THE EFFECT OF PLANT DENSITY, CULTIVAR AND SEASON ON THE GROWTH AND DEVELOPMENT OF BROCCOLI

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ABSTRACT

Two field trials (summer and winter) were conducted at the Plant Growth Unit (PGU) to investigate the effects of density and season of planting on different cultivars of broccoli. Different aspects of growth and development were studied including dry matter accumulation, leaf production, curd initiation and curd maturity.

Polynomial regression equations were fitted to the primary data and resulted in typical growth curves from which growth analysis parameters were derived. The season of planting significantly effected the developmental stages of the crop. RGR calculated according to the functional approach declined linearly with time in both winter and summer trial. It was initially highest in the summer trial but declined much faster than in winter trial. One of the components of RGR, namely LAR also showed the reduction over time, in both summer and winter plantings. The other component, NAR decline with time in summer, but showed slight increase over time in the winter trial.

LAR was consistently lower during the summer trial compared with the winter trial. This consistent reduction is associated mainly with a lower specific leaf weight (SLW) because plants have thicker leaves which may absorb more radiation and therefore be more efficient in dry matter production.

Differences in growth between seasons can be explained primarily by differences in accumulated heat units. In this study, it was evident that the number of leaves produced varied with planting season. The higher the temperature regime the more leaves produced hence, leaf count per plant was slightly higher in the summer than during the winter season. The time of head initiation were affected by planting density for both season. In the summer planting, widely spaced plants had higher leaf areas, number of leaves produced and curd yield but in the winter planting showed no significant differences in the number of leaves produced and the curd weight per plant between densities. The final number of leaves at initiation time showed variations with season of planting which suggests that leaf number can be useful index for the morphological age of the plant at curd initiation stage.

Curd initiation (an important developmental event) was found to be strongly influenced by temperature. The number of days from transplanting to curd initiation was shorter in summer and longer in winter season. Considering a normal time scale, variations in the number of days from planting to curd initiation until maturity for both season was influenced by the two developmental stages of the crop:

1) planting to curd initiation.
2) curd initiation up to maturity.

It took almost twice as long period for the plant to initiate curd during winter than during summer and the time from curd initiation to maturity was longest during the winter. The potential of the plants to produce dry matter varied with season. Total dry matter production was considerably lower in the winter crop which strongly suggests that the lower the temperature regime, the lower the potential for dry matter production. The heat unit accumulation necessary to bring the crop to the same stage of maturity varied in such a manner that it was lower when the season was cool, and higher when the season was warm.

Total biomass per unit area increased with later harvests in the summer planting. Density influenced the curd and total dry weight per plant only in the summer planting. Varietal differences were found for both season of planting. Cultivar Shogun, with the longer growing period, had the lowest dry weight per plant for both plantings.

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1.0 Introduction

Broccoli (*Brassica oleracea* L. var. *italica* Plenck) production and consumption in the US has risen dramatically over the past several decades. Production has tripled over the past 30 years with a remarkable 160% rise in the consumption in 1983 alone (Love, 1986). While 90 to 95% of the production remains in California, increased demands has resulted in an expansion of production into such areas as Mexico, Texas and to a lesser extent, parts of the Northeastern United States.

In the UK, the demand for broccoli, which is also known as calabrese, is increasing all the time and swing to healthy eating should provide a further boost. Broccoli is one of the most rapidly expanding vegetable and grown commercially throughout Europe. It has been regarded as the "growth vegetable of the eighties", with sales having increased significantly. This trend appears to be continuing into the 1990's with some Spanish farmers growing over 1,000 hectares. In addition to the fresh market, there is a rapidly increasing demand as a frozen product with UK estimated production to be over 32,000 tonnes (Sergeant, 1994). Most people now regard traditional green vegetable as being uninspiring but calabrese could change the situation dramatically. This growing awareness of the value of vitamin C rich crops as a constituent of a healthy diet provides the multiple retailers who are not currently handling calabrese with the golden opportunity to introduce it as a new product (Long, 1988). Fresh broccoli had a meteoric rise in popularity when estimated consumption increased by 940 % from 1970 to 1985 and continued to climb as more positive health attributes were discovered by nutritionist (Klassen, 1993).

In New Zealand, there is increasing interest in the production of green sprouting broccoli in the home garden and commercially acreage as both a fresh market and a processing crop, however, there are problems in maintaining the continuity of supply year round because an unpredictable climate affects both the time of curd initiation and the rate of head development.

Individual broccoli plants have essentially only one yield component of commercial importance; the head or harvested portion of the main stem including the immature inflorescence. When yield is expressed on an area basis, an additional component of yield is the plant population which can have a considerable influence on the size and weight of individual heads. Seddon (1988) found that calabrese growers have not achieved the yield potential offered by the crop because it has been grown at high plant densities to meet the supermarket's specifications for thin stems. He found out that "there is another important knock-on effect from having to use high densities-an increased risk of disease". Seddon (1988) believes growers will eventually widen their spacings to lower crop density to meet the new demands and take advantage of varieties such as Marathon and Shogun.

Yield and quality are two important attributes which will determine success in the commercial production of broccoli for processing or for fresh market. Although, the total market returns are determined primarily by crop yield, curd quality can be as important as it determines the marketability and the value of the crop (Diputado, 1989). A knowledge of the rate of development and maturity characteristics of the crop would be useful in formulating planting and harvesting schedules which ensures the efficient use of farm resources and are important in marketing aspects. For fresh vegetable crops, product quality must be considered when examining the effects of plant population on yield. The way in which plant density, variety and harvest date interact to determine yield is of interest in the quest towards maximizing the yield of a particular size at harvest.

1.1 Plant spacing

Several investigators revealed an increase in marketable yield per unit land area for many vegetables as plant population increases (Knavel, 1991; Stoffella and Bryan, 1988; Widders and Price, 1987). The relationship between plant density and yield has been extensively reviewed by Willey and Heath (1969) where the relationship is shown to conform to two curves -parabolic where the yield of crop reaches a maximum at a given plant densities and then decreases, and asymptotic curve where yield approaches maximum as population increases, but does not decline (Holliday, 1960 and Duncan, 1958). Population density and spatial arrangement of plants are very important attributes in achieving maximum crop yield. In many species when populations exceed the optimum density they often show a marked decline in yield (Field and Nkumbula, 1986). With vegetables, density is usually more important than arrangement since these crops are normally grown at densities where competition is of high intensity (Frappell, 1979). Plant density is an important variable in obtaining maximum yield and uniform maturity of vegetable crops. Of the many improved cultural practices, the use of optimum seedling age and proper spacing are important as these tremendously influence yield (Islam *et al.*, 1989).

Studies with broccoli and cauliflower (Dufault and Waters, 1985), and cabbage (Mulkey and Porter, 1987) indicated that increasing plant density by decreasing in-row spacing can result in higher yields. Optimum plant densities are likely to be achieved by varying both in-row and between-row spacing. Wang'ati (1983) states that optimum spacing should be closely tied to overall plant population up to the point where the competition between plants cannot be compensated by wider spacings between rows or groups of plants. This is particularly important in the event of reduced soil moisture where plants may not be able to develop an adequate root system to explore all the soil between widely spaced rows. There are reports that the yield of cabbage increases with increase in plant density although the size of the individual head becomes smaller (Rahman and Haque, 1982; Hossain *et al.*, 1983; Farooque and Mondal, 1987).

Broccoli yield per hectare increased with close plant spacing (Cutcliffe, 1975; Palevitch, 1970) however, high population density decrease head size (Cutcliffe, 1971, 1975). Dufault and Waters (1985) found out that increasing plant populations increased the competition among plants and subsequently reduced marketable yield and that curd weight decreased linearly as the population increased from 24,000 to 72,000 plants per hectare.

Broccoli crop can be grown at a higher population than most other brassicas. Trials can be direct drilled and therefore, a high plant stand can be established and subsequently thinned (Chowings, 1974). The effect of plant density on the maturity characteristics of broccoli had been reported by Palevitch (1970), Cutcliffe (1971 and 1975) and Chung (1982, 1985) although, the growth of heads over time has not been studied. Little work has been reported on the agronomy of broccoli in the U.K. but research elsewhere had examined the ways plant population affects yield and spear size (Zink and Akana (1951); Massey *et al.*,1962). These workers dealt with low plant populations, aimed at the production of spears larger than those required in the U.K. for freezing. The highest population examined by Zink and Akana (1951) was 14.6 m^{-2} which produced spears averaging 7 cm in diameter while Palevitch, (1970) states that 11 plants m^{-2} gave spears of 11 cm in diameter. The relationship between plant density, yield and head size also differed between spatial arrangement and planting date. At comparable densities plants grown on the square always gave higher yields than those grown at 6:1 rectangularity whereas Thompson and Taylor (1976) found that yield of calabrese were relatively insensitive to spatial arrangement. In practice however, the effect of modifying plant arrangement is likely to be small compared with the effect of modifying plant density (Nichols, 1987). Several cultivars could be used for drilled or transplanted crops to predict when heads of any required size would be produced. However, these models are based on crops grown at very high densities up to 22 plants m^{-2}. Commercially however, broccoli is grown at a range of plant densities to produce heads of different size and weight specification. This study considers how plant density and planting season affects curd development of broccoli hybrid.

1.2 Objectives of the study

This study was conducted primarily to determine:

1) the effect of planting season, cultivar, and density on yield of broccoli;

2) the combined effects of these factors on the growth, components of yield, and developmental processes of broccoli.

Chapter 2

LITERATURE REVIEW

2.1 Classification, General Characteristics and Use

Broccoli (*Brassica oleraceae var. italica*) is fast becoming an important fresh market and processing vegetable crop in many parts of the world (Morelock *et al.* 1982; Magnifico *et al.* 1979). Field trials have produced a number of promising cultivars for fresh market and processing industry (Bussell, 1984; Geelen and Greaves, 1984; McErlich, 1984) which could well be suitable for large commercial plantings. The crop is grown for its edible curd which has become a popular item in the kitchen because of its good organoleptic properties and high nutritive value (Feher, 1986). Compared with other brassica vegetables, it has been found to have the highest protein, dietary fibre and vitamin C content (Wills, Lim and Greenfields, 1984). The curd is morphologically similar to that of cauliflower (*Brassica oleraceae var. botrytis*) although certain characteristics such as branching and time of floral initiation are different (Weibe, 1975). Broccoli produces a green curd with long and slender floret-stalk bearing fertile flower buds while cauliflower produces a single compact white curd which form fertile flower buds only after the normal harvest stage. The maturity of broccoli curd is primarily determined by the developmental stage of its florets. It is harvested shortly before it losses its compactness or just before buds start to open (Marshall and Thompson, 1987a). The yield of sprouting broccoli consist of the apical flower head (curd) and the secondary flower shoots that develop after the removal of the apical one (Ahmed and Abbdullah, 1986).

2.2 Effect on Yield

2.2.1 Yield-Density Relationship

As plant population increases, the mean yield per plant decreases due to increasing competition for growth resources. On an area basis, however, the increased plant number gives greater utilization of resources, and total biological yield increases in the form of a diminishing response curve that levels off when plant population is sufficiently high for maximum resource utilization. With further increase in plant population, total yield per unit area generally remains reasonably constant (Willey, 1982). The subject of plant spacing has been discussed on a number of occasions by Bleasdale (1966, 1969a), who concluded that the most important effect of increasing the plant number per unit area (density) while retaining a constant plant arrangement is initially to increase yield per unit area in direct proportion to plant density until a point is reached at which there is little or no further increase in yield.

Weiner (1990) found that increases in density above that required for maximum yield per unit area result in corresponding decreases in mean plant weight such that the total yield remains constant. Several important changes in the population do occur at higher densities:

1) At some point on the density continuum, further increases in density are absorbed, in part, by mortality as well as by plasticity. The fraction of plants surviving decreases as the density increases.

2) Size variability within the population increases with density not only the mean plant size smaller at higher densities, but the distribution of plant sizes around the mean becomes skewed and unequal, and a larger percentage of the total yield is to be found within a smaller percentage of the population (Weiner and Thomas, 1986).

3) The relative distribution of yield components to the total yield changes with density. Specifically, at higher densities more of the total yield is to be found in structural tissues, and less in reproductive tissues or other harvestable components (Weiner, 1990).

Bleasdale (1969b) defined the type of density to give maximum yield as follows. "It should be one where within the season of growth and under the conditions prevailing the density giving maximum yield is also one which gives the size of individual plant parts that the market requires". It was found by Verheij (1970) that weight per brussels sprout plant declined asymptotically with increasing density until a levelling effect occurred. This follows the concepts outlined by Bleasdale (1966, 1969a) and Donald (1963). Generally, plant density can have a pronounced influenced on plant growth and development as well as on marketable yield of many vegetable crops.

2.2.1.1 Tomatoes

Wilcox (1970) conducted a density trial using one or two rows per bed, varying the within row spacing between plants. With the one row bed, yield increased with density up to 23,920 plants ha^{-1} and remaining constant up to 71,700 plants ha^{-1}. An asymptotic yield-density relationship was also obtained with the double row system where total yield per hectare remain constant over the density range of 11,960 to 143,520 plants ha^{-1}. Fery and Janick (1970) obtained an asymptotic yield-density relationship for marketable fruit up to 250,000 plants ha^{-1} from an early harvest with plants arranged equidistantly. This relationship became parabolic with later harvests, however, as a result of the mature fruits at higher densities, rotting maximum yields being obtained from 42,500 and 17,500 plants per hectare from mid and late harvest season, respectively. Bussell *et al.* (1975) obtained marketable yield increases per unit area with densities up to 33,000 plants per hectare but above this yield increases remained non significant. The results obtained by Wilcox (1970), Zahara (1970) and Bussell *et al.* (1975) where above a certain density, yield increases remained non significant could be an effect resulting from the form of analysis used where each density is treated as a distinct unit instead of fitting a function to the yield-density relationship. This would enable the general form of the relationship to be viewed even though differences between adjacent densities may be small.

Increasing plant population from 316,160 to 963,000 plants per hectare decreased the number of branches, leaves, flowers and fruit set per plant (Zahara and Timm, 1973). Above 963,000 plants per hectare many plants failed to flower and bear fruits, plants tended to accumulate sugars in the stem, and leaf area per plant at harvest declined. Crowder (1972) also concluded that high densities modified the morphology of tomato plant so that an early and concentrated ripening of fruit occurred. He found that yields of red ripe fruit were significantly greater at a density of 175,000 plants ha^{-1} compared to 100,000 plants ha^{-1} with no commercially significant decrease in fruit size or increase in disease incidence. Plant height and weight decreases with increasing density but total plant weight per unit area increases (Nichols and Calder, 1973). Close spacing has been shown to have a detrimental effect on tomato fruit set apparently because of an inadequate supply of photosynthesis due to shading (Zahara and Timm, 1973); Fery and Janick, 1970; Rodriguez and Lambeth, 1975).

2.2.1.2 Onion

The relationship between plant density and yield of onion bulbs was found to be parabolic by Bleasdale (1966), Buchvarev (1964), Dowker and Fennell (1974). As plant density increased, the proportion of irregular-shaped bulbs increased from large to small grades (McGeary, 1985). To produce larger 'jumbo' bulbs, planting densities of 25-50 plants m^{-2} are used. Onion bulb yields increase to an asymptote as plant as plant density increases and mean bulb size correspondingly declines (Brewster, 1994).

