations

$$RGR = \frac{1}{w} \cdot \frac{dw}{dt} = \frac{d(\log_e W)}{dt} = b + 2ct + 3dt^2 \qquad \text{\_\_\_\_\_\_} 18$$

$$LAR = \frac{A}{W} = \text{antilog}_e (\log_e A - \log_e W) \qquad \text{\_\_\_\_\_\_} 19$$

$$NAR = \frac{RGR}{LAR} \qquad \text{\_\_\_\_\_\_} 20$$

These equations, 18, 19, 20, enable instantaneous measures of R.G.R., N.A.R. and L.A.R. to be calculated.

Nichols and Calder (1973) demonstrated that increasing complexity of the regressions used to describe the changes with time in logged plant variables increases the standard errors of the derived growth analysis quantities. They also stated that over fitting is a real trap. Hunt and Parsons (1974) suggested that test should be made to determine the polynomial order that best describes the relationships of W and A with time.

The relationship between the dry weight of the leaf (W_L) and time can also be determined and the instantaneous SLA and LWR determined

$$\log_e W_L = a'' + b''t + c''\,t^2 + d''\,t^3 \qquad \text{\_\_\_\_\_\_}21$$

from which

$$SLA = \frac{A}{W_L} = \text{Antilog}_e\,(\log_e A - \log_e W_L) \qquad \text{\_\_\_\_\_\_}22$$

and

$$LWR = \frac{W_L}{W} = \text{Antilog}_e\,(\log_e W_L - \log_e W) \qquad \text{\_\_\_\_\_\_}23$$

Differences in the yield of various treatments may be explained by changes in the R.G.R. The R.G.R. variations could be due to its components N.A.R. or L.A.R. or both. N.A.R. can be considered as the difference between photosynthesis and respiration. A change in either will lead to a change in the N.A.R. However, photosynthesis and respiration cannot be easily measured in the field without altering the environment. Similarly, any changes in L.A.R. may be due to a change in the S.L.A. or L.W.R. or both.

The leaf area index (L.A.I.) is a term that has been used to define the leafiness of a crop, (Watson 1947) and is defined as the leaf area per unit area of land. In effect, L.A.I. is the number of layers of leaves of the crop, expressed as an average for the whole crop. This is a crude concept as leaves seldom form complete unbroken layers and are often at varying angles to to the horizontal (Hunt, 1978), however, it is still a useful measure of the leafiness of a crop.

CHAPTER TWO

MATERIALS AND METHODS

2.1 Experiment 1

The experimental area, 20 m x 18 m was situated in the Massey University Vegetable Crop Research Area on a Manawatu silt loam. It was sprayed with paraquat on the 26th of January, 1977 and ploughed on the 29th of January, 1977. Cultivation was carried out on the 2nd of February, 1977 along with fertilizer and herbicide application. The fertilizer, Ammophos 12:10:10, was broadcast over the whole area at the rate of 2.5 $t.ha^{-1}$ and rotary hoed in. 12 beds, 1.5 m wide and 20 m long, were marked out and Trifluralin, 1.0 $litres.ha^{-1}$, was sprayed onto the beds and immediately rotary hoed in to a depth of 6 - 8 cm.

The experimental design was a randomised complete block with 3 replications, 4 densities and 10 harvest dates. Traditional growth analysis techniques which calculate $\overline{RGR}$, $\overline{NAR}$, $\overline{LAR}$, $\overline{SLA}$ and $\overline{LWR}$ require independent samples, for example, the same t_2 figures cannot be used in both $t_2 - t_1$, and $t_3 - t_2$ calculations. This doubles the number of plots harvested at each harvest except for the first and last harvests. Consequently, this experiment comprised 216 plots. The 4 densities each had a rectangularity of 1.0 (see table 2.1)

Densities 1, 3, and 4 had a 10 plant sample and density 2 had a 9 plant sample. There was at least 20 cm of guard plants around each sample (see table 2.2).

Table 2.1: Plant density and spacing of the 4 treatments

Treatment	Spacing	Plants . m^{-2}
1	5 cm x 5 cm	400
2	10 cm x 10 cm	100
3	15 cm x 15 cm	44.44
4	20 cm x 20 cm	25

Table 2.2: Sample size and plot size of each density

Plants . m^{-2}	Rows long	Rows wide	Sample size
400	13	10	10
100	7	7	9
44.44	9	6	10
25	7	4	10

Frames were made up for each density to facilitate planting, with the area of each frame corresponding to each plot. The frames were laced with nylon twine spaced for each density. The position of each plot was marked out before planting. At planting, the appropriate frame was placed over the plot and one seed was planted to a depth of 3 cm in the centre of each square formed by the nylon twine.

All replications were planted on the 5th of February, 1977 with the cultivar 'Galatin 50,' and then irrigated. Water was then applied as and when necessary. Pest and disease control was achieved by spraying weekly with carbaryl at 1.7 kg . ha^{-1}

and benomyl at 1.4 kg . ha^{-1}, both applied with a 'Solo' motorised knapsack sprayer.

Hand weeding was necessary to remove Solanum nigrum and Chenopodium album. After weeding, the plots were gapped up on the 28th of February, 1977 using the guard plants from plots already harvested. Plants gapped up within the sample area were marked with a bamboo cane and were not included in the sampled plants.

A total of 10 harvests were taken on a weekly basis, commencing on the 17th of February, 1977. The following data were recorded from each plot:

(a) Number of plants harvested,

(b) Total leaf area,

(c) Dry weights of leaves, roots, stems, total beans and mature beans,

(d) Fresh weight of total and mature beans,

(e) Total number of flowers and flower shoots,

(f) Total number of beans,

(g) Total number of mature beans,

(h) Seed length of mature beans.

Dry weights were obtained by drying in an air oven for 2 days at 80°C. Leaf area was measured by a Lambda LI 3000 area meter. The maturity of the beans was initially assessed by sizing to sieve size grade 4 (8.34 mm to 9.53 mm).

2.2 Experiment 2

The cultivar 'Galatin 50' was also used for this experiment. The design was again a randomised complete block with 2 replications, 4 densities, 3 fertilizer levels and 10 harvest dates. The densities were the same as in experiment 1. The 3 fertilizer rates are shown in table 3.3. The compound fertilizer 'Ammophos' 12:10:10 was again used.

Table 3.3: The fertilizer level of each treatment

Fertilizer level	Tonnes . ha^{-1}
1	0
2	1.25
3	2.50

The experimental area, 80 m x 11 m, again sited on the Massey University Vegetable Crop Research Area, was sprayed with paraquat on the 9th of December 1977 and then ploughed on the 15th of December 1977. It was then cultivated to provide a fine tilth on the 22nd of December 1977 and marked out into 7 beds. Trifluralin, 1.0 litres . ha^{-1}, was rotary hoed into the top 6 - 8 cm of the soil on the 23rd of December 1977. The position of each plot was also marked out and the appropriate amount of fertilizer was applied and raked into the plot. The area was then left for 2 weeks and planting commenced on the 7th of January 1978. Replicate 1 was planted on the 7th of January and replicate 2 was planted on the 8th of January. Irrigation was applied after replicate 2 was planted and then applied as considered necessary. The whole area was sprayed with paraquat on the 9th of January 1978 to kill existing weeds. The use of this stale seed bed technique provided excellent weed control and no hand weeding was necessary. Pest and disease control were again controlled by weekly sprayings with carbaryl, 1.7 kg . ha^{-1}, and benomyl; 1.4 kg . ha^{-1}.

Harvesting commenced on the 25th of January 1978 and the same data as in experiment 1 was collected.

CHAPTER 3

EXPERIMENT 1

3.1 Results

3.1. 1 Growth Analysis

An analysis of variance on the relative growth rates ($\overline{\text{R.G.R.}}$), net assimilation rates ($\overline{\text{N.A.R.}}$), leaf area ratios ($\overline{\text{L.A.R.}}$), specific leaf areas ($\overline{\text{S.L.A.}}$) and leaf weight ratios ($\overline{\text{L.W.R.}}$) showed that both harvest date and density had a significant effect on these parameters but there were no significant interactions between harvest date and density.

Table 3.1: Time trends of $\overline{\text{RGR}}$, $\overline{\text{NAR}}$, $\overline{\text{LAR}}$, $\overline{\text{SLA}}$, $\overline{\text{LWR}}$ and $\overline{\text{LAI}}$ (all $p < .01$)

Harvest	$\overline{\text{RGR}}$ g/g/day	$\overline{\text{NAR}} \times 10^{-3}$ $g/cm^2/day$	$\overline{\text{LAR}}$ cm^2/gm	$\overline{\text{SLA}}$ cm^2/gm	$\overline{\text{LWR}}$ g/g	$\overline{\text{LAI}}$
1-2	0.0575	0.540	105	303	0.345	0.52
2-3	0.1041	0.596	176	314	0.565	1.35
3-4	0.1262	0.804	162	278	0.588	2.38
4-5	0.0750	0.536	145	261	0.559	3.28
5-6	0.0606	0.437	138	274	0.515	4.58
6-7	0.0561	0.457	127	257	0.509	6.24
7-8	-0.0029	-0.009	111	244	0.463	6.36
8-9	0.0179	0.200	95	237	0.403	6.51
9-10	0.3524	0.459	81	244	0.341	7.11
S.E. (70 df)	0.02048	0.1710	5.5	12.8	0.0150	2.272

The time trends presented in table 3.1 show that the $\overline{\text{R.G.R.}}$, after an initial increase, continued to fall until flowering (harvest 8), after which it increased. The $\overline{\text{N.A.R.}}$ followed as similar pattern with time but the L.A.R. followed a parabolic pattern with time. The L.W.R. followed a similar time trend to the L.A.R., whereas, the S.L.A. did not follow a smooth pattern with time.