2.2.1.3 Beans

In a study conducted by Tompkins *et al.* (1979) it was concluded that closer spacing offer several potential advantages:

1) more efficient utilization of incident solar radiation;

2) more complete shading of soil to suppress soil temperature and to reduce weed vigour;

3) additional plant root and stem material to physically restrain soil subject to transport by overland water flow; and

4) to absorb energy of falling raindrops which otherwise tend to loosen soil particles upon impact. Smittle (1976) reported that snap bean yield were increased with greater plant populations resulting from narrow rows.

2.2.1.4 Maize

Duncan (1958) reported that when maize is planted at increasing population levels the average yield per plants decreases due to a reduction in the supply of environmental factors on yield as each plant is forced to share with its competing neighbours. According to Soper (1952) the increase in yield per plant at lower densities as compared to higher densities is due to a larger quantity of nutrients being available to each plant, and to changes in environmental factors such as light and temperature.

2.2.1.4 Broccoli

Chung (1982) found that broccoli terminal head yield approached its asymptote at a plant density of 20 m^{-2}. Salter, Andrews and Akehurst (1984) concluded that terminal head yield of "neo-calabrese" was relatively insensitive to plant density above 20 plants m^{-2}. Cutcliffe (1975) demonstrated that the yield response to density varied among cultivars and that the asymptotic yield was approached at plant densities between 9 and 20 plants m^{-2} for most of the nine cultivars investigated. High broccoli and cauliflower population, however, have been reported to have some disadvantages. Broccoli yield per hectare increased with close plant spacing (Cutcliffe, 1975; Palevitch, 1970).

Chung (1985a) showed that the asymptotic level of yield and the relationship between plant density and head diameter for cv. 'Futura' were affected by the time of year the crop was grown. Hence, the range of plant densities suitable for the production of a high population of heads within a required size range and the economic return of the crop varied with the date of sowing. Optimum spacings can also be expected to vary with levels of crop nutrition (Zink, 1968) and irrigation.

2.2.2 Plant density and mean head size

Terminal head size varies inversely with plant density (Chung, 1982; Cutcliffe, 1975; Dufault and Waters, 1985; Salter, Andrews and Akehurst, 1984), while Brakeboer (1990) also found that head weight declined as plant density increased. Once at the asymptotic level of marketable yield, the mean head diameter of the crop can be manipulated without loss of yield, by altering the plant density at which the crop is grown. Thus, to produce high yields of terminal heads with diameters in the range of 25 to 75 mm (with a mean diameter of approximately 45 mm) suitable for individual quick freezing, researchers in Scotland (Thompson and Taylor, 1976), Tasmania (Chung, 1982) and England (Salter, Andrews and Akehurst, 1984) recommended plant densities in excess of 40 m^{-2}. The limited published data available suggests that similar results would hold under New Zealand conditions (Bussell, 1978). The size of head in respect of diameter and thickness were affected by the variation of planting distance hence, wider spacing produced large sized head than closer spacing (Farooque and Islam, 1989), i.e. high density planting decreased head size in broccoli (Cutcliffe, 1971, 1975). Although high population reduced head weight in broccoli, greater numbers of heads increased total yields (Arjona, 1980; Cutcliffe, 1975). Populations approaching 35,000 plants ha^{-1} were considered optimal for broccoli (Arjona, 1980) and cauliflower (Garner, 1978) production. Broccoli yield are highly dependent on plant spacing and continue to show increases at densities that render heads weights as to be unmarketable (Chung, 1982; Cutcliffe, 1975; Dufault and Waters, 1985). Manipulation of plant densities is perhaps the most effective method of controlling both the yield and quality.

2.2.3 Plant density and crop maturity

Changes in density can affect maturity in two ways: a) It may alter the time of maturity; b) It may change the spread of maturity. The effect will vary with crops; for example, widely spaced cabbages heart earlier than closely spaced ones (Nichols, 1970). However, the effect of density on spread of maturity is one of the more valuable attributes of high density production. There are conflicts in the literature as to the effect of plant density on the maturity date of broccoli. Some authors reported slightly earlier maturity dates with increased plant densities (Salter, Andrews and Akehurst, 1984, Thompson and Taylor, 1976) while Cutcliffe (1971, 1975) and Kahn *et al.* (1991) recorded delays in maturity as plant density increased. Salter, Andrews and Akehurst (1984) could find no obvious relationship between plant density and plant-to-plant variability in maturity of selectively harvested terminal heads of "neo calabrese" however, the coefficient of variation of head diameter was found to increase with plant density.

Bussell and Dobson (1985) noted that the popularity of the standard fresh broccoli cultivars grown in New Zealand was partially due to their tendency towards a long harvest period from a single sowing or planting date. Prolonged harvesting due to uneven maturity was considered desirable because of its smoothing effect on short-term fluctuations in market price. However, non-uniform maturity does increase harvesting costs. Wheeler and Salter (1974) have shown that net economic returns can be increased by improvements in the uniformity of maturity on cauliflower crops. Thus, harvesting of a series of smaller areas of compact maturity would appear to be more efficient for continuous production. Honma and Bert (1977) found that high plant density delayed cauliflower maturity and reduced the quality as well. Maturity is also determined in part by the size of the individual florets. Thus solar radiation which drives the growth or 'size' of the crop may also influence the date of maturity (Marshall and Thompson, 1987).

Salter (1969) showed that variability in the time of maturity of individual plants within a cauliflower crop was partially caused by variability in the time of curd initiation of different plants. This implies that any cultural or environmental factor influencing inter-plant variability in the time of curd initiation can influence the length of the maturity period of a cauliflower crop. Rossman and Cooke (1967) pointed out that increasing plant density tends to retard and even delay plant development. Investigation of close spacing using a range of harvest dates (Stockbridge House EHS 1965) showed that density had little effect on yield. Thomas (1965) found that at 45cm x 45cm spacing the crop was one month later in reaching its peak yield than at 68.5 cm x 68.5 cm. Experimental evidence showed that close spacing delayed maturity for ten days (Stockbridge EHS 1967).

2.2.4 Plant density of process crops grown in Manawatu

The current recommendation for plant spacing of broccoli crops for processing in the Manawatu region is 700 mm x 700 mm, giving a plant population of 28,570 plants ha^{-1} Davis (1992). The processing companies has made the decision to have the crop produced at relatively low plant densities using cultivars which produce terminal heads with a narrow angle of branching. The large, deeply, branched heads produced using this approach can be readily sectioned to produce smaller segments of size suitable for freezing (Bussell, 1984). It is likely that higher plant spacings would be within the capabilities of modern transplanting equipment: for example, 16 plants m^{-2} could be achieved by spacing plants at 250 mm x 250 mm. Westcott and Callan (1990) found that increasing the number of seedlings from 1 to 3 per module resulted in reduced head size and yield of transplanted broccoli over the range of plant densities where marketable heads were produced.

2.3 Use of Environmental Time scale

2.3.1 Heat Unit Concept

The heat unit concept was introduced over 200 years ago and was worked out in some detail by Boussingault and De Candolle over 100 years ago (Nichols, 1970). The theory proposes that for each plant species a threshold temperature exists below which it does not develop. Frequently, studies show that the growth pattern for a particular crop can vary markedly between planting because of the effect of variable weather conditions (Salter, 1960). For example, when a time scale such as number of days from sowing is used against which to plot the growth of plants, the resultant plant growth curves differ markedly from season to season. Nelder, Austin, Bleasdale and Salter (1960) introduced the idea of replacing chronological time in such growth equations by a time scale based on some suitable combinations of meteorological factors. The use of cumulative measurement of the main climatic variables as a "time scale" may thus provide a common scale from season to season.

2.3.2 Heat Unit System

Of the various climatic variables, most attention has been given to temperature (i.e. Wurr and Kay, 1981 and Salter, 1960 on cauliflower; Marshall and Thompson, 1987a and 1987b on broccoli; Wurr and Fellows, 1984 on lettuce) as it has been considered a major environmental factor determining variations in plant growth. The use of accumulated day degrees or heat units as a time scale is a convenient and simple method of integrating temperature with time to take into account temperature differences over different period of time. The amount of "effective heat" accumulating during the day is obtain by subtracting the base (threshold) temperature from the daily mean temperature. The "effective heat" (called heat units, degree days, day degrees, or growing degree days (Nichols, 1970) is considered to be a measure of plant growth and development. This assume that:

1. The plant response to temperature is linear over the whole temperature range.

2. Day and night temperatures are of equal importance.

3. There is only a single base temperature over the growth cycle of the plant.

4. Temperature is the major environmental factor influencing plant development.

Heat units have been of considerable practical value to agriculture as a predictive tool, and for scheduling plantings. Nevertheless, the heat unit system is far from perfect as it tends (Arnold, 1959) to over estimate the rate of plant development in:

1) warm compared with cold part of the season.

2) warm compared with cool years.

3) low compared with high latitudes.

4) low compared with high altitudes.

Gilmore and Rogers (1958) modified the heat unit calculation by correcting for the partial effect of temperatures above and below an optimum range (a non-linear response), so that:

1) If the daily minimum was less than the base temperature it was given a value equal to the base temperature.

2) If the daily maximum exceeded a selected upper limit

a) the daily maximum was equated to the upper limit.

b) the excess temperature above the selected upper limit was subtracted from the daily mean temperature. The concept of accumulated temperature above a base temperature or thermal time provides a unifying temperature-modified time scale on which to express the progress of a crop towards maturity (Gallagher, 1979; Monteith, 1977, 1981). Arnold (1960) has shown that from a graphic standpoint the heat sum is the area beneath the temperature curve and above the base temperature and in many cases this is the same as the mean temperature minus the base. Anon. (1954) determined the area under the curve by using one of four formulae, depending on the position of the base temp in relation to the mean temperature.

1) Base temperature greater than mean temperature

$$HU = \frac{Max.\ temp.\ -\ Base\ temp.}{4}$$

2) Base temperature less than the mean temperature

$$HU = \frac{Max.temp. - Basetemp.}{2} - \frac{Basetemp. - Min.temp.}{4}$$

3) Base temperature less than minimum temperature

$$HU = \frac{Maximum + Minimum}{2} - Base\ temp.$$

4) Base temperature greater than maximum temperature

$$HU = 0$$

2.3.3 Using Appropriate Base temperature

Arnold (1959) has reported that in earlier studies two methods have been used in the determination of the base temperature, namely, the least variability and the regression coefficient method. In the former, the heat unit summation from a series of plantings were calculated on a number of base temperature and the one giving the least variation is found by the process of elimination. The latter involves a calculation of a regression equation relating mean temperature and the heat unit summations. A correct base temperature resulting is one which gives a zero regression. Based on his findings, he concluded that the base temperature resulting in the lowest coefficient of variation instead of the standard deviation is shown to be the appropriate one which agreed closely with the regression coefficient method. Hence, the base temperature resulting in the best curve fit (highest R^2) was chosen.

2.4 Growth Analysis

Historically, 'growth analysis' has referred to the analysis of biomass growth, a field that developed in the early 1900s (Chiariello *et al.*, 1989). Ecological studies examine growth in two different, but complementary ways. The first emphasize productivity and views growth as the change in mass of live biomass through time. The second emphasizes demographic processes and views growth as the difference between the production of new biomass units such as leaves, stems twigs and roots. Growth during a time interval can be calculated by simple subtraction-biomass or module number at the end of the interval minus that at the beginning (Chiariello *et al.*, 1989). The simple calculation of growth, a variety of approaches commonly called "growth analysis" can be used to account for growth in terms that have functional or structural significance. This type of growth analysis requires measurements of plant biomass and assimilatory area (usually leaf area) and methods of computing certain parameters that describe growth. Growth analysis may be approached in two ways:

a) The component approach, or

b) The classical approach.

2.4.1. The component approach

The component approach divides the plant into component of yield. One of the first attempt to analyze yield in terms of antecedent growth was made by Balls and Holton in 1915 on cotton crop in Egypt as cited by Watson (1952). They measured the daily growth in height of the main stem, the daily rate of flowering and the weekly rate of boll production throughout the latter part of the growing season. Hardwick and Milburn (1967) used a similar method for peas, in which the final yield for the whole plant is factorized into components, as in weight per plant, seeds per pod, pods per node and podding node per plant.

2.4.2. The classical approach

The classical or interval approach estimates mean values for the parameters during time intervals between successive pairs of harvest. Equations for the mean values of parameters are derived by integrating the instantaneous expressions for the parameters dividing by the time between harvests. Mean relative growth rate is one of the most useful parameters in this approach because the instantaneous expression (equation 5) which gives the true mean RGR (Radford, 1967). If growth is exponential as it often during early vegetative growth (Hunt, 1978), RGR is constant throughout the interval between harvests. The instantaneous expression for NAR (equation 6) can not be integrated without knowing the relationship between biomass (W) and assimilatory area (A) or the relationship between W and t with that of A and t. In the development of the classical approach, W and A are assumed to be linearly related (Briggs *et al.*, 1920a and b; Williams, 1946), but other functions (i.e. quadratic, exponential) may describe their relationship better. Similar considerations apply to the calculation of mean leaf area ratio because the instantaneous expression for LAR (equation 7) cannot be integrated without knowing A/W versus t, or A versus t and W versus t. Growth analysis can provide an insight into the mode of plant growth and the physiological development of the components of yield. Watson (1952) approach to growth analysis involves the calculation of the Relative Growth Rate (*RGR*), and its components, the Net Assimilation Rate (*NAR*) and the Leaf Area Ratio (*LAR*). Radford (1967) has defined these growth analysis formulae at an instant of time (t) when **W** is a measure of plant material present and **A** is a measure of the magnitude of the assimilatory system as follows:

Relative Growth Rate (RGR)

This is the rate of production of new material per unit weight (**w**) per unit time (**t**).

$$RGR = \frac{1}{W} \cdot \frac{dt}{dw}$$

Net Assimilation Rate (NAR)

This expresses the rate of increase in dry weight per unit time per unit area of leaf (**A**).

$$NAR = \frac{1}{A} \cdot \frac{dt}{dw}$$

Leaf Area Ratio (LAR)

This is the ratio of leaf area to weight of plant usually excluding the roots (Hunt, 1978).

$$LAR = \frac{A}{W}$$

RGR = NAR x LAR

$$\frac{1}{W} \cdot \frac{dw}{dt} = \frac{1}{A} \cdot \frac{dw}{dt} \cdot \frac{A}{W}$$

LAR can be considered as being made up of two components (Evans and Hughes, 1961).