Table 3.2: Effects of density on $\overline{RGR}$, $\overline{NAR}$, $\overline{LAR}$, $\overline{SLA}$, $\overline{LWR}$, and $\overline{LAI}$ (all $p < .01$)

Plants.m^{-2}	$\overline{RGR}$ g/g/day	$\overline{NAR}$ x10^{-3} g/cm^2/ day	$\overline{LAR}$ cm^2/gm	$\overline{SLA}$ cm^2/gm	$\overline{LWR}$ g/g	$\overline{LAI}$
400	0.0306	0.207	137	321	0.422	7.01
100	0.0576	0.425	127	270	0.469	4.29
44.44	0.0650	0.498	123	246	0.502	3.11
25	0.0824	0.652	119	235	0.512	2.34
S.E. (70 df)	0.01366	0.1140	3.7	8.5	0.0100	1.437

Table 3.2 shows that as density increases, the $\overline{RGR}$, $\overline{NAR}$, and $\overline{LWR}$ all decrease, whereas, the $\overline{LAR}$, $\overline{LAI}$ and $\overline{SLA}$ increased.

3.1.2 Morphology

Table 3.3 shows that as density increases, there is a decrease in the number of beans/ flowering shoot, Flowering shoots/plant, flowers/plant, beans/plant and the percentage of flowers that are set. The number of flowers/shoot shows a slight increase with increasing density.

Table 3.3: Effects of density on the morphology of plants

Plants/ m^2	Flowers/ shoot	Beans/ shoot	Flowering shoots /plant	Flowers/ plant	Beans/ plant	% set
400	4.3	2.3	1.8	7.6	3.9	52.8
100	4.1	2.5	5.0	20.7	12.4	60.1
44.44	4.2	2.8	8.4	35.4	23.4	66.2
25	4.0	2.9	11.9	47.1	34.7	73.7

Table 3.4: Mature bean data at harvest 10

Plants /m^2	Mature beans /shoot	Mature beans /plant	%beans mature	seed length(*)	Mean fresh weight /pod (gm)
400	0.05	0.08	2.0	51	4.4
100	0.16	0.82	6.6	57	5.1
44.44	0.24	2.00	8.6	60	5.5
25	0.28	3.21	9.2	68	5.9

(*) in mm from method described by Gane et. al. (1975).

Table 3.4 shows that as the density increases, the number of mature beans/flowering shoot and per plant, the percentage of beans, that are mature, the seed length and the mean fresh weight/pod all decrease.

When some of the data in tables 3.3 and 3.4 are converted to an area basis (table 3.5), some of the trends are reversed. As density increases, the number of flowering shoots/m^2, the number of flowers/m^2 and the number of beans/m^2 all increase. The number of mature beans/m^2 shows a parabolic pattern with density.

Table 3.5: Effects of density on the morphological components of yield/unit area

Plants $/m^2$	Flowering shoots/m^2	Number of flowers/m^2	Number of beans/m^2	Number of mature beans/m^2
400	704	3020	1582	32
100	500	2065	1241	82
44.44	373	1573	1042	89
25	295	1177	867	80

3.1. 3 Yield

Because of cold weather in the latter part of the trial, the resulting slow growth delayed the maturity as reflected in the seed length figures in table 3.4. With the need for weekly harvests, the experiment came to an end before full maturity had been reached.

Table 3.6: Total bean yield/plant (gm) and per ha (tonnes) at harvests 9 and 10.

Plants	Yield/plant (gm)			Yield/ha (tonnes)		
$/m^2$	Harvest 9	Harvest 10	Mean	Harvest 9	Harvest 10	Mean
400	2.1	5.0	3.6	8.4	20.0	14.2
100	6.3	18.4	12.4	6.3	18.4	12.4
44.44	12.7	40.4	26.6	5.6	17.9	11.8
25	16.1	66.6	41.4	4.0	16.6	10.3
Mean	9.3	32.6	21.0	6.1	18.3	12.2

S.E. of Harvest (14df) = 1.92
S.E. of Density (14df) = 2.72
S.E. of Harvestxdensity (14df) = 3.89

S.E. of Harvest (14df) = 1.33
S.E. of Density (14df) = N.S.
S.E. of Harvestxdensity (14df) = N.S.

Table 3.6 shows that as density increases, the yield of total beans/plant decreases at both harvest times. All densities, except the highest, show a significant increase in total bean yield/plant from harvest 9 to harvest 10, with the lowest density showing the greatest increase.

Table 3.7: Mature bean yield/plant (gm) and per ha (tonnes) at harvest 10

Plants $/m^2$	Mature yield /plant (gm)	Mature yield /ha (tonnes)
400	0.5	2.1
100	4.2	4.2
44.44	11.0	4.9
25	19.0	4.7
S.E. (6df)	3.43 ($p < .01$)	N.S.

As density increases, the mature bean yield/plant decreases markedly. Although not significant the mature bean yield/ha shows a parabolic pattern with density. The mean bean yield in this trial was 3.975 tonnes/ha.

3.2 Discussion

The results presented in table 3.1 shows that the $\overline{\text{R.G.R.}}$ to be dependent on the $\overline{\text{N.A.R.}}$, which shows a similar pattern with time, rather than the $\overline{\text{L.A.R.}}$ The efficiency of the leaves as producers of photosynthates (i.e. $\overline{\text{N.A.R.}}$) starts to decline with age after intra-plant competition for light begins. Once the pods are set, the $\overline{\mathrm{N.A.R.}}$ increases rapidly, with the rise at this stage probably due to a strong sink effect of the pods. This is similar to the results found by Moorby (1968) with potatoes, where, after tuber initiation, the $\overline{\mathrm{N.A.R.}}$ showed a rapid increase.

The $\overline{\mathrm{L.A.R.}}$ after an initial slight increase fell steadily with time. In proportion, greater structural growth (stems) is required to support the leaves as time goes on and the lower leaves will begin to senesce, leading to a reduction in the $\overline{\mathrm{L.A.R.}}$, brought about by a reduction in $\overline{\mathrm{L.W.R.}}$ and $\overline{\mathrm{S.L.A.}}$

The efficiency of the leaves as producers of assimilates falls with increasing density due to competition for light caused by shading, which in turn is due to a higher $\overline{\mathrm{L.A.I.}}$ The $\overline{\mathrm{S.L.A.}}$ also increases with increasing density and may play a part in the lower $\overline{\mathrm{N.A.R.}}$'s. Plants with a low $\overline{\mathrm{S.L.A.}}$, that is, 'thick' leaves, may absorb more radiation or convert it to photosynthates more efficiently than leaves with a high $\overline{\mathrm{S.L.A.}}$, that is, 'thin' leaves.

The decreasing $\overline{\mathrm{N.A.R.}}$ with increasing density is also manifest in the decreasing seed lengths, that is, as density increases, the maturity of the pods is delayed.

The potential for yield/plant at high density is reduced by fewer flowers/plant, decreased flower set and a reduced fresh weight/ pod. The decreased fresh weight/pod at the high density may be due to a difference in the relative maturity of the beans at each density.

The reduction in the number of flowers/plant with increasing density is due to a reduction in the number of flowering shoots/plant because as density increases, lateral branching is suppressed and so the number of flowering shoots/plant will decrease (Jones, 1967). The number of flowers/flowering shoot are relatively unaffected by changes in density. The reduction in the number of beans/plant and number of mature beans/plant with increasing density is due to a higher flower abortion and pod abortion rate.probably caused by a lower N.A.R., that is, a reduced assimilate supply.

Based on the number of flowers produced/m^2, there is a higher potential for yield at the higher densities, even though, on a per plant basis there are less flowers. However, for the reasons above; the actual yield is lower. Also, at a density of 400 plants/m^2 there were some plants that did not produce any flowers and / or beans. Every plant at 100 plants/m^2 produced flowers but not all produced mature beans. Thus, some plants at the higher densities may be classed as 'weeds' because they contribute nothing to marketable yield but still compete for resources. All plants at the lower densities produced mature beans.

3.2. 1 Yield-density relationships

The total dry matter yield/plant was fitted to the yield-density equation.

$$w^{-\theta} = A\rho + B \qquad \text{———} 4$$

Where A and B are constants and w is the dry matter yield/plant at density ρ. For the whole plant, θ was assumed to equal unity as the total dry matter usually exhibits an asymptotic relationship with density (Bleasdale and Thompson, 1966; Jones, 1967, Nichols, 1974). Equation 4 is a competition model, and as such, is only applicable where competition is occuring (Nichols, 1970). Thus, before the data was fitted to this model, an analysis of variance was carried out on the dry matter yield at each harvest to determine if there were any significant differences in the dry matter yield between the densities. The results showed that there were no significant differences until the fourth harvest date. The total dry matter data from harvest 4 to 10 were then fitted to equation 4 using the weighted least squares method.

An analysis of variance on the A and B parameters showed that both fell with time. $\frac{1}{B}$ can be considered as the genetic yield potential of a plant growing free of competition. The $\log_e \frac{1}{B}$ figures were analysed using orthogonal polynomials and was found to have a significant quadratic relationship with time (table 3.8). This indicates that the genetic potential increases with time up to a point and then decreases, which describes closely the growth of an annual plant. $\frac{1}{A}$ can be considered as the yield potential of the environment. The $\log_e \frac{1}{A}$ figures were also analysed using orthogonal polynomials and a linear relationship with time was found (table 3.9) indicating that with time, the environmental potential yield increases.

The total bean dry weight data from harvests 9 and 10 was also fitted to equation 4. The yield of a plant part usually follows a parabolic relationship with time and, hence, a θ value of less than unity is appropriate. Jones (1967) was not able to detect a θ of less than unity (using fresh weights) although he states that a lesser value would be appropriate. Stang (1974) and

Nichols (1974) who also used fresh weight, using equation 5, have found values of less than unity.

$$\log_{10} W_T = K + \theta \cdot \log_{10} W_p \qquad \text{—— 5}$$

where W_T is the total plant weight and W_p the weight of the plant part.

Table 3.8: B and $\log_e \frac{1}{B}$ at harvests 4 to 10

Time (Harvest)	B	$\log_e \frac{1}{B}$
4	.383	0.966
5	.202	1.611
6	.103	2.424
7	.045	3.145
8	.032	3.491
9	.032	3.474
10	.014	4.740
S.E. (13df)	.0243 ($p < .01$)	2.46 ($p < .01$)

The relationship of $\log_e \frac{1}{B}$ to time was found to be described by

$$y = -2.795 + 1.008x - .039x^2$$

Table 3.9: A and $\log_e \frac{1}{A}$ at harvests 4 to 10

Time (Harvest)	A($\times 10^{-3}$)	$\log_e \frac{1}{A}$
4	1.626	6.432
5	1.495	6.509
6	1.305	6.715
7	1.121	6.795
8	1.179	6.766
9	0.792	7.146
10	0.[illegible]09	7.142
S.E. (12df)	.2494 ($p < .05$)	.2160 ($p < .05$)

The relationship of $\log_e \frac{1}{A}$ was found to be described by

$$\bar{y} = 5.9238 + 0.1232\, x$$

Analysis of variance on the θ's obtained with this equation (using dry weights) showed no significant difference between the two harvest times so a mean θ value of 0.8745 was used to fit the bean dry weight to equation 4 using the weighted least squares method.

Analysis of variance showed no significant difference in the A parameter but the B parameter fell significantly with time ($p < .05$) (table 3.10).

Table 3.10: A and B parameters for bean dry weight at harvests 9 and 10

Harvest	A Parameter	B Parameter
9	0.009183	0.5163
10	0.005497	0.0949
S.E. (13df)	N.S.	0.07920 ($p < .05$)

The lack of time data do not enable clear conclusions to be drawn.

CHAPTER 4

EXPERIMENT 2

4.1 Results

4.1. 1 Growth Analysis

The $\overline{R.G.R.}$ (Table 4.1) was significantly affected by harvest ($p < .01$) and density ($p < .01$) but there was no significant interaction.

Table 4.1: $\overline{RGR}$ at each harvest for each density g/g/day

Plants /m²	Harvest period 1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Density Mean
400	.0781	0.235	.0206	.0186	.0314	.0225	.0173	.0247	-.0060	.0256
100	.1190	.1026	.0562	.0716	.0542	.0409	.0451	.0079	.0022	.0555
44.44	.1141	.1064	.1335	.0328	.0421	.0368	.0725	-.0012	.0263	.0626
25	.1292	.1225	.0903	.0787	.0637	.0663	.0596	.0102	.0008	.0690
Mean	.1101	.0888	.0751	.0504	.0471	.0416	.0486	.0104	.0058	

S.E. of harvest (107df) = .01236 ($p < .01$)   S.E. of density (107df) = .00823 ($p < .01$)

S.E. of harvest by density (107df) = N.S.

The results presented in table 4.1 show that the $\overline{R.G.R.}$ falls with time until pod set (harvest 6-7), when it shows a slight increase, and then continues to fall. This is similar to the results in experiment 1. As density increases, the $\overline{R.G.R}$ falls markedly which is also similar to the results of the first experiment. Although there was no significant harvest by density interaction, as density increases, the rise in $\overline{R.G.R.}$ at pod swell is occuring at a later time.

The $\overline{N.A.R.}$ (Table 4.2) was also significantly affected by harvest ($p < .01$) and density ($p < .01$) and there was no significant interaction between harvest and density.

Table 4.2: $\overline{NAR}$. (x 10^{-7}) at each harvest for each density g/cm^2/day

Plants /m^2	Harvest period 1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Density Mean
400	529	141	136	125	250	217	263	386	-263	198
100	873	720	412	525	486	476	674	165	107	493
44.44	845	768	1126	268	383	429	880	-197	603	587
25	986	891	771	666	623	776	907	174	171	646
Mean	808	630	611	396	435	475	681	176	116	

S.E. of harvest (107df) = 1657.7(x10^{-7})($p < .01$)
S.E. of density (107df) = 1105.1(x10^{-7})($p < .01$)
S.E. of harvest by density (107df) = N.S.

The result in table 4.2 show that the $\overline{N.A.R.}$ decreases with time until flowering (harvest 5-6) when it increases up to maturity and then decreases again, which is a similar trend to the $\overline{R.G.R.}$ except that the rise occurs earlier. As density increases, the $\overline{N.A.R.}$ falls markedly.

The $\overline{L.A.R.}$ was significantly affected by harvest date ($p < .01$), density ($p < .01$) and there was a harvest by density interaction ($p < .01$) (table 4.3). The $\overline{L.A.R.}$ after an initial slight increase continued to fall throughout the period of the trial, that is, it followed a parabolic pattern with time. As density increased, the

$\overline{\text{L.A.R.}}$ also increased. The harvest by density interaction shows that at the beginning, the high density plants have a higher $\overline{\text{L.A.R.}}$ and the initial increase is also greater than with the low density plants, but, as time goes on, the difference in $\overline{\text{L.A.R.}}$ between densities becomes less until finally they are all very similar.

Table 4.3: $\overline{\text{LAR}}$ at each harvest for each density cm^2/g

Plants $/m^2$	Harvest period 1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Density Mean
400	148	166	154	132	123	98	80	66	53	113
100	136	142	134	132	112	86	67	58	44	101
44.44	136	141	119	123	110	87	67	57	47	98
25	131	137	121	117	102	86	66	54	47	96
Mean	137	146	132	126	112	89	70	59	48	

S.E. of harvest (107df) = 2.2 ($p < .01$)
S.E. of density (107df) = 1.5 ($p < .01$)
S.E. of harvest by density (107df) = 4.5 ($p < .01$)

The $\overline{\text{S.L.A.}}$ was significantly affected by harvest ($p < .01$), density ($p < .01$) and there was a significant harvest by density interaction ($p < .01$) (table 4.4).

The results in table 4.4 shows that the $\overline{\text{S.L.A.}}$ to vary in an erratic manner with time, decreasing until harvest 3-4 then increasing until flowering (harvest 6-7), then another fall until it finally increases at the end. The lowest density fluctuated the least throughout the trial whilst the plants at $44.44/m^2$ fluctuated the most. As density increased, the $\overline{\text{S.L.A.}}$ also increased.

Table 4.4: $\overline{\text{S.L.A.}}$ at each harvest for each density cm^2/g

Plants $/m^2$	Harvest period 1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Density Mean
400	288	313	311	303	318	315	287	284	308	303
100	239	245	241	259	259	248	240	231	261	248
44.44	234	234	200	234	245	240	225	232	253	233
25	226	226	206	217	225	226	213	216	236	221
Mean	247	254	240	254	262	257	241	243	265	

S.E. of harvest (107df) = 4.7 ($p < .01$)
S.E. of density (107df) = 3.1 ($p < .01$)
S.E. of harvest by density (107df) = 9.3 ($p < .05$)

The $\overline{\text{L.W.R.}}$ was significantly affected by harvest ($p < .01$), density ($p < .01$) and there was also a harvest by density interaction ($p < .01$) (table 4.5).

Table 4.5: $\overline{\text{L.W.R.}}$ at each harvest for each density g/g

Plants $/m^2$	Harvest period 1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Density Mean
400	.5733	.5319	.4946	.4368	.3867	.3125	.2760	.2317	.1751	.3732
100	.5694	.5828	.5570	.5095	.4340	.3478	.2771	.2390	.1689	.4095
44.44	.5805	.6017	.5982	.5227	.4496	.3632	.2961	.2459	.1844	.4269
25	.5800	.6057	.5952	.5426	.4566	.3786	.3079	.2512	.2002	.4353
Mean	.5608	.5805	.5612	.5029	.4317	.3505	.2897	.2419	.1821	

S.E. of harvest (107df) = .00576 ($p < .01$)
S.E. of density (107df) = .00384 ($p < .01$)
S.E. of harvest by density (107df) = .01152 ($p < .01$)

The results of table 4.5 show that the $\overline{\text{L.W.R.}}$ after an initial increase falls throughout the rest of the growing period. As the density increases, the L.W.R. also increases. The harvest by density figures are very similar to those of the $\overline{\text{L.A.R.}}$ figures.