Specific Leaf Weight (SLW)

This is the mean area of leaf displayed per unit leaf weight (L_w).

$$SLW = \frac{A}{L_w}$$

Leaf Weight Ratio (LWR)

This give an indication of the leafiness of the plant on weight basis.

$$LWR = \frac{L_w}{W}$$

Thus, LAR = SLW x LWR or

$$\frac{A}{W} = \frac{A}{L_w} \cdot \frac{L_w}{W}$$

This concept enables differences in leaf area ratio to be attributed either to the differential distribution of photosynthetic products between leaf growth and other plant growth or differences in leaf density or relative thickness. These subdivisions of LAR may be inserted into equation to give:

$$\frac{1}{W} \cdot \frac{dw}{dt} = \frac{1}{A} \cdot \frac{dw}{dt} \cdot \frac{A}{L_w} \cdot \frac{L_w}{W}$$

RGR = NAR x SLW x LWR

The classical approach to growth analysis has traditionally involved the use of these parameters in the form of the mean values calculated over regular time intervals using the formulae:

$$RGR = \frac{Log_e\ W_2 - Log_e\ W_1}{t_2 - t_1}$$

$$NAR = \frac{W_2 - W_1}{t_2 - t_1} \times \frac{Log_e\ A_2 - Log_e\ A_1}{A_2 - A_1}$$

$$LAR = \frac{A_2 - A_1}{W_2 - W_1} \times \frac{Log_e\ W_2 - Log_e\ W_1}{Log_e\ A_2 - Log_e\ A_1}$$

$$SLW = \frac{L_2 - L_1}{L_{w_2} - L_{w_1}} \times \frac{Log_e\ L_{w_2} - Log_e\ L_{w_1}}{Log_e\ L_2 - Log_e\ L_1}$$

$$LWR = \frac{L_{w_2} - L_{w_1}}{W_2 - W_1} \times \frac{Log_e\ W_2 - Log_e\ W_1}{Log_e\ L_{w_2} - Log_e\ L_{w_1}}$$

(Subscripts 1 and 2 denotes first and second harvest) assuming that the weight and leaf area vary exponentially with time.

An alternative approach to growth analysis has been termed the dynamic approach by Radford (1967). This involves fitting mathematical functions by regression technique to experimental data to describe the relationship between plant growth and time (Hunt, 1978). From these functions (growth curves) fitted values of data are obtained and then used to describe the various growth analysis quantities which may subsequently be plotted as fitted instantaneous values.

There are several advantages in using the dynamic (functional) approach in favour of the classical one. More frequent harvest of fewer plants are used to provide information about the growth of the plants on a more or less continuous basis (Hughes and Freeman, 1967). This means that less information is at risk from accidental loss at any one harvest and the work load is more evenly spread throughout the period of measurements. There is no need for arbitrary pairing of sample plants across harvest as in the classical method. The regression technique utilizes information from all available harvest in determining values at any point in time, whereas the traditional method only use data from two consecutive harvests. Small deviations from the overall trend of the original experimental data against time are 'smoothed' often making the final results less erratic (Hunt, 1973). This effect can, however, result in actual fluctuations from the overall trend being overlooked. The only assumption required for the effective use of dynamic approach is that the fitted growth curves adequately describe the relationship between the parameters under investigation over time. A variety of functions can be describe the time trends of W and A, such as exponential or logistic equations or polynomial expressions of different orders.

The functions can be fitted to raw data or logarithmic transformations. The result of functional analysis are sensitive to the choice of curve fitting procedure (Nicholls and Calder, 1973; Hunt and Parson, 1974). Generally, there is a trade-off between goodness of fit and maximizing standard errors on the derived growth analysis parameters. In the extensive work on functional approach by Hunt (1982) cited 12 advantages of this method. Among them are the following:

(1) The functional approach provides a clearer perception of ontogenetic drift;

(2) Assumptions involved in the calculation of mean values of NAR are avoided;

(3) Statistical analyses may be integrated into the same analytical procedure as the calculation of the derived quantities. Despite these valid claims the functional approach does not necessarily result in correct values for RGR, NAR and the confidence limit of these parameters. Poorter and Lewis (1986) showed that the testing differences in RGR had only limit biological meaning. Wickens and Cheeseman (1988) argued that the functional approach is of limited value if plants are subjected to short-term environmental changes.

Chapter 3

MATERIALS AND METHODS

3.1. Introduction

Broccoli, which is known calabrese or green sprouting broccoli, is one of the most rapidly increasing vegetable. Per capita consumption of broccoli has increased 330% since 1975 (Hamm, 1988). As a result, fresh market broccoli hectarage has increased by 10% annually since the early 1970s (Karst, 1990). Production acreage has expanded to include nontraditional broccoli producing areas, where broccoli is viewed as an alternative to traditional agronomic crops (Hamm, 1992). Recognising this, it has been entered into the research and development programme. Much of the prior research investigating plant density of broccoli focused on determining the greatest population density that produces marketable head sizes for either processing or fresh market bunching broccoli (Cutcliffe, 1971, 1975; Chung, 1982; Palevitch, 1970). Several cultivars were used to develop a better understanding on the relationship between growth and heat units accumulation as means of improving plantings to have a continuous supply of the product. In addition to the fresh market, there is a rapidly increasing demand for it as a frozen product.

3.2 The Site

The experiments were conducted during 1993-94 (summer experiment) and 1994 (winter experiment) at the Plant Growth Unit of Massey University. The site had been previously cropped with asparagus. Prior to land preparation the entire field was sprayed with the non-selective herbicide glyphosate (round-up) at 1.5 kg active ingredient (a.i.) ha^{-1}. In both instances, the trial site were ploughed one month before planting and then rotary hoed to a fine tilth.

3.2.1 The Experiment

Summer and winter experiments were conducted at the Plant Growth Unit. A Randomized Complete Blocks Design (RCBD) was used with 3-4 varieties depending on the experiment. There were three replicates with harvest dates as randomized subplots within each main plot. Each replicate (3 meters by 72 meters) contained 16 plots (summer, appendix 1) and 12 plots (winter, appendix 2). All plots were three metre in width (comprising two beds at 1.50 meter centre) but had variable length to accommodate the different spacing within the row (24, 20, 16 and 12 metre for the 6, 9, 12 and 16 plants m^{-2} densities, respectively).

3.2.2 Summer Trial

Four broccoli hybrids 'Greenbelt, Marathon, Shogun and Variety 'X' were sown in cell trays on 6 November 1993. The four plant densities (PD) were 6, 9, 12 and 16 plants m^{-2} (Table 1) corresponded to 22, 14, 11 and 8 cm within row spacing. A granulated fertilizer (12% N, 10% P, 10% K and 2% S) was evenly broadcasted at the rate of 1,000 kg ha^{-1}. The experimental area was then formed into flat beds at 1.50m centres. The cultivars were transplanted in the designated plots (Appendix 1.) on 8 December 1993, in twin row per bed of varied length (Table 2).

3.2.3 Winter Trial

Three cultivars 'Green belt, Marathon and Shogun were sown on 23 March 1994 in cell trays as in the summer time. The experimental area was deeply cultivated by a sub soiler and rotary hoe. Plots were then formed into raised beds and arranged at plant densities of 6, 8, 10 and 12 plants m^{-2} (Table 1) corresponding to 22, 18, 14 and 11 cms within row spacing. A complete fertilizer (7% N, 6% P, 7% K, 14% S) plus potash at the rate of 1000 kg and 300 kg ha^{-1}, respectively was applied prior to final cultivation (Appendix 2). The cultivars were transplanted on 5 May 1994 in twin row beds of varied length (Table 2).

3.2.4 Production of transplants

The broccoli seeds were sown in cellular trays in a glasshouse which was maintained a minimum temperature of $16^{O}C$ via the heating system and ventilated when temperatures were above $25^{O}C$. The propagation medium was 100% bark with fertilizer additions (dolomite and agricultural lime at 300g per 100 litre bark). Supplemental feeding (Appendix 3) was applied twice a week to ensure uniform seedling growth and development (Plate 1). The cell trays were supported on benches so that air pruning of the roots took place.

Table 1. Planting densities and treatments for summer and winter trials.

Season	Treatments	Plants m^{-2}
Summer 1993-94	1	6
	2	9
	3	12
	4	16
Winter 1994	1	6
	2	8
	3	9
	4	12

Table 2. Plot and sample size for each density.

Season	Plants m^{-2}	Row length (meters)	Sample size (length meters)
Summer 1993-94	6	24	1 x 6
	9	20	1 x 5
	12	16	1 x 4
	16	12	1 x 3
Winter 1994	6	18	1 x 6
	8	15	1 x 5
	10	12	1 x 4
	12	9	1 x 3

Plate 1. Seedlings grown in glasshouse supplied with liquid feeding.

The cultivars were taken from the glasshouse and the seedling hardened off in a shade house a week before transplanting in the trial field.

3.2.5 Irrigation, pests, diseases and weed control

An overhead sprinkler system of irrigation (using perforated aluminum pipes) was applied twice a week when rainfall was not adequate. A broad spectrum pesticide were applied regularly from planting onwards using the spray program outlined in Appendix 4. To safeguard the plants from rabbit damage, a 0.40-m high electric fence was installed around the trial field. Weeds were controlled by mechanical means using a push hoe and a mini rotary hoe.

3.2.6 Data collection

Sampling for growth analysis commenced two weeks after transplanting. Plant growth characteristics were evaluated by the destructive harvest of four plants per plot taken weekly (summer trial) and every two weeks (winter trial). Shoots were divided into leaves, stems and heads. Leaves were weighed, counted and the leaf areas were determined using a leaf area machine, recorded and oven-dried at 80^0C to a constant dry weight. Leaves and stems were oven-dried, weighed and recorded separately. Heads were harvested from 15 to 24 February 1994 and 20 August to 21 September, 1994 for the summer and winter experiments, respectively. Head diameter, fresh and dry weight were measured once the heads became visible. Daily maximum and minimum temperatures were recorded at the New Zealand Meteorological Service Station (Daily Climatological Observations), Agricultural Research, Palmerston North, having a Lat of 40^{o} 23 S, Long of 175^{o} 637 E.

3.3. Data analysis

The statistical program MSTAT was used for data analyses procedures. Initially, the primary data on leaf area, leaf and total dry weight (on per plant basis) were transformed into logarithm and a polynomial equations used to describe the relationship of the different variables with time.

3.3.1 Calculation of growth analysis parameters

The primary growth data (leaf area, leaf and total dry weight on a per plant basis) were transformed into a logarithm, and fitted to a polynomial equation using the chronological time scale. From the equation, predicted values were determined and the different growth analysis parameters, relative growth rate (RGR), net assimilation rate (NAR), leaf area ratio (LAR), specific leaf weight (SLW), and leaf weight ratio (LWR) were calculated from the growth curve equations.

$$Log_e\ W = a + bt + ct^2$$

$$Log_e\ A = d + et + ft^2$$

$$Log_e\ W_L = g + ht + it^2$$

These equations were derived the growth analysis parameters for harvest date for the different blocks, densities and cultivars.

$$RGR = \frac{1}{W} \cdot \frac{dw}{dt}$$

$$NAR = RGR \times LAR$$

$$LAR = \frac{A}{W}$$

$$SLW = \frac{A}{W_L}$$

$$LWR = \frac{W_L}{W}$$

3.3.2 Fitting Curd Growth Data of 0.6mm to 130mm.

Curd growth data consisted of weekly (summer) and biweekly (winter) measurements of curd diameter. The time to 0.6 mm and 130 mm diameter were estimated by taking the logarithm of head size with the harvest date as dependent and independent variables, respectively. Data were fitted into a quadratic models relating the logarithm of curd diameter to time. The times of 0.6 diameter to 130mm diameter were derived from the curves. Difference in days from initiation (0.6mm) to maturity (130mm) were calculated from the estimated time at 130mm in diameter minus the time at 0.6mm diameter.

3.3.3. Heat units calculation

Daily climatological data were fitted from the first harvest onwards. The accumulated heat units were calculated (equation 1, 2, 3 and 4, section

2.3.2) from the appropriate base temperatures (threshold) which gives the best curve fit (measured as R^2) of the regression model.

3.3.4. Fitting the summer and winter total dry weight and curd diameter data to HU scale.

Total dry weight and curd diameter data for summer and winter were fitted into a regression model with the logarithm of total dry weight and mean head size as dependent variables and the heat units as the independent variable with time. The appropriate base temperatures was chosen on the basis of the goodness of fit measured as R^2.

3.3.5. Fitting the reciprocal yield-density equation to curd fresh weight data

The common models relate individual plant yield-density data fitting through a reciprocal equation, such as that proposed by Holliday (1960):

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

where: W is individual plant weight or yield,

p is plant density, a and b are constants.

This linear form of the equation describes an asymptotic response of yield to planting density.

3.3.6. Allometric equation to curd dry weight and total plant dry weight data

The allometric relationship of the total plant dry weight to curd was calculated using the formula derived by Bleasdale (1967) using a linear regression equation. Basically, the allometric relationship between two plant variates *X* and *Y* may be expressed thus:

$$Y = bX^K$$

where X represent the size of the whole organism (plant), Y represent for some differentially-growing component (head), whereas b and K are both constants. Taking the logarithms of this equation;

$$Log\ Y = \log b + K \log X$$

This provides a convenient practical method of evaluating equation 3, since a plot of Y against X on a double logarithm scale will feature K as its slope and b as the intercept.

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Results

4.1.1 Growth Analysis

Trends in the different growth analysis parameters for summer and winter trials were derived from the regression values of leaf area, total plant and leaf dry weights. The relative growth rate (RGR) assumed an inverse linear pattern (Figure 1) whereas, net assimilation rate (NAR) increase slightly with time during winter but decrease very rapidly in the summer study (Figure 2). Leaf area ratio (LAR) and specific leaf weight (SLW) were higher at the start and declined progressively with time (Figure 3 and 4). Leaf weight ratio (LWR) initially increased then declined very rapidly during the developmental stages of the crop (Figure 5).

Initial RGR was found to be higher for the summer planting than winter and this was probably due to the better growing conditions in the field (e.g. greater number of heat units per day). This is similar to the finding of Diputado (1989) who found the shorter the duration of the crop the higher was the initial RGR. Basically, the relative growth rate is not constant but varies with the developmental stage of the crop and depends upon the net assimilation rate (NAR) which is a measure of the efficiency of the leaves to produce new parts as the assimilatory organ of the crop, whereas leaf area ratio (LAR) is a measure of the

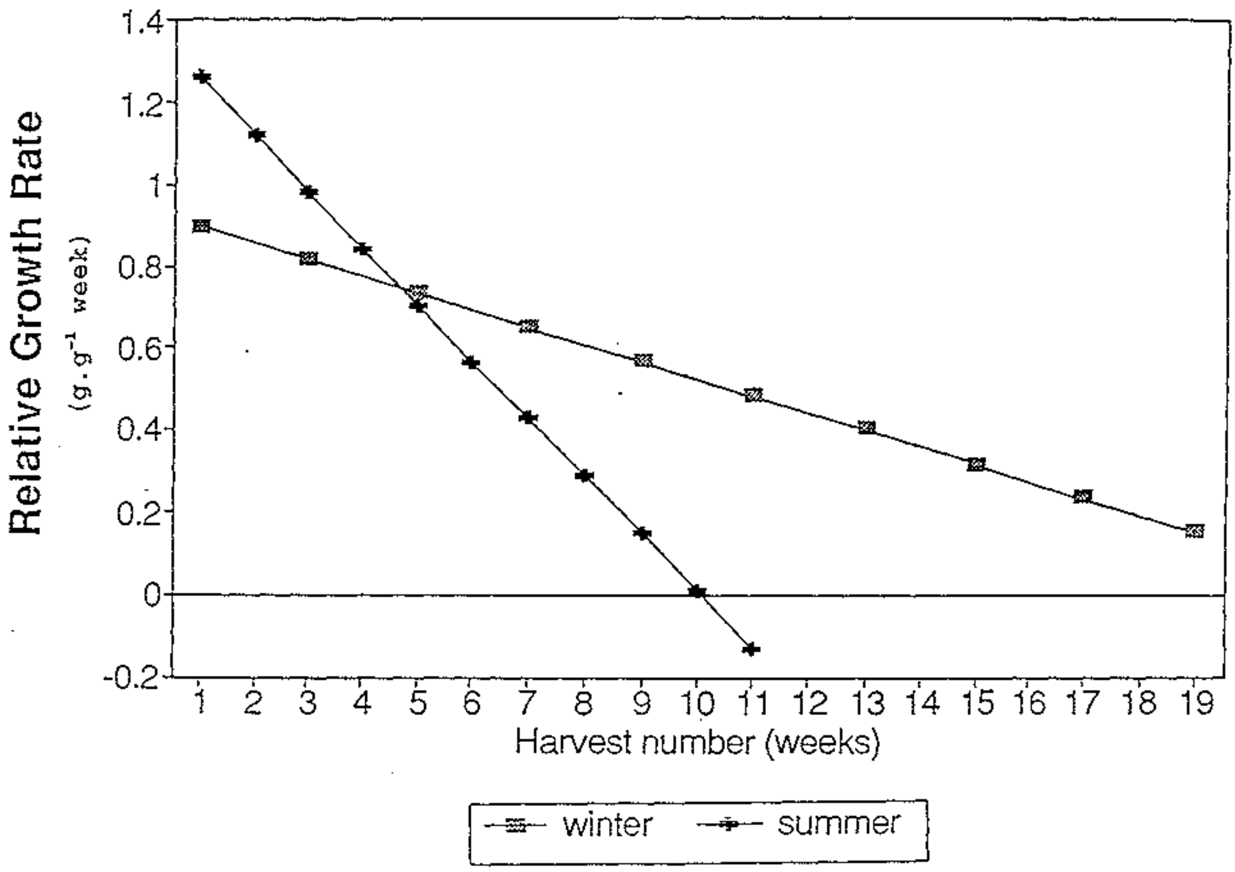

Figure 1. Relative growth rate (RGR) during summer and winter trial over time.