The $\overline{\text{L.A.I.}}$ was significantly affected by harvest ($p < .01$), density ($p < .01$) and there was also a harvest by density interaction ($p < .01$) (table 4.6).

Table 4.6: $\overline{\text{LAI}}$ at each harvest for each density

Plants /m^2	Harvest period 1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Density Mean
400	3.48	5.51	6.72	8.01	8.54	7.52	7.19	7.02	6.27	6.44
100	1.13	2.48	3.77	5.33	6.71	6.52	6.12	5.09	4.13	4.37
44.44	0.57	1.25	2.39	3.63	4.65	5.03	5.35	5.24	4.76	3.55
25	0.31	0.86	1.61	2.74	3.94	4.56	4.89	4.94	4.91	3.13
Mean	1.37	2.53	3.62	4.93	5.96	5.91	5.89	5.57	5.02	

S.E. of harvest (107df) = 0.246 ($p < .01$)
S.E. of density (107df) = 1.55 ($p < .01$)
S.E. of harvest by density (107df) = .491 ($p < .01$)

The results in table 4.6 show that $\overline{\text{L.A.I.}}$ increases in the beginning and then decreases in the latter part. As density increases the $\overline{\text{L.A.I.}}$ increases. From the harvest by density figures, it can be seen that as density increases, the $\overline{\text{L.A.I.}}$ peaks earlier, that is, leaf production ceases at and earlier stage with increasing density.

The level of fertilizer applied had a significant effect on the $\overline{\text{L.W.R.}}$ ($p < .01$) and there was a significant fertilizer by time interaction ($p < .05$) (table 4.7).

The results presented in table 4.7 show that the $\overline{\text{L.W.R.}}$ increases with the level of fertilizer applied. From the fertilizer by time figures it can be seen that as time goes on, the higher fertilizer is maintaining a higher $\overline{\text{L.W.R.}}$

Table 4.7: $\overline{\text{LWR}}$ for each level of fertilizer at each harvest g/g

Fertilizer	Harvest period									Fertilizer
tonnes/ha	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Mean
0	.5512	.5733	.5651	.5098	.4179	.3367	.2720	.2359	.1617	.4028
1.25	.5617	.5798	.5585	.5117	.4345	.3499	.3014	.2403	.1853	.4137
2.50	.5694	.5885	.5602	.4871	.4411	.3650	.2944	.2497	.1955	.4172

S.E. of fertilizer (107df) = .00353 ($p < .01$)
S.E. of harvest (107df) = N.S.
S.E. of harvest by fertilizer (107df) = .00998 ($p < .05$)

There was also a significant harvest by fertilizer effect on the $\overline{\text{L.A.R.}}$ ($p < .05$) (table 4.8).

Table 4.8: $\overline{\text{LAR}}$ for each level of fertilizer at each harvest cm^2/g

Fertilizer	Harvest period								
tonnes/ha	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
0	140	153	137	130	109	88	65	58	42
1.25	138	145	130	124	116	90	74	58	49
2.50	134	142	134	124	110	90	70	60	52

S.E. of harvest (107df) = N.S.
S.E. of fertilizer (107df) = N.S.
S.E. of harvest by fertilizer (107df) = 3.9 ($p < .05$).

The results in table 4.8 show that initially the lower fertilizer level has the highest $\overline{L.A.R.}$ but with time, the highest fertilizer level maintains the $\overline{L.A.R.}$ at a higher level compared to the lower fertilizer level.

Fertilizer also had a significant effect on the $\overline{S.L.A.}$ ($p < .01$) and the $\overline{L.A.I.}$ ($p < .01$) (table 4.9).

Table 4.9: Effect of fertilizer level on $\overline{SLA}$ and $\overline{LAI}$ (both $p < .01$)

Fertilizer tonnes/ha	$\overline{SLA}$ cm^2/g	$\overline{LAI}$
0	256	4.14
1.25	251	4.42
2.50	247	4.55
S.E. (107df)	2.7	0.135

Table 4.9 shows that as the level of fertilizer increases the $\overline{L.A.I.}$ increases but the $\overline{S.L.A.}$ decreases, that is, more leaves are produced with the application of fertilizer and they are also 'thicker' than leaves of a low fertilizer level.

4.1. 2 Morphology

The data presented in table 4.10 shows that as density increases the number of flowers/shoot, beans/shoot, flowering shoots/plant, flowers/plant, beans/plant and the percent set all decreases

Table 4.10: Effects of density on the morphology of the plant

Plants /m^2	Flowers /shoot	Beans /shoot	Flowering Shoots /plant	Flowers /plant	Beans /plant	% Flower set
400	3.07	1.84	2.58	7.92	4.74	60
100	4.22	3.51	4.39	18.51	15.43	83
44.44	4.59	4.01	6.22	28.54	24.92	87
25	5.76	4.93	7.93	45.70	39.12	86

Table 4.11: Mean mature bean data from harvests 7 to 10

Plants /m^2	Mean mature beans/shoot	Mean mature beans/plant	% mature beans	Mean mature bean weight (g)
400	0.39	1.01	21.3	4.49
100	0.80	3.50	22.7	7.15
44.44	1.15	7.13	28.6	6.95
25	1.59	12.59	32.2	8.44

As density increases, the mean number of mature beans/shoot, mean number of mature beans/plant, percent of beans that are mature, and the mean mature bean weight all decrease (table 4.11).

When some figures in tables 4.10 and 4.11 are converted to an area basis (table 4.12), as density increases, so does the number of flowering shoots/m^2, the number of flowers/m^2, the number of beans/m^2 and the mean number of mature beans/m^2.

In general fertilizer had very little effect on the morphology of the plant. Table 4.13 shows that fertilizer had a significant effect on the number of beans/plant ($p < .01$) but when these figures were converted to an area basis, there was no significant differences. As the level of fertilizer increases, the number of beans/plant also increases.

Table 4.12: Effect of density on the morphological components per m^2

Plants $/m^2$	Flowering shoots$/m^2$	Flowers $/m^2$	Beans $/m^2$	Mean mature beans$/m^2$
400	1032	3168	1896	404
100	439	1851	1543	350
44.44	276	1268	1107	317
25	198	1143	978	315

Table 4.13: Effect of fertilizer on the number of beans per plant

Fertilizer (tonnes/ha)	Number of beans/plant
0	16.8
1.25	17.1
2.50	19.1

S.E. of fertilizer (47df) = 0.79 ($p < .01$)

The level of fertilizer also had a significant interactive effect with time on the number of flowers/plant ($p < .01$) (table 4.14).

Table 4.14: Flowers/plant at each harvest date for each fertilizer level

Fertilizer (tonnes/ha)	4	5	6
0	7.12	11.96	4.09
1.25	7.65	12.12	6.23
2.50	5.94	11.93	8.48

S.E. of harvest by fertilizer (35df) = 1.056 ($p < .01$)

The results in table 4.14 show that as the level of fertilizer increases, the flowering period is prolonged and the peak flowering period occurs at a later stage.

Density had a significant effect with time on the number of flowers/plant ($p < .01$) (table 4.15).

Table 4.15: Flowers/plant at each density at each harvest date

Plants P/m^2	Harvest 4	5	6
400	2.72	4.86	0.35
100	7.32	9.42	1.78
44.44	7.77	14.36	6.41
25	9.81	19.37	16.52

S.E. of harvest by density (35df) = 1.221 ($p < .01$)

The results in table 4.15 show that the flowering period becomes more compact as density increases. This is similar to the results of Jones (1967).

Density also had a significant effect with time on the number of beans/plant ($p < .01$) (table 4.16). The results show that the lower densities retain more pods on the plant, or conversely, the plants at the higher densities have a higher pod abortion rate than the plants at the lower densities.

There was a significant harvest by density interaction on the mean total bean weight ($p < .05$) (4.17).

Table 4.16: Beans/plant for each density at each harvest

Plants /m^2	Harvest 7	8	9	10
400	5.1	4.4	3.7	2.9
100	16.2	13.9	10.9	9.8
44.44	25.0	24.8	18.7	17.33
25	40.2	35.2	29.8	25.0

S.E. of harvest by density (47df) = 1.591 ($p < .01$)

Table 4.17: Mean total bean weight (g) for each density at each harvest

Plants /m^2	Harvest 7	8	9	10
400	0.73	1.40	1.72	2.03
100	1.35	2.28	3.08	3.57
44.44	1.75	2.55	2.90	3.88
25	1.99	2.59	3.75	4.61

S.E. of harvest by density (47df) = 0.314 ($p < .05$)

The results in table 4.17 show that the pods at the lower densities are still increasing in weight in a linear fashion, whereas with the pods at the high density, the increase in weight is slowing down, that is, at high density the maturity is more compact.