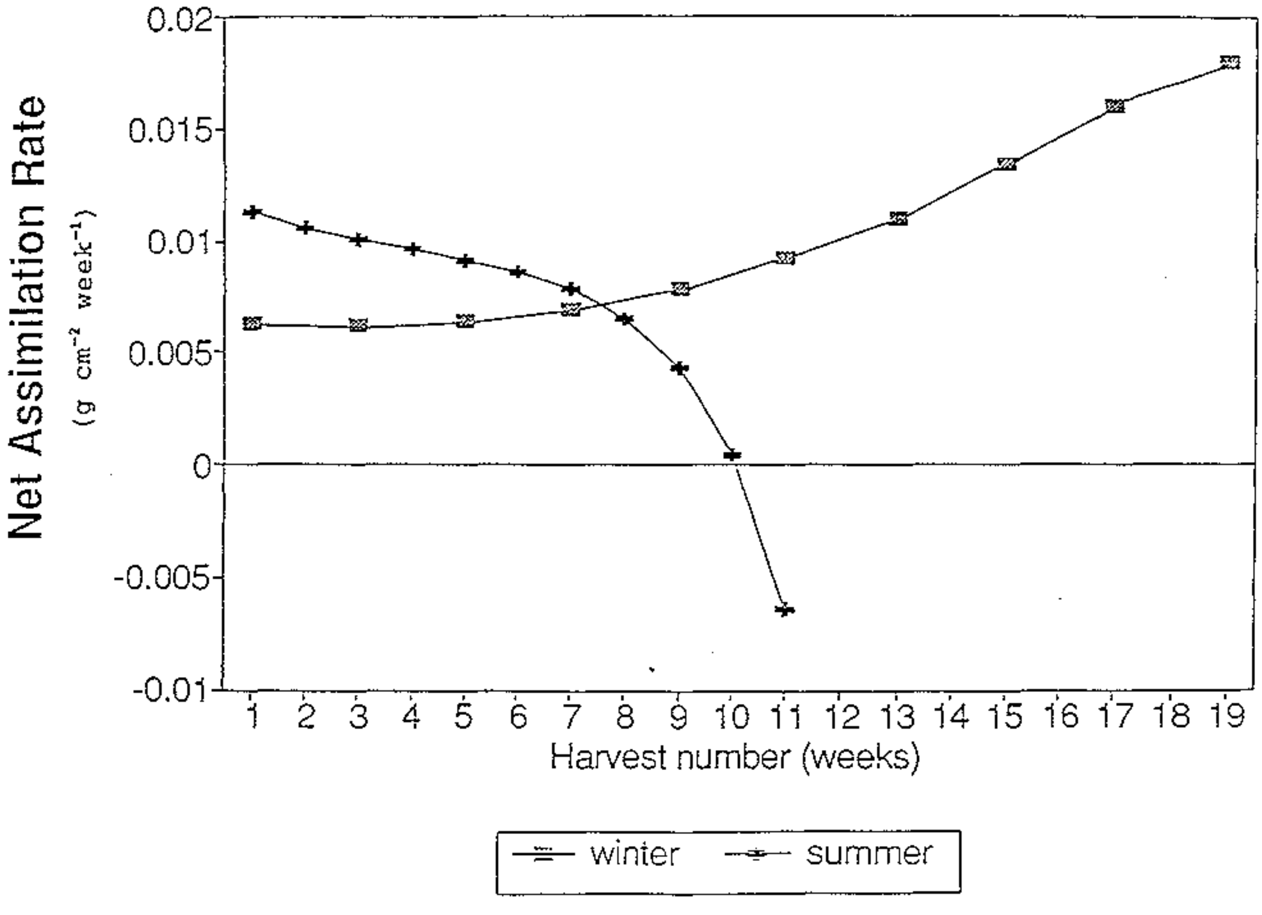

Figure 2. Net assimilation rate (NAR) during summer and winter trial over time.

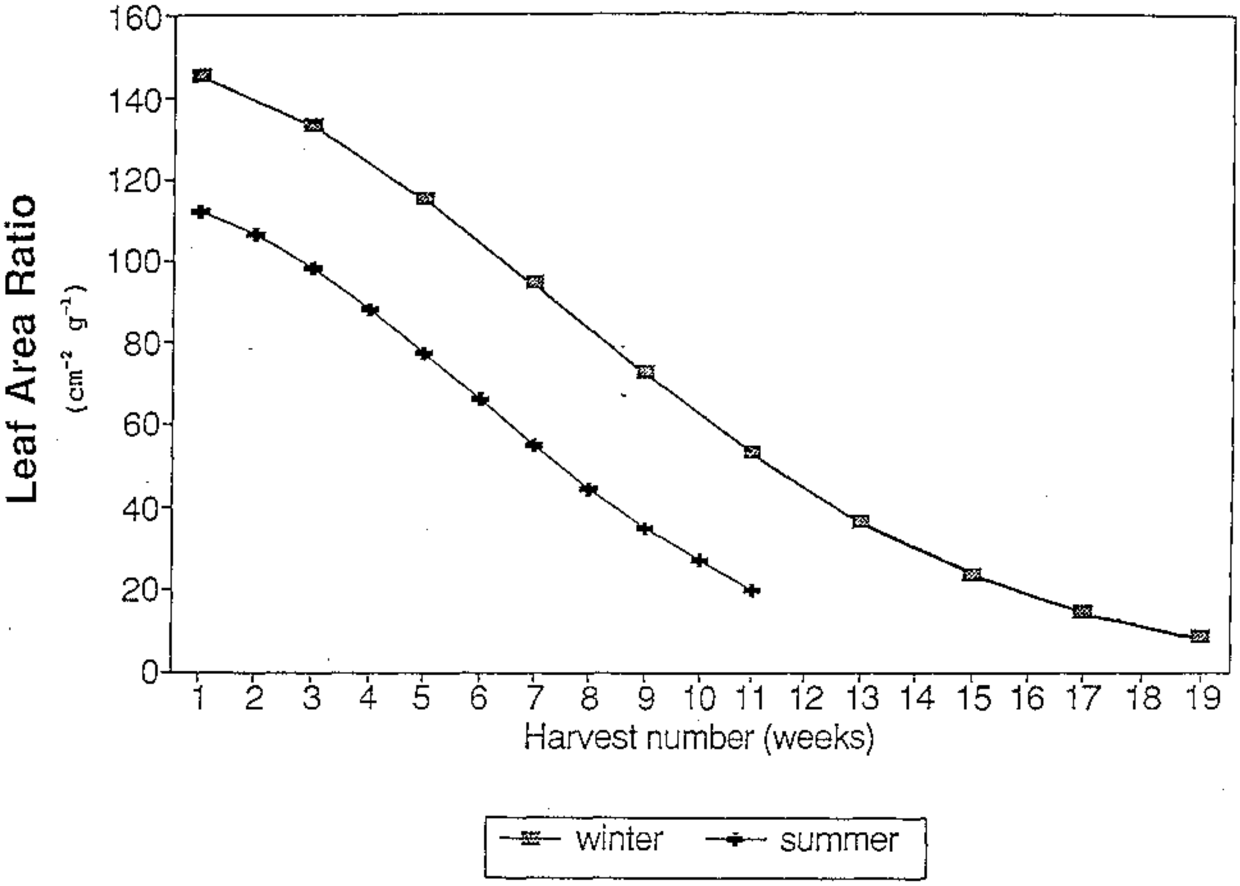

Figure 3. Leaf area ratio (LAR) during summer and winter trial over time.

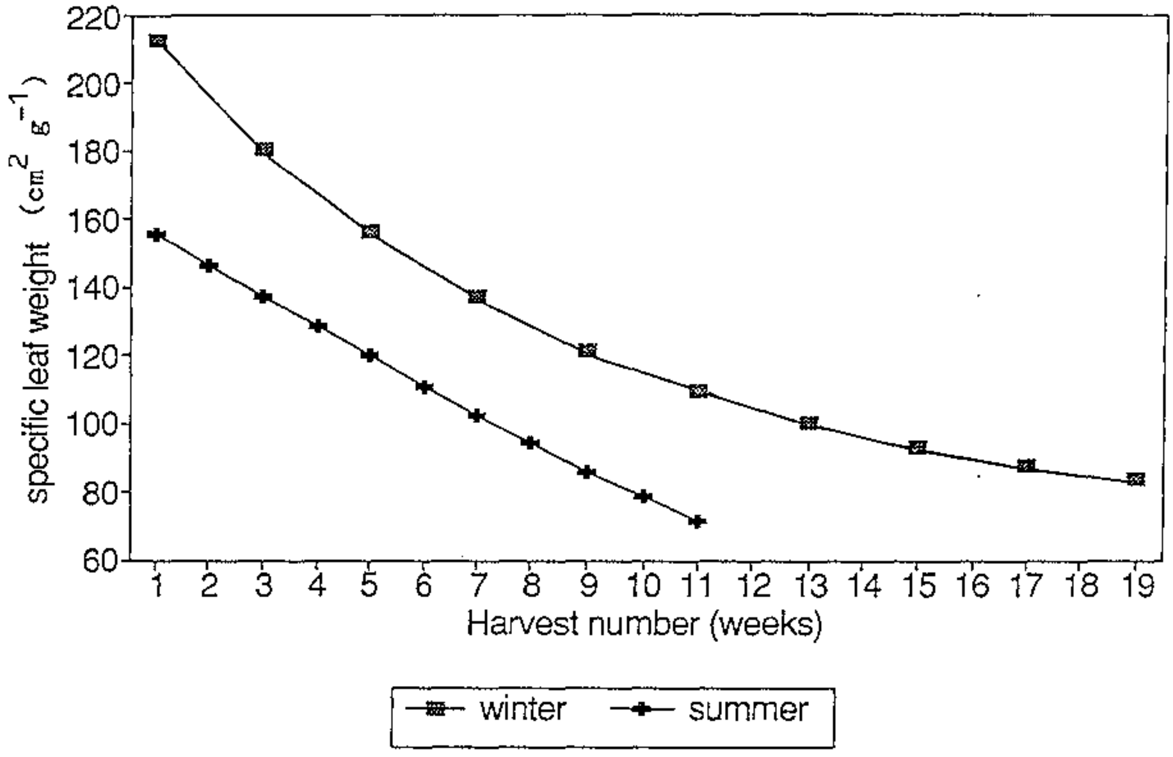

Figure 4. Specific leaf weight (SLW) during summer and winter trial over time.

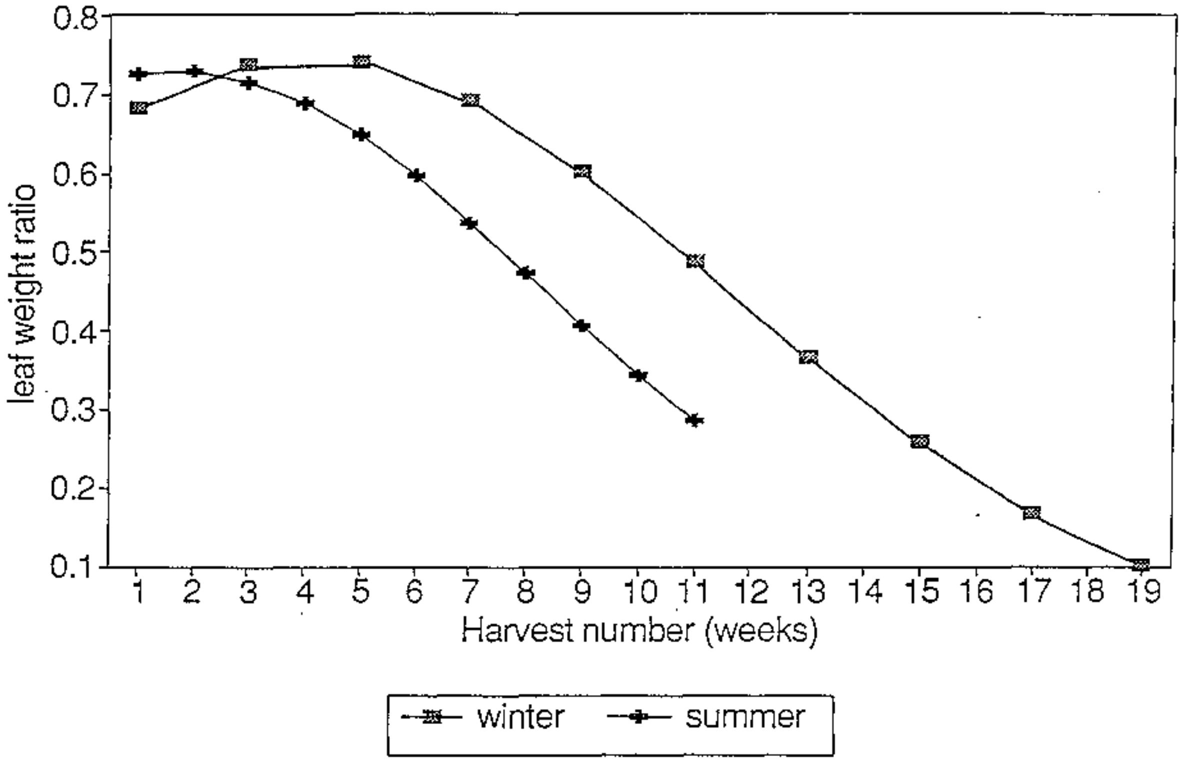

Figure 5. Leaf weight ratio (LWR) during summer and winter trial over time.

leafiness of the plant (Hunt, 1982). The rapid decrease of NAR during summer season can be attributed mainly to the seasonal increase in light incident on the crop and to the greater mutual shading caused by increasing leaf area while the increase in NAR during the latter part of the growing season with the winter planting may be a response of the photosynthetic apparatus to an increased demand for assimilate which was due to the rapid growth of the sink (head) (Koller *et al.*, 1970). Consequently, the rate of growth per unit of leaf area (NAR) or per unit of weight (RGR) changes systematically during the growing season in a way which usually obscures the correlation with light and other environmental factors (Monteith, 1981). When a crop grows at a rate which changes systematically with irradiance (or with any other environmental factor), corresponding changes of NAR tend to be marked by temporary changes of leaf area which always increases during early growth and often decreases towards maturity.