There was also a significant harvest by density interaction on the number of mature beans/plant ($p < .01$) (table 4.18). The results show that the number of beans reaching maturity at the high density is starting to decrease, whereas, at the low density, the number of beans reaching maturity is still increasing.

Table 4.18: Number of mature beans/plant at harvest for each density

Plants $/m^2$	Harvest 7	8	9	10
400	0.30	0.89	1.44	1.39
100	1.44	3.99	4.06	4.50
44.44	2.90	8.41	7.55	9.67
25	5.25	12.50	15.64	16.95

4.1. 3 Yield

The yield of beans was looked at in terms of crop maturity. Using the orthogonal polynomial approach, it was found that the seed length, which was determined using the method described by Gane et. al. (1975), varied in a quadratic manner with time. Analysis of variance showed that density and time had a significant effect on the seed length (both $p < .01$) but there was no significant interactions on significant fertilizer effects. Plots of seed length against time for each density are shown in figures 4.1, 4.2, 4.3, 4.4.

The quadratic equations describing the relationship that seed length had with time were determined using polynomial curve fitting for each density and replicate. The time of 110 mm seed length, the optimum seed length for 'Galatin 50', was then ascertained from these equations. Although not significant, the trend was for maturity to

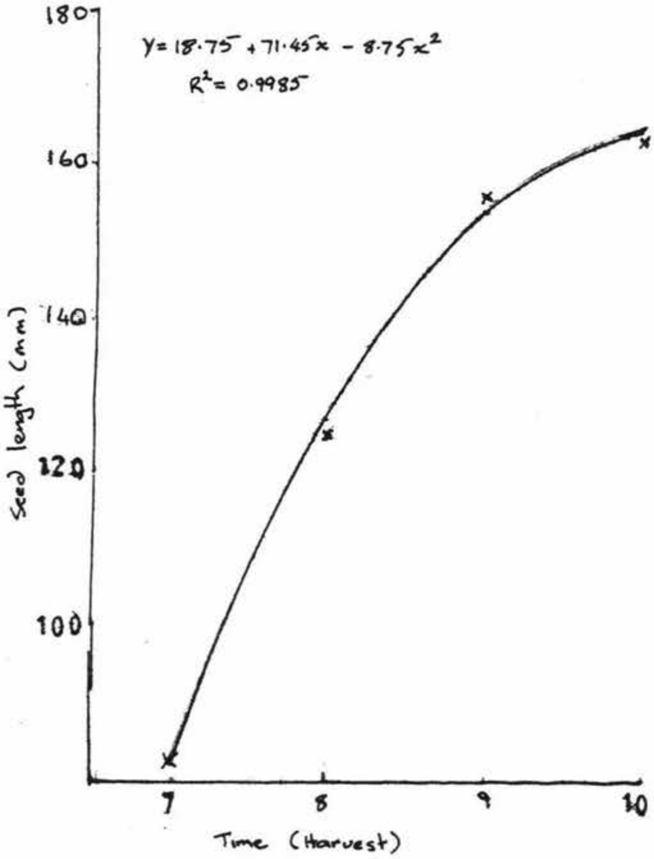

Fig. 4.1: Seed length vs time for 400 plants/m²

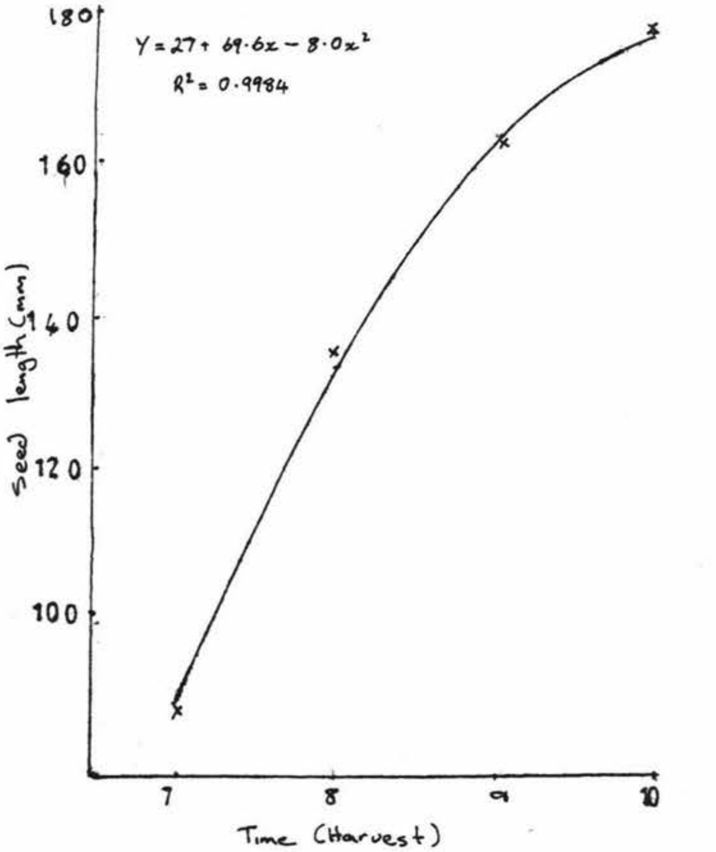

Fig. 4.2: Seed length vs time for 100 plants/m²

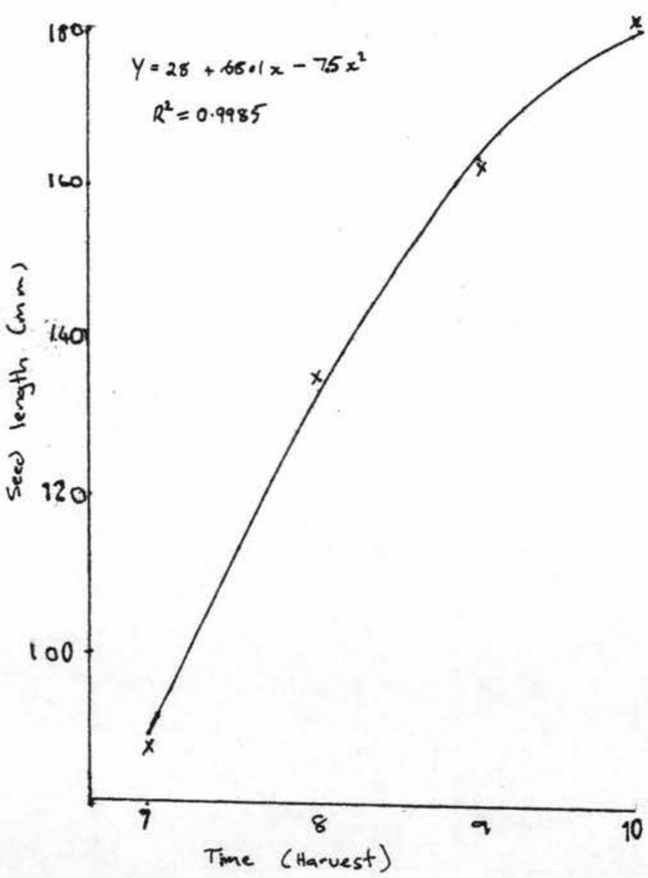

Fig 4.3: Seed length vs time for 44.44 plants/m²

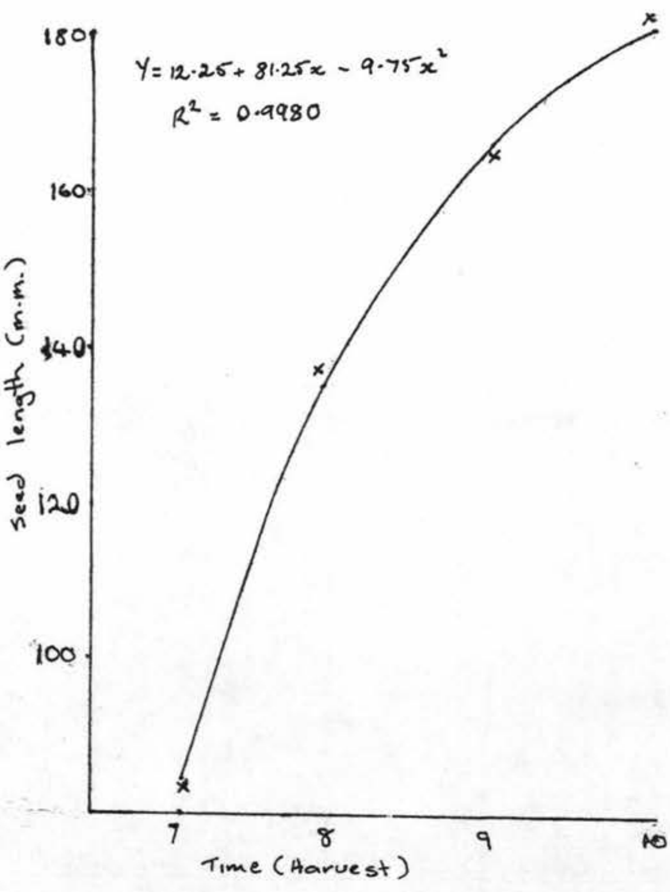

Fig 4.4: Seed length vs time for 25 plants/m²

be delayed with increasing density (table 4.19), which is similar to the results of Tompkins, Sistrunk and Horton, (1972).

Table 4.19: Weeks to maturity from first harvest for each density

Plants/m^2	Optimum maturity date (weeks)
400	7.5
100	7.3
44.44	7.3
25	7.2

S.E. of harvest by density (3df) = N.S.

The relationship between time and the mean total bean weight, the number of mature beans, and the mean mature bean weight were also found to be quadratic. Density and harvest date were the only factors to affect these parameters. With the total number of beans/plant, however, the fertilizer rate also had a significant effect ($p < .01$) (see table 4.13). However, when these figures were converted to an area basis it was found that the total number of beans/m^2 was affected by density and time only, with the relationship between the number of beans/m^2 and time being linear. From the polynomial equations, the total number of beans/m^2, mean total bean weight, the number of mature beans/plant and the mean mature bean weight were calculated for each density and replicate at the time of optimum maturity as determined from table 4.19. The results are shown in table 4.20 with the number of mature beans/plant converted to an area basis.

Table 4.20: Components of yield at optimum maturity for each density (all $p < .01$)

Plants $/m^2$	Total Beans $/m^2$	Mean Total Bean weight (g)	Mature Beans $/m^2$	Mean Mature bean weight (g)
400	1896	1.06	266	4.54
100	1543	1.68	222	6.52
44.44	1108	2.14	206	7.02
25	978	2.41	183	8.01
S.E. of density (47df)	84.2	0.052	16.4	0.215

At maturity, the total number of beans/m^2 and the number of mature beans/m^2 both increase with increasing density. However, the mean total bean weight and the mean mature bean weight both decrease with increasing density.

The total number of beans/m^2 was multiplied by the mean total bean weight at optimum maturity and the result converted to yield/ha (table 4.21). The number of mature beans was multiplied by the mean mature bean weight, at optimum maturity, with the result again being converted to yield/ha (table 4.21).

Analysis of variance on the data in table 4.21 showed that density had no effect on either the total or mature bean yield/ha at optimum maturity. The mean total bean yield was 23.3 tonnes/ha and the mean mature bean yield was 13.95 tonnes/ha. The total yield of beans/unit area shows a parabolic relationship with time.

Table 4.21: Yield of mature and total beans (tonnes/ha) at optimum maturity

Plants /m^2	Total beans	Mature beans	Harvestable Yield
400	20.1	12.10	16.1
100	25.9	14.57	20.2
44.44	23.7	14.47	19.1
25	23.6	14.68	19.1
Mean	23.3	13.95	18.6

S.E. of density (4df) = N.S. (for both total and mature beans)

The mature bean yield is a measure of beans that were greater than sieve size 4 but would still add to the total yield. The harvestable yield in table 4.21 is an approximation of the yield that could have been obtained by machine harvesting by using the following formula:

$$\text{Harvestable yield} = (\text{Total yield} - \text{Mature yield})/2 + \text{Mature Yield}$$

4.2 Discussion

The results of experiment 2 agree with those of experiment 1 and showed the $\overline{\text{R.G.R.}}$ to be dependant on the $\overline{\text{N.A.R.}}$ component rather than the $\overline{\text{L.A.R.}}$ component. The $\overline{\text{N.A.R.}}$ again shows a rise at the flowering stage (harvest 6) probably due to the sink effect of the pods. It is unlikely that the ability of the pods to re-fix CO_2 from respiration to play an important part in the initial increase in the $\overline{\text{N.A.R.}}$ around flowering/pod set.

As density increases, the $\overline{\text{L.A.I.}}$ also increases and it peaks earlier. The $\overline{\text{N.A.R.}}$, however, decreases with increasing density probably due to the shading effect causing inter and intra-plant competition for light. The $\overline{\text{S.L.A.}}$ also may play a role in that it increases with increasing density - the 'thicker' leaves of the lower density may absorb more radiation or convert it more efficiently to photosynthates. The lower densities maintain the $\overline{\text{L.W.R.}}$. at a higher level than do the higher densities. Thus, leaf production is being maintained at the lower densities for a longer period whilst at the higher densities leaf production ceases at an earlier stage. Thus, although there is a greater leaf area at high densities, those leaves are not as efficient in producing assimilates.

The level of fertilizer had very little effect on the growth analysis parameters. As the level of fertilizer increases, the leaves comprise a greater proportion of plant weight ($\overline{\text{L.W.R.}}$) through an increased area ($\overline{\text{L.A.I.}}$) and 'thickness' ($\overline{\text{S.L.A.}}$). Also, at later harvest, the higher fertilizer levels maintain a higher $\overline{\text{L.A.R.}}$ and $\overline{\text{L.W.R.}}$ than the lower fertilizer levels.

The potential for yield/plant at high density is reduced in 3 ways

(a) Firstly by a lower number of flowers/plant, and

(b) Secondly, a higher flower abortion rate, and

(c) Thirdly, the beans are of a lesser weight when mature.

It is likely that all of the above reasons for a lower yield are brought about by the lower $\overline{\text{N.A.R.}}$ at the higher density. Inter and intra-plant competition limit the supply of assimilates available for growth. The reduction in the number of flowers/plant is due to a reduction in the number of flowering shoots/plant and in the number of flowers/flowering shoot with increasing density. In the first experiment, the number of flowers/flowering shoot showed a slight increase. The decrease in flowers/flowering shoot would be due to the lower N.A.R. as would the higher flower abortion rate and the lower mean bean weight. The decreases in the number of total beans and mature beans/plant would be due to the higher flower abortion rate initially, along with the lower N.A.R.

Again, on an area basis, the higher densities have the potential for the highest yield. However, due to the reasons above the actual yield is lower. As density increases, the number of total beans and mature beans increases but their mean weight decreases, that is, there is a negative correlation between pod number and pod weight. This decreasing size of each economic unit with increasing density also occurs with onions (Bleasdale and Thompson, 1966), tomatoes (Fery and Janick, 1970, 1971), and sweet corn (Mack,1972). The level of fertilizer applied did not increase the N.A.R. and this is probably why it did not affect the mean bean weight; it only increased the number of beans/plant.

Density also had a effect on the time to maturity and the spread of maturity. As density increases, the flowering period occurs at a later stage. Increasing the level of fertilizer applied also had the same effect. This effect of a more compact but delayed flowering pattern due to increased density carried through to the maturity of the pods, that is, optimum maturity occurs at a later date but is more compact at the high density. The reduced size of each bean would offset the benefits of a more compact maturity which facilitates once over machine harvesting.

In this trial, not all sample plants at the high density produced flowers and some did not produce mature beans, although the 'average' plant did. Thus, again some plants, at the high density could be considered as weeds because they add nothing to the marketable yield.

Although optimum maturity is delayed at high densities, when yield comparisons of both total and mature beans/ha are made at the same seed length, density has no significant effect, which it does when yield comparisons are made at the same chronological time.

There were differences in the morphology between the plants of the two experiments. In experiment 1, as density decreased, the number of flowers/shoot decreased from 4.3 to 4.01 whereas in experiment 2 they increased from 3.07 to 5.76. The percentage set also showed a difference. In experiment 1 it fell from 73.7% to 52.8% with increasing density whereas in experiment 2 it fell from 86% to 60%. The higher percentage set in experiment 2 is probably due to warmer temperatures during the flowering period. The number of flowering shoots/plant in experiment 1 ranged from 1.8 at 400 plants/m^2 to 11.9 at 25 plants/m^2. In experiment 2 the number of flowering shoots/plant ranged from 2.58 at 400 plants/m^2 to 7.93 at 25 plants/m^2. However, the plants at densities of 25 to 100 in experiment 1 had more flowers than the corresponding plants in experiment 2. However, the lower percentage set of the plants in experiment 1 led to the plants in experiment 2 to have a greater number of beans/plant.

4.2. 1 Yield-density relationships

Analysis of variance on the total dry mattter showed there to be a significant difference due to density from the first harvest but only between the highest density and the other 3 densities, that is, the lower three densities did not vary significantly. It was not until the third harvest was there a significant difference between all densities. The total dry matter figures from harvests 3 to 10 were fitted to equation 4 using the weighted least squares method.

$$w^{-\theta} = A\rho + B \qquad \text{\_\_\_\_\_\_} 4$$

where w is the total dry matter at density ρ, A and B are constants. θ is assumed to be unity for the whole plant.

Analysis of variance on the constants, A and B, showed them to be significantly affected by the time only. Because the rate of fertilizer had no significant effect on the constant B, the total dry matter data was re-fitted to equation 4 using a constant intercept (B) for each harvest date. Analysis of variance on the resulting constant A's showed that they were significantly affected by time only. Nichols (1974) found the A parameter to have a significant decreasing linear relationship with increasing amounts of fertilizer.

$\frac{1}{A}$ can be considered as the yield potential of the environment. $\log_e \frac{1}{A}$ was found to have an increasing linear relationship with time (table 4.22).

The figures is table 4.22 are very similar to those is table 3.9. The equations which describe the relationships of $\log_e \frac{1}{A}$ with time are similar for both experiments.