The fall in LAR may be due partly to fluctuating temperature, but is likely to be largely developmental, the young plants' leaves being relatively thin. NAR and LAR are inversely related, mainly because reduction in LAR implies increased leaf thickness hence, increased the capacity for CO_2 assimilation (Hunt *et al.*, 1984) and because a reduction in NAR can depress storage of dry matter formed in assimilation and so lead to higher ratios of leaf area to dry weight. NAR may be somewhat affected by the specific leaf weight (SLW) which determine the thickness of the leaves, hence it is a morphological character often been correlated with CO_2 exchange rate per unit leaf area (Barnes *et al.*, 1969; Dornhoff and Shibles, 1976).

4.1.2 Yield and Maturity

4.1.2.1 Yield-Density effects

The effect of plant density on the relationship between curd weight (yield) per unit area during summer showed an asymptotic curve response (Figure 6) in which as density increases, yield rises to a maximum and remain constant. Yield at maturity were significantly influenced ($P < 0.01$) by plant density. As total weight per unit area increased with increasing plant density, it was assumed that total yield showed an asymptotic relationship with plant density (Figure 6a and 6b). Such a relationship was not found with the winter crop as there was no significant difference in head weight during winter planting possibly due to plants being less leafy (Plate 2) as the poor light conditions limit both the growth and development of the crop. Indeed, light appears to be the primary environmental factor influencing either head weight or maturity date. The role of light in determining yield is emphasized by (a) increasing the amount of light incident on the crop, (b) improving the efficiency of the leaves in intercepting incident light, and (c) utilizing the intercepted light more efficiently in CO_2 assimilation (Hunt *et al.*, 1984). Crop yield depends on the length of the growing season which in turn determines the maximum amount of light that a canopy can intercept.

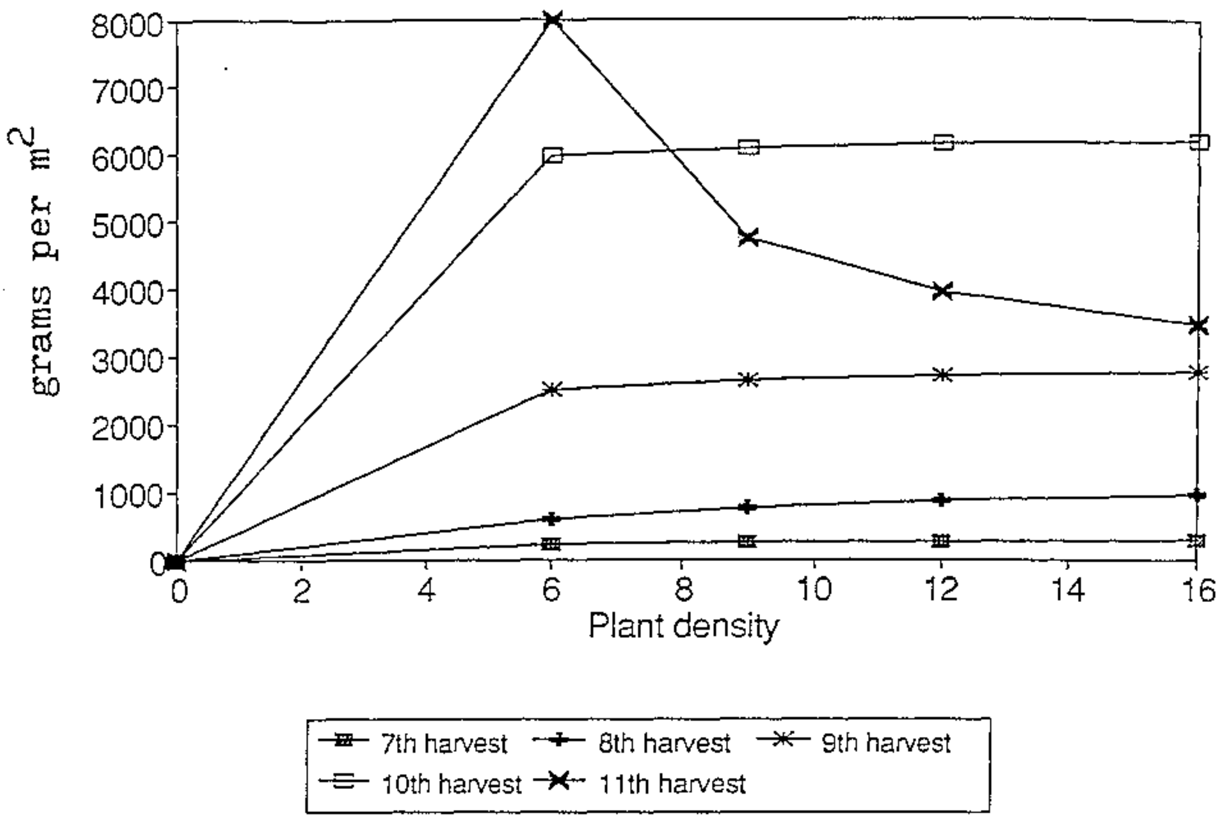

Figure 6a. Yield-density relationship of curd weight per unit area at summer planting.

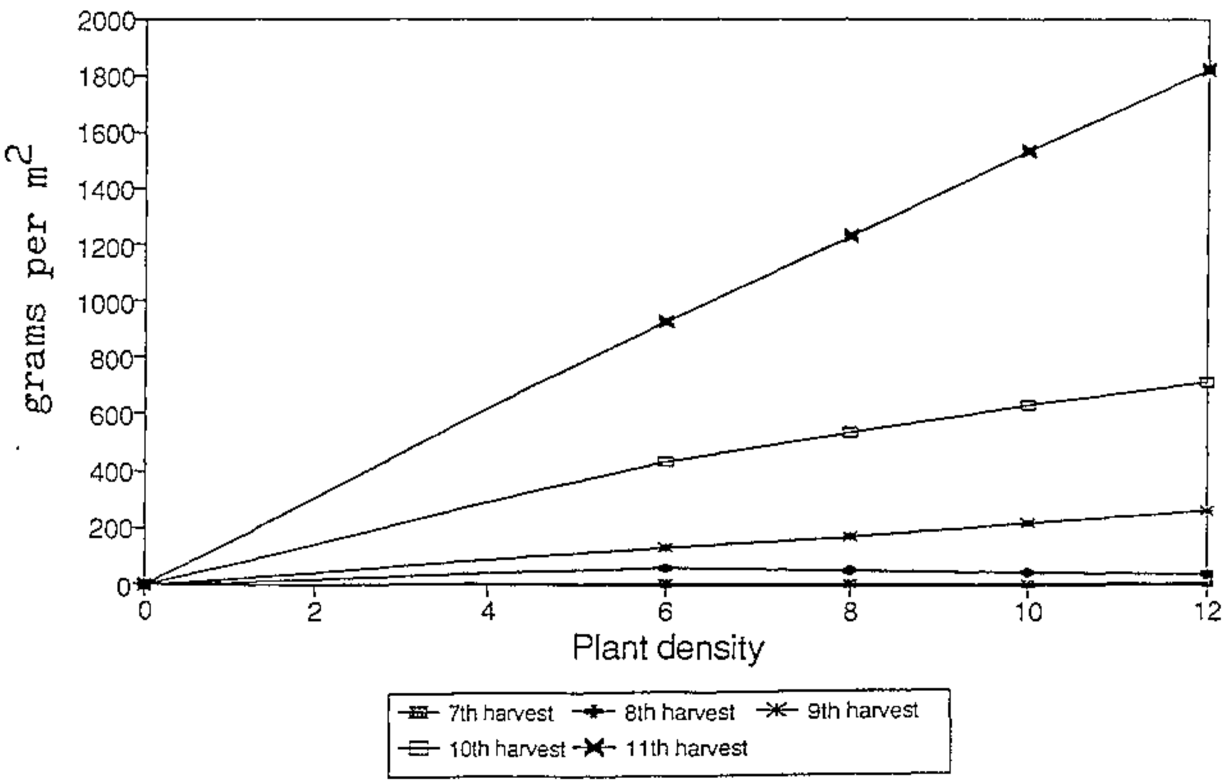

Figure 6b. Yield-density relationship of curd weight per unit area at winter planting.

Plate 2. Broccoli plants grown on the north and south rows during winter season.

Potential yield of a crop is therefore correlated with the rate at which leaves grow and the timing of their senescence. Actual yield is less than the potential yield in the winter season partly due to the photosynthetic efficiency of the leaves being limited by an environmental factors such as light and temperature.

4.1.2.2 Control of Head Size

During crop growth, curd development in relation to environment was monitored. Control over the head size in the summer can be obtained by regulating the planting density according to these results. The higher the density, the lower the weight per plant, resulting in a smaller curd during summer plantings. Curd initiation was also found to be influenced by plant density (Table 3). In both seasons, closely spaced plants were found to initiate curds earlier and later in the widely spaced crops. However, this did not result in earlier head maturity, as there was a longer initiation time with the earlier curd maturity. These effects on the time of head maturity must have arisen during the growth period of the head either by an effect on individual curd growth rates or on curd size at maturity. The relationship between heat unit requirements and curd growth was investigated to provide "check points" on the progress of the head development for both seasons with respect to heat accumulations. Temperature influences the curd growth and development of cauliflower in two ways (Wurr, 1988).

1) By affecting the time of curd initiation;

Table 3. Mean differences in time of curd initiation (0.6mm) to maturity approximately 130 mm in diameter) for both seasons.

Season	Density (plants m^{-2})	Time of 0.6 mm (weeks)	Time of 130 mm (weeks)	Differences from 0.6 to 130 mm (days)
Summer 1993-94	6	5.01	9.11	28.71
	9	4.25	9.60	37.41
	12	5.10	9.54	31.11
	16	4.92	9.36	31.11
Winter 1994	6	5.02	9.88	68.03
	8	4.70	10.02	74.47
	10	4.95	10.17	72.97
	12	4.44	9.95	77.07

2) By affecting the rate of curd growth.

The mean time from transplanting to curd initiation varied from 34.25 days for the summer planting to 62 days (Table 4) for the winter planting which clearly suggest that broccoli is different from cauliflower as there is no vernalization requirements for curd initiation. Gauss and Taylor (1969b) argued that there is no quantitative nor qualitative cold requirements for curd initiation in broccoli while Fujime (1988), Fontes *et al.* (1967) and Miller *et al.* (1985) suggested otherwise. After curd initiation, the logarithm of curd diameter increase in a curvilinear manner with accumulated day degrees until maturity (Figure 7). Although curd initiation is later in winter than in summer, once initiation takes place the response of curd growth to accumulated temperature is similar. A base temperature of $0^{o}C$, provided the best-fit curve ($R^2 = 0.993$). Summer plantings received higher solar radiation and this resulted in bigger leaves (Plate 3), which did not affect curd growth in any way. The evidence suggests that (a) light does not limit yield nor NAR; but (b) the growth rate of a crop is almost proportional to the radiation intercepted by its canopy; and (c) the rate of photosynthesis increases with irradiance up to a saturating point beyond which it is nearly constant (Monteith, 1981). Previous work of Hall (1990) pointed out that highest yield of economic product per unit land area, crops should intercepts solar radiation fully during the growth stages, when photosynthesis contributes carbohydrates to the economic product. Curd diameter seems to relate directly to head weight irrespective of varieties (Table 5) hence, temperature after curd

Table 4. Days from planting, date and accumulated heat units at initiation.

Season	Cultivars	Days from planting	Date of head initiation	Accumulated Heat Units (^{o}C)
Summer 1993-94	Greenbelt	32	09/01	338
	Marathon	32	09/01	338
	Shogun	41	18/01	498
	Variety "X"	32	09/01	338
Mean		34.25		
Winter 1994	Greenbelt	54	27/06	340
	Marathon	55	28/06	346
	Shogun	77	20/07	498
Mean		62.00		

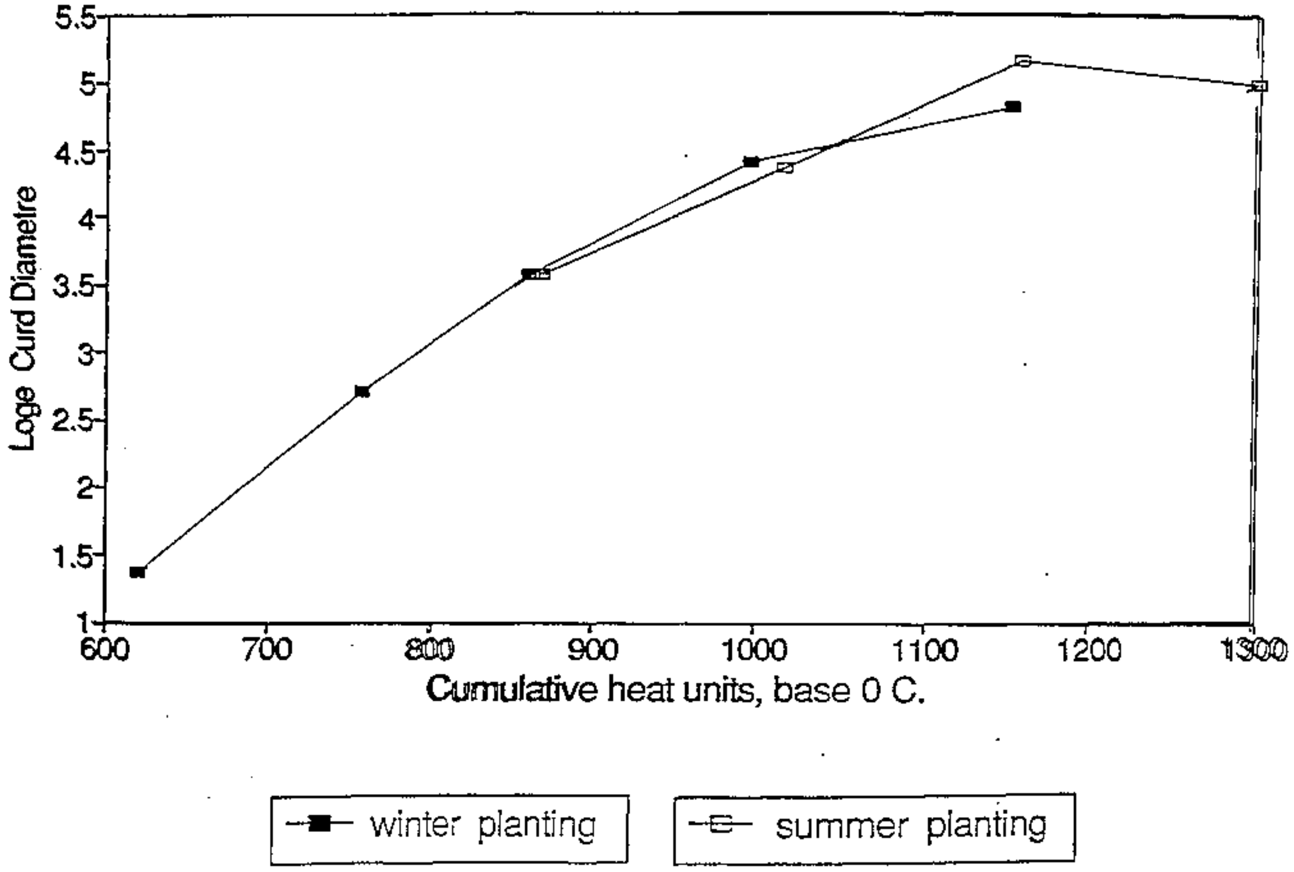

Figure 7. Logarithm of curd diameter plotted against accumulated heat units during summer and winter plantings (mean of densities and cultivars).

Plate 3. Broccoli plants grown during summer experiment.

Table 5. Relationship of curd diameter to head weight of different densities during summer and winter trial (mean of varieties).

Season	Density (plants m^{-2})	Curd diameter (mm)	Head weight (gms)
Summer Trial	6	169.6	632.4
	9	117.8	268.0
	12	108.5	256.7
	16	86.2	160.3
Winter Trial	6	53.9	47.5
	8	55.4	44.1
	10	52.5	43.2
	12	52.6	45.0

initiation affect the time of maturity because the curd will grow faster at higher than at lower temperatures.

An important factor in determining the harvest date is the time of curd initiation. The regression of $\log_e$ head diameter against days from planting indicated that curd initiation for *cv* Shogun was substantially later as for *cvs* Greenbelt, Marathon and variety "X" even though accumulated heat units from planting to curd initiation showed considerable variation between planting season. As a further complication in winter planting curd yields were higher in the north rather than the south row (Plate 4). Curd fresh weight per plant at maturity were significantly influenced ($P < 0.01$) by row position with a mean of 90.474 and 66.162 grams for north and south row, respectively. Bigger leaf areas were also found on north rows. This may be due to the differences in the interception of solar radiation (Hall, 1990) and likewise increase soil temperature (Watts, 1973) with the south rows being partly shaded by the plants in the north row. Changes in root zone temperature affect all rate processes involved in root activity and indirectly in many aspects of shoot activity in plants. Growth and partitioning between shoots and roots may be sensitive to changes in root temperature via effects on specific rates of nutrients and water uptake, producing transitory changes in nutrients levels in the internal regulatory pools (MacDuff, 1989). An interpretation of the responses to root temperature as shown by the idea of "functional equilibrium" between shoot and root activity (Brouwer, 1962).

Plate 4. Matured broccoli curd on the north and south rows during winter season.

Increasing the water or nutrient supply may tends to increase shoot growth relative to root growth, while the opposite occurs if light intensity increased. Davidson (1969) used this approach to explain the effects of temperature on specific activities of shoot (photosynthesis) and root (nutrient and water uptake), concluding that adverse effect on the activity of one part is compensated by relatively greater growth of the affected part. Johnson and Thornley (1987) proposed a semi-mechanistic basis for partitioning strategy, treating partitioning as responding to changes in substrate concentrations (i.e. carbohydrates, amino acid) within the plant, influenced by environmental factors acting on specific activities of shoot and root (MacDuff, 1989).

4.1.2.2.1 Differences in time from 0.6mm to 130mm curd diameter.

Mean differences in time to curd initiation from transplanting showed that a planting density of 9 plants m^{-2} was earliest with a mean of 4.25 weeks but the latest to attain the curd diameter of 130 mm with a mean of 9.60 weeks a difference of 37.4 days (Table 3). These results suggests that planting densities with earlier curd initiation took the longest time to attain a curd diameter of 130 mm for both season but summer planting revealed significant differences ($P < 0.01$) on the the time of 0.6mm to 130mm. However, at winter planting, no significant differences occurred in the different densities used. The planting density of 6 plants m^{-2} had the least number of days from 0.6mm to 130mm for both season (Table 3) which suggest that widely spaced crops intercepts more incident radiation mainly due to bigger leaf area hence, earlier maturity. This is similar to the findings of Monteith (1981) that potential yield of crop is correlated with the leaf growth.

4.1.2.3 Effects of Season

The season of planting influenced both the curd yield and other plant growth characteristics. Summer planting produced plants with a shorter period of days to curd initiation hence, earlier maturity. The season of planting affected significantly the period required for initiation of the curd which is consistent with the findings of Ahmed and Abdullah (1986). The variable growth caused by changing temperature and radiation as the season progresses must also be taken into account. Summer weather conditions are more favourable for growth and therefore regular plantings stand more chance of providing regular cuttings (Martin, 1985). Plantings for winter harvesting need to be more frequently, to account for the natural delay in maturity as days shorten and temperatures decline. Differences in above-ground biomass production were much greater between season than between treatments. Differences in growth between season could largely be attributed by differences in accumulated growing degree days (GDD) (Beech and Leach, 1989). When the dry weight per plant was plotted against the accumulated heat units for both season (Figure 8) the calculated base temperature which had the best-fit curve ($R^2 = 0.9834$) irrespective of cultivars was 5^0C. Similar heat unit accumulation is necessary to bring a crop to the same stage of

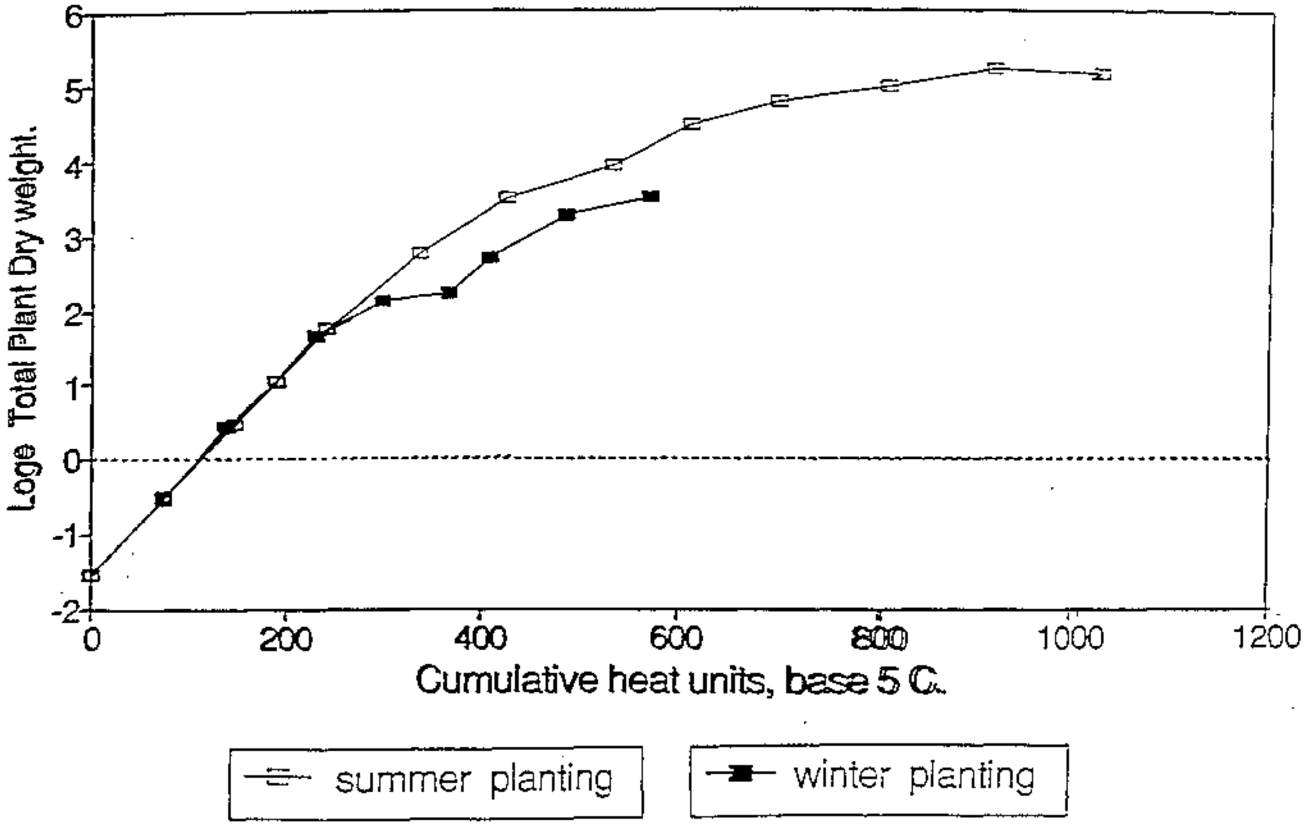

Figure 8. Logarithm of total dry weight per plant plotted against accumulated heat units during summer and winter plantings.

maturity (Katz, 1952), but varied in such a manner that it was lower when the season was cool (winter) and higher when the season was warm (summer).

At the summer planting, plants at higher densities complete their canopy sooner and so make more use of the available incident radiation than plants at low density. The convergence at higher densities, the weight of plant part clearly shows that light ultimately limits the curd growth and thus defines the upper limit for the plant density. This explain the decrease in harvest index as densities increase (Caballero, 1987). During winter planting, bird damage on leaves was a problem which brought a major effect on the leaf area and total dry weight of the plant at maturity. However, fluctuations in the yield of a crop from season to season can be correlated with the incoming radiation (Monteith, 1981) although yield is also influenced by many other enviromental variables in particular, by rainfall, temperature and the incidence of diseases.

4.1.2.4 Density effect on maturity

The data was analyzed to see whether any variation originated at the time of curd initiation or from differences in curd growth within the crops or both. Results showed that density significantly affected ($P < 0.01$) curd maturity for both season. Although the cultivars grown produce curds at every spacing used they were found to respond differently to increasing plant density. During the summer trial widely spaced plants had bigger leaf areas and the highest total dry weight per plant. These results are consistent with the theory of Bleasdale (1966) that differences in plant weight (i.e. biological yield) established early in the growth of two population of a crop can be moderated or completely lost due to the effects of inter-plant competition later in the growth of the crop. Bleasdale's model suggest that once total weight differences between plants of the different plant populations have been removed, then subsequent growth should occur at the same rate for both populations. However, this considers only the total dry matter and the situation can be more complex for crops such as broccoli and cauliflower in which economic yield consist of a plant part, rather than the whole plant, since factors causing early differences in total dry weight or distribution of dry matter may also influence the initiation and development of the curd. Widely spaced plants (6 plants m^{-2}) matured earlier than the close spaced plants during both the summer and the winter trial. The later that curd initiation occurred then the earlier maturity period whereas the earlier the initiation the longer maturity time.

4.1.3 Plant Growth

4.1.3.1 Density-variety effect on number of leaves produced

During summer trial the number of leaves produced per plant was significantly affected ($P<0.01$) by both the density of planting and varieties. Plants at wider spacing (6 plants m^{-2}) had the highest number of leaves (18.0) per plant (Figure 9a) compared to planting densities of 9, 12, 16 plants m^{-2} with a mean of 16.80, 16.45, 16.40, respectively. Varietal differences were observed on leaf count over time. Marathon was found to produce more leaves (Figure 9b) compared to the other varieties. However, no significant differences was obtained on density x variety interaction. During winter plants at different densities had similar patterns in the number of leaves produced (Figure 10a), while with cultivars there were significant differences ($P<0.01$). Leaf count with *cv* Marathon was found to be consistently higher (Figure 10b) compared to Greenbelt and Shogun.

4.1.3.2 Density-variety effects on leaf area per plant

During summer experiment leaf area per plant was significantly influenced by density of planting. At low density (6 plants m^{-2}) plants produced bigger leaves (Plate 3, Figure 11a). At high planting density (16 plants m^{-2}) plants produced markedly smaller leaves. This result was not found during winter trial where there was no density effect on the leaf area per plant. However, there was a rapid decline (Figure 11b, harvest 11 and 13) due to bird damage which could have caused a decrease in yield.

4.1.4 Total plant dry weight

4.1.4.1 Curd and total dry matter production.

The potential for dry matter production varied with season and planting density (Table 6). Results showed that curd and total dry matter production were lower during winter season inspite of a longer growing period than the summer

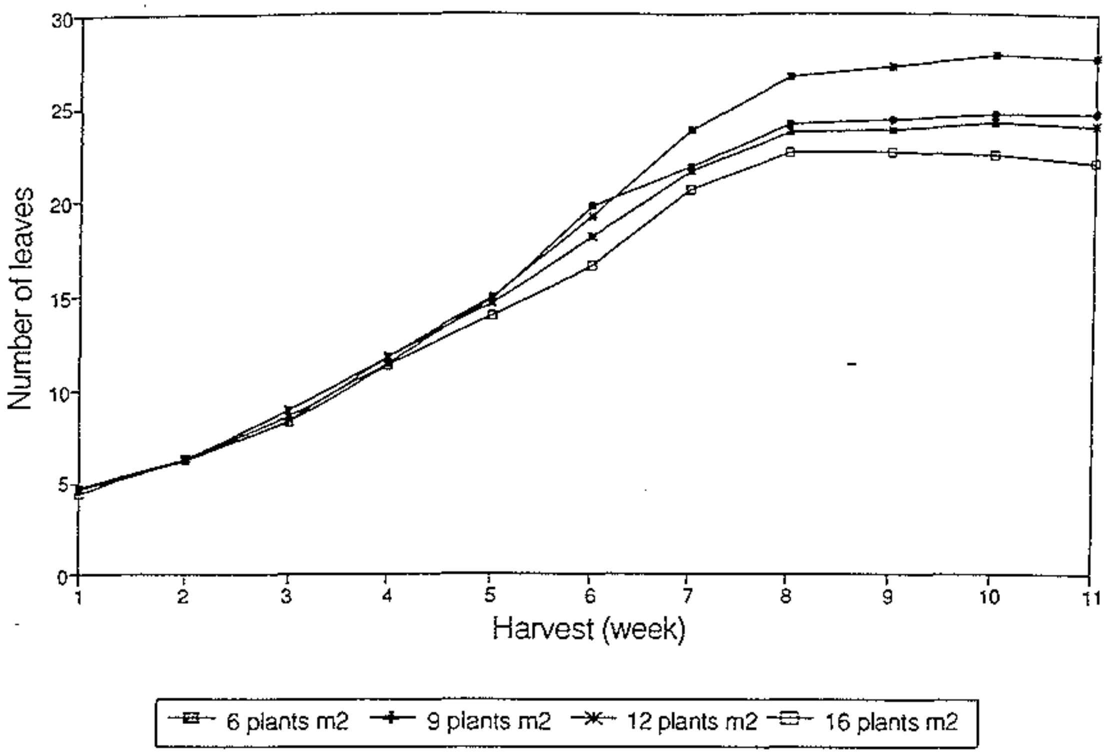

Figure 9a. Means of leaves number per plant at different densities during summer trial.