Table 4.22: A and $\log_e \frac{1}{A}$ at harvest 3 to 10

Time (Harvest)	A	$\log_e \frac{1}{A}$
3	.001941	6.2444
4	.001728	6.3608
5	.001454	6.5337
6	.001269	6.6697
7	.00143	6.7745
8	.000957	6.9515
9	.000866	7.0516
10	.000813	7.1144
S.E. (20df)	.0002131 ($p < .01$)	.23196 ($p < .01$)

The relationship between $\log_e \frac{1}{A}$ and time was found to be described by:

$$y = 5.8690 + 0.1298 x$$

$\frac{1}{B}$ can be considered as the genetic yield potential of a plant growing free of competition. $\log_e \frac{1}{B}$ was found to have a quadratic relationship with time (table 4.23).

The figures in table 4.23 shows the genetic potential, $\log_e \frac{1}{B}$, increases with time up to a point and then decreases. The $\log_e \frac{1}{B}$ figures in table 4.23 are higher than the corresponding figures in table 3.8.

Table 4.23: B and $\log_e \frac{1}{B}$ at harvests 3 to 10

Time (Harvest)	B	$\log_e \frac{1}{B}$
3	.2362	1.4438
4	.0984	2.3195
5	.0515	2.9682
6	.0242	3.7381
7	.0122	4.4091
8	.0046	5.3638
9	.0041	5.5110
10	.0031	5.8131
S.E. (6df)	.2611 ($p < .01$)	2.5193 ($p < .01$)

The bean dry matter for each replicate by fertilizer rate by harvest date was fitted to equation 4. θ was calculated using the formula derived by Bleasdale (1967) using linear regression.

$$\log_{10} W_T = K + \theta \log_{10} W_p$$

where W_T is the total plant dry weight, W_p is the bean dry weight and K is a constant.

Analysis of variance showed θ to vary significantly ($p < .01$) with time only and a mean θ of 0.8505 is very similar to that for experiment 1, where θ was 0.8745. Nichols (1974) using fresh weight data found a θ value of 0.896.

Analysis of variance on these A's and B's showed them to vary significantly with time only ($p < .01$). If θ is less than unity, this suggests that with increasing plant density, a smaller proportion of assimilates is partitioned to the pods and more to the ...

stems and leaves (Nichols, 1974). A, $\log_e \frac{1}{A}$, and B $\log_e \frac{1}{B}$ for bean dry weight data are shown in table 4.24.

Table 4.24: A, $\log_e \frac{1}{A}$, B and $\log_e \frac{1}{B}$ for bean dry weight data

Time (Harvest)				
6	.01070	4.5373	.2981	1.2103
7	.00535	5.2302	.0542	2.9148
8	.00314	5.7626	.0263	3.6401
9	.00232	6.0672	.0247	3.7003
10	.00819	6.2721	.0189	3.9668
S.E. (14df)	.0017188 ($p<.01$)	.25321 ($p<.01$)	.03944 ($p<.01$)	.31683 ($p<.01$)

The figures in table 4.24 show that both A and B decrease with time $\log_e \frac{1}{A}$ and $\log_e \frac{1}{B}$ were both found to have a quadratic relationship with time, indicating that both the environmental potential bean yield and the genetic bean yield of a plant growing free of competition both increase and then decrease.

CONCLUSIONS

Snap beans were grown at 4 densities in two experiment. Three fertilizer levels were also included in the second experiment. Cold weather in the latter part of the growing season in experiment 1 resulted in slow growth and delayed maturity. With the need for weekly harvests, the experiment came to an end before pod maturity had occured.

The $\overline{\text{R.G.R.}}$ fell with time until pod swell when it showed an increase and then fell again. The $\overline{\text{N.A.R.}}$ followed a similar trend but the increase occured at flowering rather than pod swell, demonstrating the dependence of the $\overline{\text{R.G.R.}}$ on the $\overline{\text{N.A.R.}}$ component rather than $\overline{\text{L.A.R.}}$ component, which followed the normal ontogenetic drift of an initial increase followed by a steady decrease through the rest of the growing period. The $\overline{\text{L.W.R.}}$ followed a similar trend to the $\overline{\text{L.A.R.}}$ whilst the $\overline{\text{S.L.A.}}$ followed an erratic path with time.

Fertilizer had a significant effect on the $\overline{\text{S.L.A.}}$ which fell with increasing level of fertilizer and the $\overline{\text{L.W.R.}}$ which increased, indicating that more leaves are produced with the application of fertilizer and these leaves are 'thicker'. A higher rate of fertilizer will also maintain the $\overline{\text{L.A.R.}}$ and $\overline{\text{L.W.R.}}$ at a higher level.

The $\overline{\text{R.G.R.}}$, $\overline{\text{N.A.R.}}$ and $\overline{\text{L.W.R.}}$ fell with increasing density whereas the $\overline{\text{L.A.R.}}$, $\overline{\text{S.L.A.}}$ and $\overline{\text{L.A.I.}}$ all increased with increasing density, indicating that at the higher densities the leaves are less efficient in producing assimilates.

Yield results from the first experiment are incomplete as explained previously. As density increases the maturity of the pods is delayed, probably of the lower $\overline{N.A.R.}$ As density increases, the number of flowers/plant, beans/plant, and mature beans/plant and flower set all decrease but the number of flowers/m^2, beans/m^2 and the number of mature beans/m^2 all increase with increasing density. However, the mean bean and mean mature bean weight both decrease, thus, there is a negative correlation between the number of pods and pod size. As density increases, the flowering period becomes more compact as does the maturity of the pods.

Fertilizer had very little effect on the morphology of the plant. The number of beans/plant increases with increasing fertilizer application, but higher levels of fertilizer delay flowering.

The reciprical yield-density relationships showed that fertilizer had no effect on the A or B parameters for total plant weight or for the bean dry weight. The allometric log plant weight to log bean weight relationship showed that the ratio of beans to total plant weight decreases with increasing density, that is, at higher densities, more plant material is required to produce 1 unit of pods than at lower densities, due probably to a change in the dry matter partitioning.

Lang et. al. (1956) found yield differences due to fertilizer and many other workers have found yield differences due to density. In this trial, when yields were compared at the same stage of maturity, it was found that fertilizer and density had no effect.

Thus, although a higher density will have a more compact maturity it also results in a delay in maturity and a decrease in the size of each pod. Also at high densities some plants do not produce pods.

FUTURE WORK

Further work is required to determine the full effects of density.

(a) What percentage of pods are in the various maturity grades at each density and how do the percentages change with time?

(b) What is the effects of density on crops sown at different times?

(c) What is the effect of density on various cultivars?

(d) Is it economical to sow at a high density when the cost of seed is high?

(e) Is chemical weed control adequate or will cultivation be required?

BIBLIOGRAPHY

ANON., (1978) "N.Z. Horticulture Statistics 1978"
M.A.F. Information Services.

ASGROW SEED COMPANY, (1977) "Seed for Today"
Descriptive Catalogue of Vegetable Varieties No. 22
Asgrow Seed Company

BARRIGA, C. (1961) Effects of mechanical abuse of Navy bean seed at various moisture levels.
Agronomy Journal 53: 250-1

BLEASDALE, J.K.A. (1966) The effects of plant spacing on the yield of bulb onions grown from seed.
J. Hort. Sc. 41: 145-53

BLEASDALE, J.K.A. (1967) The relationship between the weight of a plant part and the total weight as affected by plant density.
Ibid 42: 51-8

BLEASDALE, J.K.A. (1969) "Plant Spacing"
A paper presented by Dr. Bleasdale at the Australian Vegetable Research Conference, 1969.

BLEASDALE, J.K.A. (1973) "Plant Physiology in Relation to Horticulture"
Science in Horticulture series. Macmillan, London.

BLEASDALE, J.K.A. and NELDER, J.A. (1960) Plant population and crop yield.
Nature, London. 188: 342

BLEASDALE, J.K.A. and THOMPSON, R. (1966) The effects of plant density and the pattern of arrangement on the yield of parsnips.
J. Hort. Sc. 41: 371-8

CROOKSTON, R.K., O'TOOLE, J., LEE, R., OZBUN, J.L. and WALLACE, D.H. (1974.a.)
Photosynthetic depression in beans after exposure to cold for one night.
Crop Sci. 14: 457-64

CROOKSTON, R.K., O'TOOLE, J., and OZBUN, J.L. (1974.b.)
Characterization of the bean pod as a photosynthetic organ.
Crop Sci. 14: 708-12

CROOKSTON, R.K., TREHARNE, K.J., LUDFORD, P. and OZBUN, J.L. (1975)
Response of beans to shading
Crop Sci. 15: 412-6

DICKSON, M.H., DUCZMAL, K., and SHANNON, S. (1973)
Imbibtion rate and seed composition as factors affecting transverse cotyledon cracking in bean (*P. vulgaris. L.*) seed.
J. Amer. Soc. Hort. Sci. 98: 509-13

DONALD, C.M. (1963) Competition among crop and pasture plants.
Advances in Agronomy 15: 1-118

DUBETZ, S. and MAHALLE, P.S. (1969) Effect of soil water stress on bush beans (P. vulgaris. L.) at three stages of growth.
J. Amer. Soc. Hort. Sci. 94: 479-81

ENGLEDOW, F.C. and WADHAM, S.M. (1923) Investigations on yield in cereals.
J. Ag. Sci. 13: 390-439

EVANS, G.C. and HUGHES, A.P. (1961) Plant growth and the aerial environment. I. Effect of artificial shading on Impatiens parviflora.
New Phytol. 61: 322-7

EVANS, L.T. (1975) The physiological basis of crop yield pp 327-55. In "Crop Physiology" edited by L.T. Evans. Cambridge. U. Press.