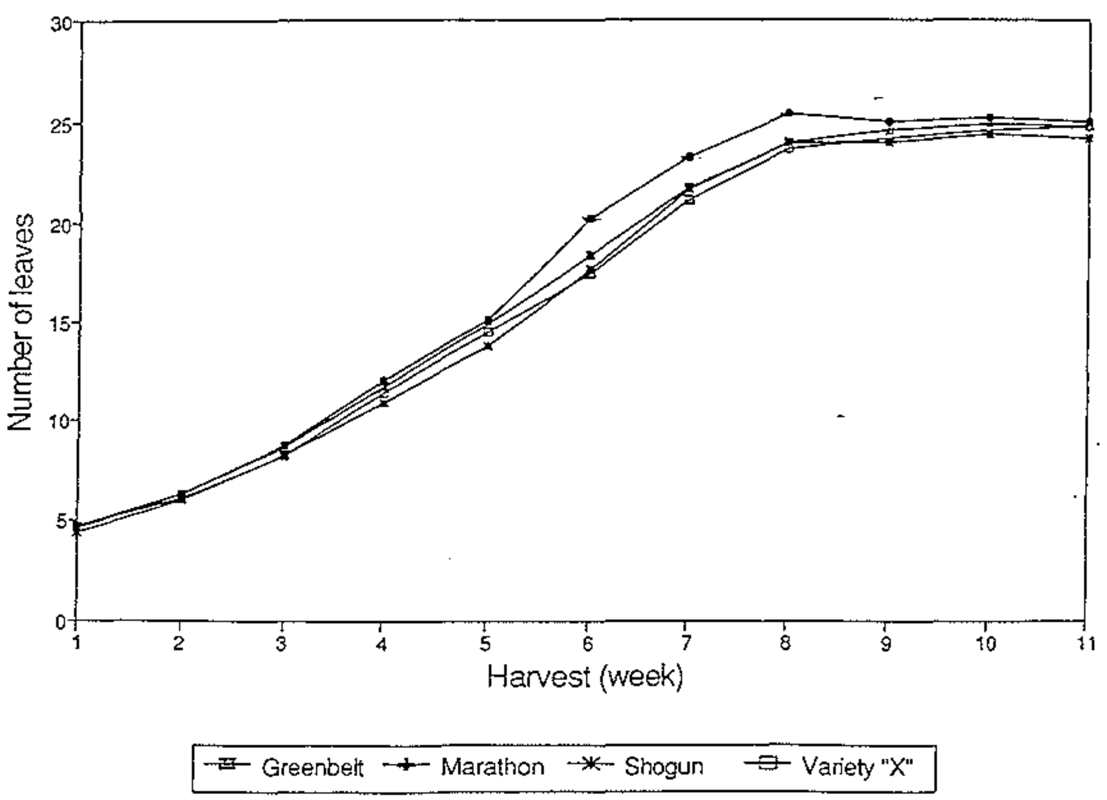

Figure 9b. Leaf number means of different cultivars during summer trial.

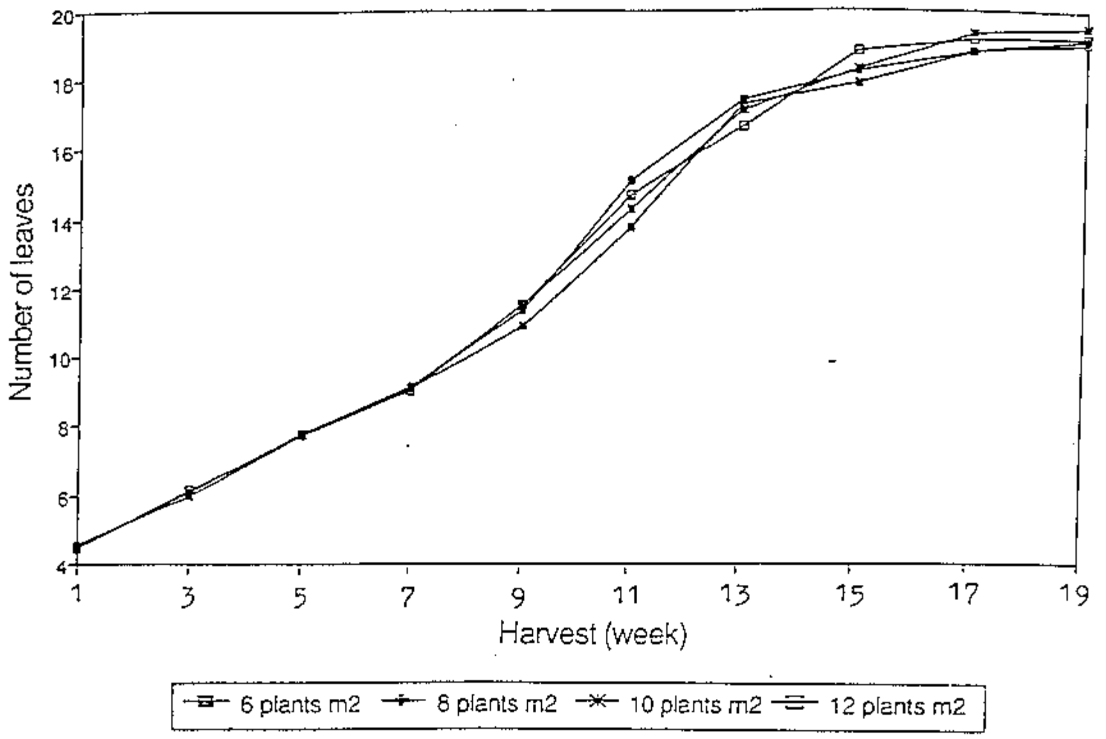

Figure 10. Means of leaves number per plant at different densities during winter trial.

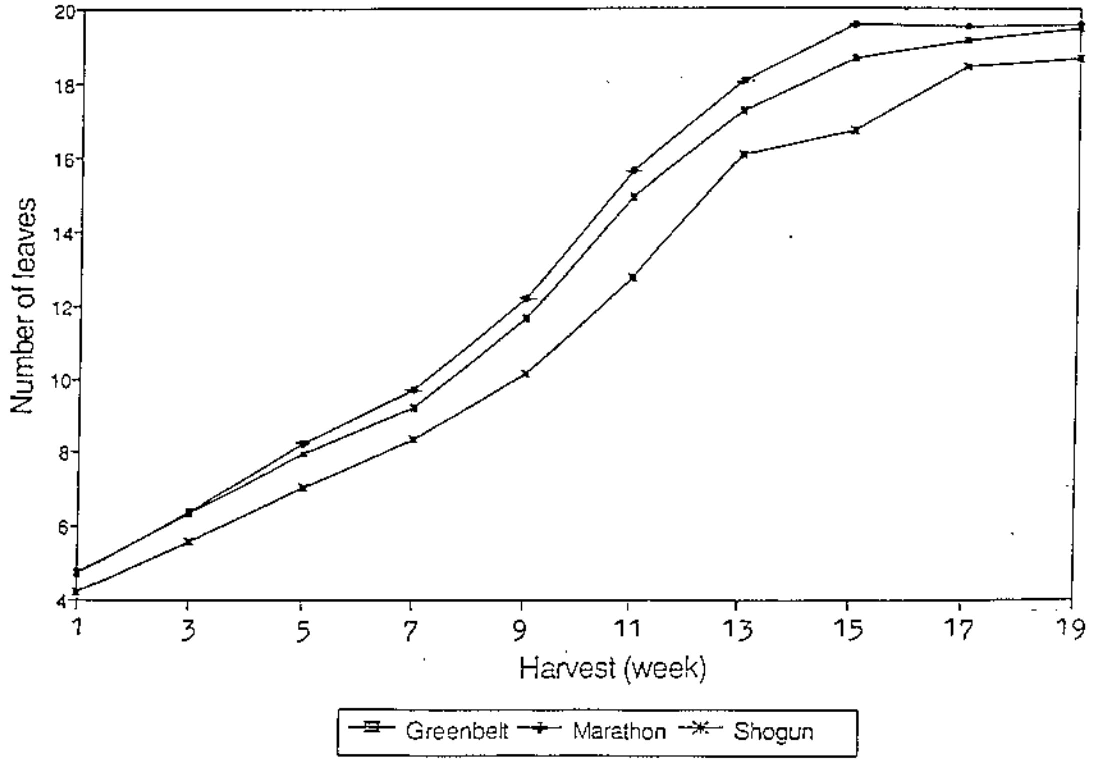

Figure 10b. Leaf number means of different cultivars during winter trial.

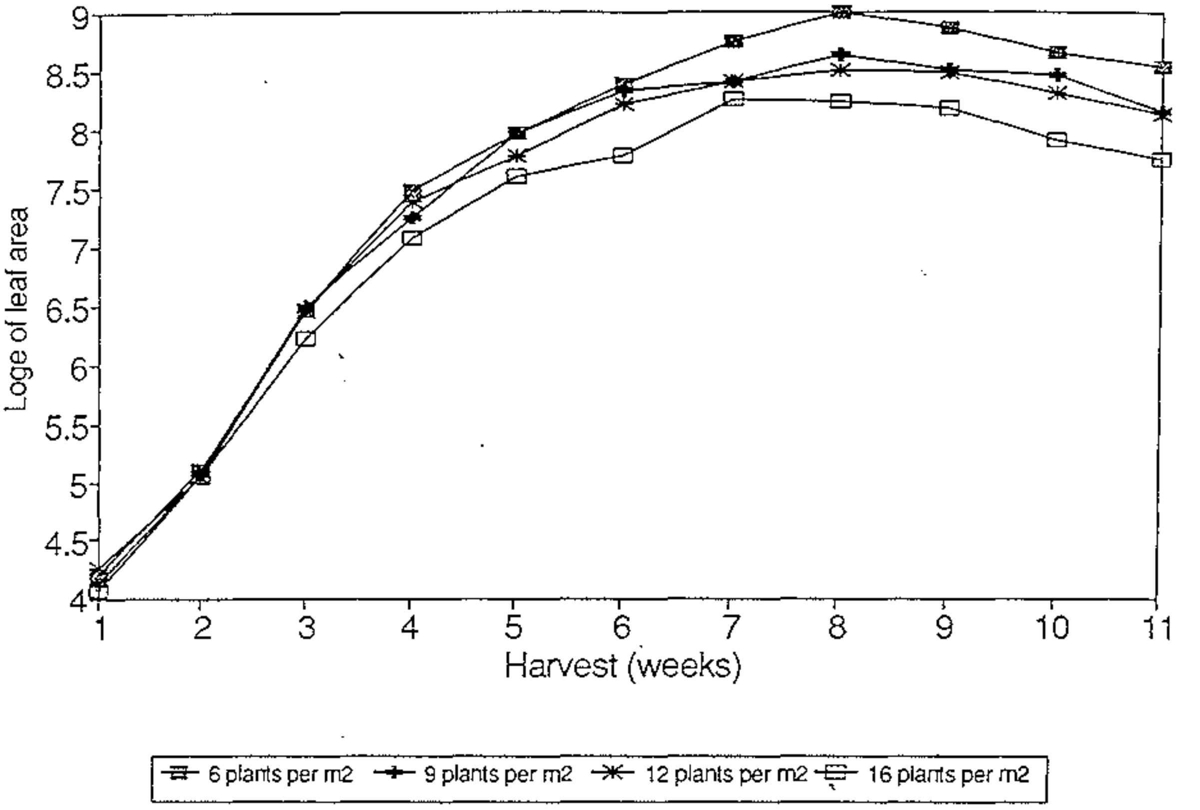

Figure 11. Logarithm of leaf area at different densities during summer trial.

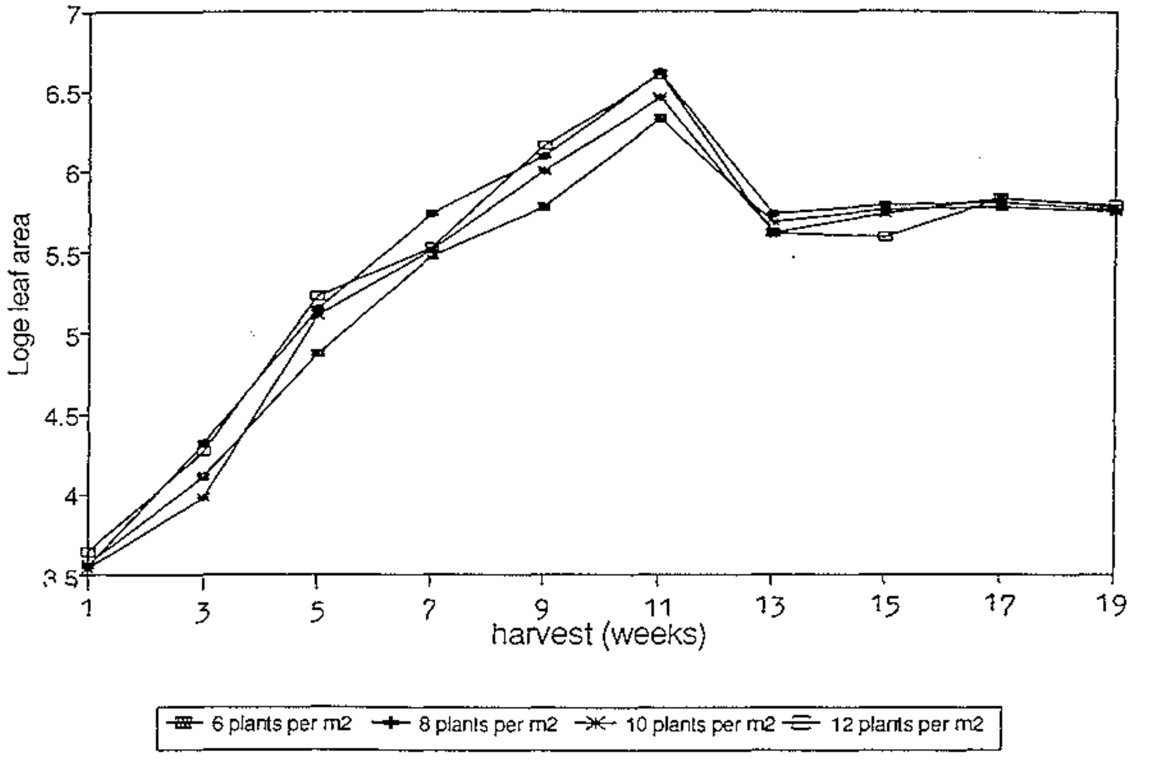

Figure 11b. Logarithm of leaf area at different densities during winter trial.

Table 6. Log_e of total dry matter production of different cultivars during summer and winter planting (means of all harvest).

Cultivars	Total Dry Weight (grams per plant) Summer Trial	Winter Trial
Greenbelt	3.362	1.616
Marathon	3.360	1.643
Shogun	3.200	1.198
Variety "X"	3.342	-

planting. Total plant dry weight and curd diameter showed a highly positive correlation with the accumulated heat units per week (summer) and biweekly (winter) during the growing period ($R^2 = 0.98$ and $R^2 = 0.99$, respectively). Curd and total dry weight also varied with cultivars. Greenbelt (summer) and Marathon (winter) had the highest total dry matter production while Shogun was the lowest. Mean dry curd weight appeared to be influenced by season of planting although the trend was curvilinear over time (Figure 12). Winter planting significantly reduced the total dry matter and thus reflected in the changes in the parameters of the yield density relationship.