FERY, R.L. and JANICK, J. (1970) Response of tomatoes to population pressure.
J. Amer. Soc. Hort. Sci. 95: 614-24

FERY, R.L. and JANICK, J. (1971) Effect of time of harvest on the response of tomatoes to population pressure.
J. Amer. Soc. Hort. Sci. 96: 172-6

FISHER, V.J. and WEAVER, C.K. (1974) Flowering, pod set and pod retention of Lima beans in response to night temperature, humidity and soil moisture.
J. Amer. Soc. Hort. Sci. 99: 448-54

GANE, A.J., KING, J.M. and GENT, G.P. (1975) "Pea and Bean Growing Handbook Vol. II. - Beans, Processors and Growers Research Organisation.

HARDWICK, R.C. and MILBURN, G.M. (1967) Yield analysis in the vining pea.
Agric. Progress: 42: 24-43

HOFFMAN, J.C. (1971) Injury of snap bean pods associated with machine harvesting and handling.
J. Amer. Soc. Hort. Sci. 96: 21-4

HOLLIDAY, R. (1960a) Plant population and crop yield.
Nature, London. 186: 22-4

HOLLIDAY, R. (1960b) Plant population and crop yield.
Field Crop Abst. 13: 159 -67 and 247-54

HUGHES, A.P. and FREEMAN, P.R. (1967) Growth analysis using frequent small harvests.
J. Appl. Ecol. 4: 553

HUNT, R. (1978) "Plant Growth Analysis"
Edward Arnold (Publishers) Ltd.

HUNT, R. and PARSONS, I.T. (1974) A computer programme for deriving growth functions in plant growth analysis.
J. Appl. Ecol. 11: 297

JONES, L.H. (1967) Factors affecting the productivity of dwarf French beans.
Ag. Progress. 42: 32-52

KEMP, G.A., KROGMAN, K,K. and HOBBS, E.H. (1974) Effect of sprinkler irrigation and cooling on yield and quality of snap beans.
Can. J. Plant. Sci. 54: 521-8

LITTMAN, M.D. (1974a) Effect of stage of development of bean pods at harvest on post harvest changes.
Queensland J. of Agr, and Animal Sciences. 24: 261-70

LITTMAN, M.D. (1974b) Effect of temperature on the post harvest deterioration in quality in beans.
Queensland J. of Agr. and Animal Sciences. 24: 271-8

LOOMIS, R.S. and WILLIAMS, W.A. (1969) Productivity and the morphology of crop stands: Patterns with leaves. p27-47. In Physiological aspects of crop yield, proceedings of a symposium, ed. by J.D. Eastin and others.
Amer. Soc. Agronomy, Madison

MACK, H.J. (1972) Effects of population density, plant arrangement and fertilizers on yield of sweet corn.
J. of Amer. Soc. Hort. Sci. 97: 757-60

MACK, H.J. and HATCH, D.L. (1968) Effects of plant arrangement and population density on yield of snap beans. Proc. for the Amer. Soc. for Hort. Sci. 92: 418-25

MACK, H.J. and SINGH, J.N. (1969) Effects of high temperature on yield and carbohydrate composition of bush snap beans. J. Amer. Soc. Hort. Sci. 94: 60-2

MATTHEWS, S. and BRADNOCK, W.T. (1968) Relationship between seed exudation and field emergence in peas and French beans. Hort. Sci. 8: 89-93

MEAD, R. (1970) Plant density and crop yield Appl. Stats. 19: 64-81

MOORBY, J. (1968) The influence of carbohydrate and mineral nutrient supply on the growth of potato tubers. Ann. Bot. 32: 57-68

NEALES, T.C. and INCOLL, L.D. (1968) The control of the leaf photosynthesis rate by the level of assimilate concentration in the leaf: A review of the hypothesis. Bot. Review. 34: 107-25

NICHOLS, M.A. (1970) "Growth sutdies with lettuce" PhD Thesis, Massey University.

NICHOLS, M.A. (1974) Effect of sowing rate and fertilizer application on yield of dwarf beans. N.Z. J. of Exp. Agric. 2: 155-8

NICHOLLS, A.O. and CALDER, D.M. (1973) Comments on the use of regression analysis for the study of plant growth. New Phytol. 72: 571

PADDA, D.S. and MUNGER, H.M. (1969) Photoperiod, temperature and genotype interactions affecting time of flowering in beans. (P. vulgaris. L.) J. Amer. Soc. Hort. Sci. 94: 157-60

RADFORD, P.J. (1967) Growth analysis formulae - their use and abuse. Crop Sci. 7: 171-175

ROBINSON, W.G., WILSON, D.E., MAYER, J.C., ATKIN, J.D. and HAND, D.B. (1964) Quality versus yield of snap beans for processing. Proc. Amer. Soc. Hort. Sci. 84: 339-47

SALTER, P.J. (1961) The irrigation of early summer cauliflower in relation to stage of growth, plant spacing and nitrogen level. J. Hort. Sci. 36: 241-55

SHINOZAKI, K. and KIRA, T. (1956) Intra-specific competition among higher plants. VII. Logistic theory of the C-D effect. J. Inst. Polytech. Osaka City Univ. Ser. D. Biol. 7: 35-72

SHOEMAKER, J,S, (1947) Vegetable growing

SILBERNAGEL, M.J. and DRAKE, S.R. (1978) Seed index, an estimate of snap bean quality.
J. Amer. Soc. Hort. Sci. 103: 257-60

SMITH, F.L. and PRYOR, R.H. (1962) Effects of maximum temperature and age on flowering and seed population in three bean varieties.
Hilgardia 33: 669-88

SMITTLE, D.A. (1976) Response of snap beans to irrigation, nitrogen fertilization and plant population.
J. Amer. Soc. Hort. Sci. 101: 37-40

STANG, J.R. (1974) Influence of nitrogen fertilizer and plant density on the pod yield of green beans.
Hort. Sci. 9: 281

STOKER, R.E. (1974) Effect on dwarf beans of water stress at different phases of growth.
N.Z. J. of Exp. Agric. 2: 13-15

THOMAS, T.H. (1966) Competition studies.
Report. N.V.R.S. 1965 pp 40-42

TOMPKINS, D.R., SISTRUNK, W.A. and HORTON, R.D. (1972) Snap bean yield and quality as influenced by high plant population.
ARK. FARM. RES. 21(1): 4

TREHARNE, K.J., OZBUN, J.L., O'TOOLE, J., CROOKSTON, R.K., and PEET, M. (1973) Effect of light intensity during growth of P. vulgaris on photosynthesis, photorespiration, activity of related enzymes and leaf anatomy. Hort. Sci. 8: 252

WALLACE, D.H. (1973) Plant architecture and physiological efficiency in the field bean. in "Potentials of field beans and other food legumes in Latin America". C.I.A.T. series seminars No. 2E.

WALLACE, D.H. and MUNGER, H.M. (1965) Studies of the physiological basis for yield differences I. Growth analysis of six dry bean varieties. Crop Sci. 5: 343-8

WALLACE, D.H., PEET, M.M. and OZBUN, J.L. (1976) Studies of CO_2 metabolism in P. vulgaris L. and applications for breeding. pp 43-58. In. "Harry Steebock Symposium 'CO_2 Metabolism and Plant Productivity'" Edited by R.H. Burris and C.C. Black.

WARREN-WILSON, J. (1972) Control of crop processes. pp 7-30. In "Crop Processes in Controlled Environments" eds. A.R. Rees, K.E. Cockshull, D.W. Hand and R.C. Hurd. Acad. Press. N.Y.

WATSON, D.J. (1947) Comparative physiological studies on the growth of field crops. I. Variation on net assimilation rate and leaf area between species and varieties and within and between years.
Ann. Bot. N.S. II: 41-76

WATSON, D.J. (1952) The physiological basis for variation in yield.
Adv. in Agron. 4: 101-45

WATSON, D.J. and WITTS, K.J. (1959) The net assimilation rates of wild and cultivated beets.
Ann. Bot. N.S. 23: 431-9

WILLIAMS, C.F., CRABTREE, G., MACK, H,J, and DERBY-LAWES, W. (1973) Effect of spacing on weed competition in sweet corn, snap beans and onions.
J. Amer. Soc. Hort. Sci. 98: 526-9

WILLIAMSON, R.E. and SMITTLE, D.A. (1976) Trials with a commercial high density bean harvester.
Hort. Sci. 11: 227

WIVUTVONVANA, M. and MACK, H.J. (1974) Floral anatomy of P. vulgaris. L. cultivars 'Galatin 50' and 'Oregon 58'.
Hort. Sci. 9: 462-4