4.1.4.2 Allometric relationship

The allometric relationship is usually applied to data where plant size varies as a result of differences in plant age.

(1) Fitting the allometric relationship of the logs total plant dry weight

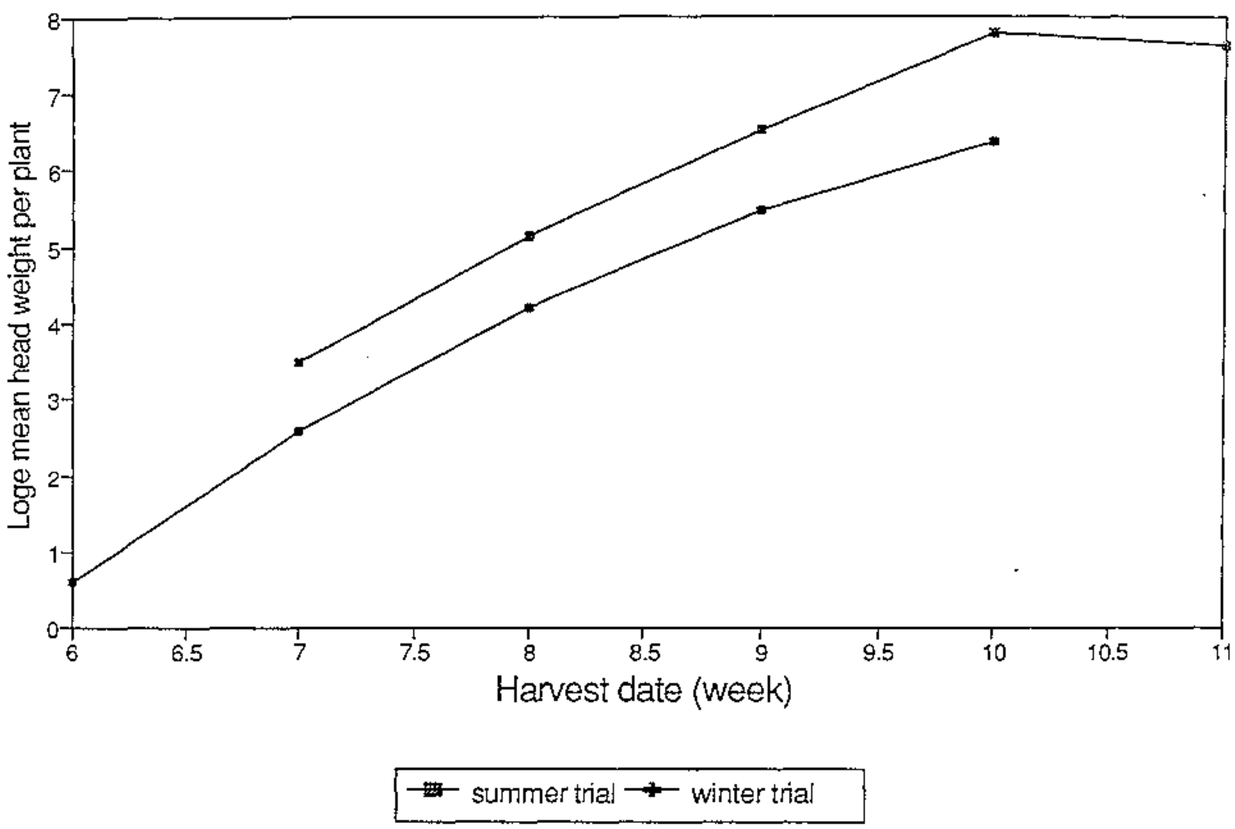

Figure 12. Mean head weight (grams) during summer and winter trial.

against log of curd dry weight showed that in both the summer and winter trials the slope was about 0.5. This suggests that the proportion of curd to total plant weight decreases with increasing density, irrespective of cultivars.

(2) With the slope constant (0.552) the intercepts is a measure of the proportion of curd to total plant weight, and in Table 7 shown the total plant weight (grams) required to produce one gram of curd. This shows a higher proportion of curd to total dry weight in later harvest which means that the quantity of head dry weight as a percentage of total weight for all the cultivars increased with time and was considerably higher for Shogun as for other cultivars (Table 8). In the winter season there was no significant differences between cultivars whereas during the summer planting cultivar differences were significant ($P < 0.01$) though such differences may probably be due to the effect of harvest date.

Table 7. Means of intercepts with constant slope (0.552) on curd yield at different harvest date for both season.

Harvest (week)	Summer Trial	Winter Trial
7	2.129	1.190
8	1.883	1.068
9	1.613	1.040
10	1.363	1.016
11	1.362	-

Table 8. Means of intercepts with constant slope (0.552) of different cultivars for both season.

Cultivars	Summer Trial	Winter Trial
Greenbelt	1.558	1.079
Marathon	1.712	1.058
Shogun	1.854	1.098
Variety "X"	1.555	-

4.2 Discussion

4.2.1 Plant growth and development

Initial relative growth rate of broccoli as a function of chronological time varies with the developmental stages for both season of planting. It was found higher in summer planting due to enhanced solar radiation as well as temperature which together affect the instantaneous maximum RGR (Hunt and LLoyd, 1987). Cumbus and Nye (1982) who concluded that growth rate, indicated by the leaf area were higher at 30°C and 25°C but the extreme cold environment markedly reduced the rate. High rates of leaf area increase at 25°C and 30°C were associated with the greater cell expansion and strongly influenced by temperature (Milthorpe, 1959) as shown by total dry matter. During summer planting, broccoli growth in the early stage prior to initiation is likely to be affected by temperature, since all the leaves are probably light saturated under normal conditions. Watts (1973) showed that growth rates in the early stages depend on temperature of the apical meristem which is more closely related to soil temperature at 5 cm depth than to air temperatures. In the later stages of growth (i.e. after curd initiation), self shading of leaves occurs and increases as growth proceeds. Radiation rather than temperature is then likely to be more important factor affecting growth (Gray and Morris, 1978). During summer, planting density may influenced the growth pattern of the crop. Widely spaced plants were found to be higher in the number of leaves produced likewise bigger leaf area probably due to higher temperature during the growing period of the crop. At the winter planting there were no density effects on leaf number per plant but there were cultivar differences on the number of leaves produced with Marathon having higher leaf number than Greenbelt and Shogun.

Plotting the initial relative growth rate (RGR) against time for both season suggested that the relationship was not similar which was confirmed by regression analysis. Plants grown in the winter took a longer period to reach maturity than in the summer. Maturity differences occurred in the time of curd initiation for both seasons of planting. These results confirmed that plants with early curd initiation may mature later and vice versa. This simply mean that growth and time of maturity are affected by variations in temperature and total radiation above a threshold of 11-12^{o}C (Gray and Morris, 1978).

The pattern of increase in dry weight for both season was logistic in form. Thus the growth curves obtained were not similar and such differences could not be entirely eliminated by replacing chronological time with 'time' scales based on accumulated heat units.

Another feature of the results obtained was the variation in curd yield at winter planting between the north than the south facing rows. Row orientation may probably influenced the produce with the south row being partly shaded by the plants on the north row. Fresh head weight at maturity varied between planting season. Head weight per plant (grams) in the summer planting was found to be higher than during winter planting regardless of densities and cultivars. An hypothesis to account for these effects would be that temperature, light intensity, daylength or any combination of these, affects the 'frame' size (related to the size of the leaves) of the plant prior to curd initiation. Thus differences in plant potential for curd and total dry matter production with planting season was also related to differences in temperature regimes as therefore showed good correlations with accumulated heat units during each growing period. The lower the temperature regime, the longer the growing time. Hence, the potential for dry matter production declines.

When curd diameter was plotted against accumulated heat units (base temperature $0^{o}C$) the growth of the curd was almost linear in form until maturity. The gradual senescence of the leaves resulting in the reduction supply of photosynthesis to the curd (Diputado, 1989) may possibly have contributed to the decline in the growth rate of the curd at the last harvest during summer trial.

The regression analysis of the yield data during summer planting showed that curd yield on a per unit area basis (g m^{-2}) increased with increasing planting density hence, planting density can be considered to be an ideal cultural factor in regulating the size of the curd. However, in the winter planting there were no differences in total curd yield per unit area which suggest that planting density is less important at this season of planting.

The yield-density relationships for total dry matter and curd yield were asymptotic for the summer planting. The lower values for both dry matter and curd yield for winter planting compared during summer indicate that lower accumulated heat units and shorten days experienced could be a major contributing factor. This is in agreement with the work of Thompson and Taylor (1970) in Scotland.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

(1) The relative growth rate (RGR) parameters provided a useful index on growth rates of the plants as affected by planting season and density. Variation may also be explained by the changes in the other growth parameters as these are interrelated hence, RGR is dependent upon NAR and LAR, LAR on SLW and LWR. Trends of these growth parameters varied with season where:

RGR was higher in summer than in winter but the reduction with time is greater.

NAR increases with time in winter but decreases with time very rapidly in summer.

LAR was lower in summer planting than during winter.

Generally, differences in RGR exist with season of planting on curd initiation and curd maturity.

(2) The period from planting to curd initiation and from initiation to maturity are the two important developmental phases in broccoli. During these stages plants progressively becomes faster maturing with increasing temperature regimes. Thus, solar radiation which drives the growth or 'size' of the crop, may also influence the date of maturity (Marshall and Thompson, 1987a). The cultivars used do not appear to have any cold requirement to initiate curd as plants

developed curd regardless of temperature. Curd growth regardless of cultivars showed a predominantly linear pattern with accumulated heat units hence its development is temperature dependent.

(3) The number of leaves produced, leaf area, curd weight, curd diameter and total dry weight per plant was influenced by planting density during summer trial. No cultivar differences was found during this season of planting which means that density of planting is of primary importance in the summer time. However, the reverse effect was found at winter planting where density had apparently no influence on leaf count per plant, leaf area and curd yield whereas cultivars were found to be variable on the number of leaves produced, curd weight and total dry weight per plant.

(4) Summer planting outyielded the winter crop in terms of fresh head weight and diameter. Spear diameter seems to be directly related to head weight, hence, increase in yield per unit area which shows a clearly defined response to accumulated temperature (Pearson and Hadley, 1988). The use of heat units highlights the significance of temperature as a major environmental component determining the duration of the developmental stages of the crop. Hence, this is useful in formulating planting schedules in order to have a regular supply of broccoli for either fresh market or for processing.

(5) Variation in economic yield with season of planting were related largely to differences in the potential of the crop for dry matter accumulation. The potential for dry matter production is determined primarily by the RGR. Cultivar differences in total dry matter accumulation was probably due to the length of the growing period.

(6) Yield in terms of curd weight and diameter per plant were found to be higher in summer than during winter. The yield-density equation showed an asymptotic trends at the highest levels of density. Allometric relationship shows a higher proportion of curd to total plant weight at maturity which suggest that quantity of head dry weight as a component of total plant weight increased with time irrespective of cultivars. This relationship may quantify the required total plant dry weight to produce one gram of curd.

(7) The right planting density can do much to ensure that the required size of the produce is obtain at the right time for maximum profit. However, the ability to chose the right density to suit a particular environment and economic set of circumstances will depend upon having a full understanding of the response of the crop.

Finally, bird damage was a problem in winter but this may not have a major effect on the over-all size and yield of the plant at maturity.

4.2 Recommendations

The foregoing brief analysis of the principles underlying the effect of planting density, cultivar and season of planting on yield revealed several areas of research and development which need attention.

(1) Summer weather conditions are more favourable to growth. Planting for winter production need to be more frequently, to account for the natural delay in maturity as days shorten and temperature declines. Further studies are required to determine the appropriate sowing dates to ensure a regular supply of product.

(2) Developing a better working knowledge on the effect of soil temperature on crop growth and development especially at winter time.

(3) The way in which plant density affects the partition of assimilates to the plant parts clearly affects the ability of the horticulturist to use plant density as a means of achieving the control of product size for today's markets.

(4) Incorporating the use of solar radiation with temperature to quantify the combine effect on plant growth and development.

(5) When determining the variables to describe the maturity of broccoli on the basis of field experiments, growers must accept the prevailing weather conditions and care must be taken in the analysis to separate the possible effects of different environmental factors affecting growth and development of this crop.

(6) The result of this study indicated that further investigations through the accumulation of more accurate and detailed phenological data may lead to a more precise forecast as to the time any planting may be expected to mature.

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Appendix 2. Experimental Field Layout for Winter Trial

BLOCK - I	BLOCK - II	BLOCK - III
D1 V1	D2 V2	D4 V3
D1 V3	D2 V3	D4 V2
D1 V2	D2 V1	D4 V1
D3 V3	D4 V1	D2 V2
D3 V1	D4 V3	D2 V1
D3 V2	D4 V2	D2 V3
D2 V2	D3 V3	D1 V1
D2 V3	D3 V1	D1 V2
D2 V1	D3 V2	D1 V3
D4 V3	D1 V1	D3 V2
D4 V2	D1 V3	D3 V1
D4 V1	D1 V2	D3 V3

Area per block = 162 m^2 Total Area = 486 m^2

Legend: Density
D1 = 6 plants per m^2
D2 = 8 plants per m^2
D3 = 10 plants per m^2
D4 = 12 plants per m^2

Cultivars
V1 = Greenbelt
V2 = Marathon
V3 = Shogun

Appendix 1. Experimental field layout for summer trial.

BLOCK = 1	BLOCK = II	BLOCK = III
D1 V1	D3 V4	D2 V2
D1 V2	D3 V1	D2 V4
D1 V3	D3 V2	D2 V1
D1 V4	D3 V3	D2 V3
D2 V2	D4 V3	D3 V3
D2 V3	D4 V4	D3 V1
D2 V4	D4 V1	D3 V4
D2 V1	D4 V2	D3 V2
D3 V3	D1 V2	D4 V1
D3 V4	D1 V3	D4 V3
D3 V1	D1 V4	D4 V2
D3 V2	D1 V1	D4 V4
D4 V4	D2 V1	D1 V4
D4 V1	D2 V2	D1 V2
D4 V2	D2 V3	D1 V3
D4 V3	D2 V4	D1 V1

Legend: D = Density V = Cultivar

D1 = 6 plants m^{-2} V1 = Green belt

D2 = 9 plants m^{-2} V2 = Marathon

D3 = 12 plants m^{-2} V3 = Shogun

D4 = 16 plants m^{-2} V4 = Variety X

Experimental Area = 648 m^{-2} Area per Block = 216 m^{-2}

Appendix 3. Nutrient solutions applied to cell transplants.

Compound	Amount dissolved in 20 liters water (grams)
Formulation of stock solution (CF 20)	
Macro elements in one stock solution (Solution A).	
Fe	158.0
$CaNO_3$	1,976.0
KNO_3	1,316.0
KM_2PO_4	544.0
$MgSO_4$	993.0
Micro elements in one stock solution in ppm (Solution B).	
Mn	12.30
Bo	3.42
Cu	0.55
Mo	0.18
Zn	0.62

Appendix 4. Pesticides spray programme in the field.

Product Name	Active Ingredients (a.i.)	Rate of a. i.	Application Dates
Attack[R]	Permethrin pirimiphos methyl (EC)	25g lit^{-1} plus 475g lit^{-1}	Every two weeks from planting.
Copper oxychloride	500g kg^{-1}		Every three weeks.