Dry matter accumulation and phenological development of four brassica cultivars sown in Canterbury.

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Abstract

Four cultivars of brassica (cv Goliath rape, Gruner kale, Kestrel kale and Green Globe turnip) were sown in the field at four dates (16 January, 3 February, 18 February and 8 March) during one cropping season. Both sowing date and cultivar had a significant effect on maximum dry matter yield. Yields of 11,000 to 4,500 kg DM/ha were recorded for the 16 January and 8 March sowing times respectively. Yields of 8,900, 7,800, 7,400 and 4,700 kg DM/ha were achieved by Gruner kale, Kestrel kale, Goliath rape and Green Globe turnip, respectively. All treatments reached leaf yields of around 4 t DM/ha, therefore the major contributing factor to total yield differences was stem production.

Base temperature for leaf appearance was calculated using a least-variable and regression coefficient method (Yang *et al.,* 1995). Data gathered from the months January to May gave an estimate of base temperature for leaf appearance of 4 ^{o}C. It is suggested that the reliability of this estimate could be improved by increasing the range of temperatures experienced by these crops. Leaf appearance rate (days/leaf) decreased during the season due to lower temperatures. When expressed against thermal time (base temperature 4 ^{o}C) the phyllochron for all four cultivars was found to be linear. Gruner kale, Kestrel kale, Goliath rape and Green Globe turnip had a phyllochron of 65, 68, 61 and 51 ^{o}Cd respectively. Leaf senescence rate (days/leaf) followed the same trend as leaf appearance. However, lower temperatures and aphid damage during May caused accelerated senescence. When expressed against thermal time (base temperature 4 ^{o}C) leaf senescence was linear. The senescence rates for Gruner, Kestrel, Goliath and Green Globe were 93, 99, 76 and 70 ^{o}Cd, respectively. A thermal time model was developed to predict the effect of sowing time on brassica yield (assuming a base temperature of 4 ^{o}C). The model showed that these brassicas accumulate dry matter at 1,100 kg DM/ha/100 ^{o}Cd. It also showed that stem yield accumulated at a linear rate (900 kg DM/ha/100 ^{o}Cd).

Additional keywords: forage, yield, leaf appearance, base temperature, rape, turnip, kale.

Introduction

Brassica species are used worldwide for human consumption, stock food and oil production (White *et al.*, 1999). In New Zealand there are four main brassica species that are used for animal production, these include:

B. campestris, sub-species *napifera* -turnip;
B. napus, variety *napobrassica* -swede;
B. napus, sub-species *oleifera* -rape;
B. oleracea, variety *acephala* -kale (Stewart and Charlton, 2003).

Traditionally these cultivars have been used to provide forage during the winter when pasture growth does not meet animal demand (Banfield and Rea, 1986). Brassicas are tolerant of frosting which allows them to grow during periods of the autumn and winter, when cool-season perennial ryegrasses and legumes have limited growth (White *et al.,* 1999). Brassica crops produce high dry matter yields, 5 – 18 t DM/ha which can be stored *in situ* and grazed with little decline in feed value (White *et al.,* 1999).

Yield and nutritional quality of brassicas are affected by sowing date, environmental conditions, and length of the growing season, (Harper and Compton, 1980). The agronomy and husbandry factors required in growing a high yielding (>15 t DM/ha) crop are not well documented in the literature. The development of models is one way that can be used to determine the effects of agronomy treatments on brassica growth. Some key factors that need to be understood to develop models include phenology and temperature relationships which influence growth via the amount of radiation intercepted by the canopy (Hay and Walker, 1989; Nanda *et al.,* 1996). Wilson *et al.* (2004) is developing a potential yield model of brassica growth. The model is based on canopy development and light interception. The model at this stage is simplistic and requires more parameters to be measured to be accurate.

The lack of knowledge behind the factors that influence brassica yield has been the main driving force behind the present study. The main aim of the study was to provide data that is able to be used to describe the effect of sowing time on yield in different areas of New Zealand. The second aim was to provide parameters that may be used in the future to develop a model of brassica growth, which will provide farmers with a tool that can explain the effect of husbandry treatments on the yield of brassicas.

Materials and Methods

The experiment was situated at Wrightson Kimihia research farm, Canterbury (latitude 42° 38'S), with a mean annual rainfall of 624 mm (Fleming, 2004).

The design was a 4 x 4 factorial arranged in a randomised complete block with four replicates. Four cultivars of brassica were sown at four different times as follows:

a) Cultivars - Goliath rape
- Green Globe turnip
- Gruner kale
- Kestrel kale

b) Sowing times - 16 January 2004
- 3 February 2004
- 18 February 2004
- 8 March 2004

The experiment was on a Tempelton silt loam soil. Plots measured 8 meters by 1.8 meters to give sufficient area for phenological and harvest measurements. The area had previously been in cereal crops for the last 12 months. Soil test results before sowing were: pH 5.9, Olsen P 38, potassium 0.59, calcium 9.5, magnesium 1.27 and sodium 0.27 prior to sowing. Soil nitrogen levels and soil structure had been seriously depleted previously due to excessive cropping and cultivation.

Fertiliser applications consisted of 250 kg/ha of 'Cropmaster 15' (15% N, 10% P, 10% K, 8% S) applied before the first sowing date to the whole area. The first two sowing times received 100 kg N/ha in a split application of 50 kg N/ha. The last two sowing times received a single application of nitrogen at 50 kg N/ha. Application of nitrogen fertiliser took place on the 13 of February and the 4 of March for the first sowing date, 4 and 17 of March for the second sowing date, 17 of March for the third sowing date and 5 of April for the last sowing date.

Site preparation consisted of conventional cultivation after deep ploughing. Germination tests were carried out for all species with both kales having 90 % germination. Goliath rape and Green Globe turnip had a germination of 95 %. Both kales and Goliath rape were sown at a sowing rate to achieve 90 plants/m^2 across all treatments and the bulb turnips were sown achieve 55 plants/m^2 (Claridge, 1972; Scott, 1971). Seeds were planted using an Øyjoord drill in 15cm rows at a depth of 2cm (Lamp, 1962).

Prior to drilling Tridan480 at 1.44 kg *ai*/ha was pre-incorporated into the soil to control weeds. Post sowing, Frontier was applied at 1.125 kg *ai*/ha to control Shepherd's purse (*Capsella bursa-pastoris*). It was applied in dry soil conditions and caused a significant amount of phytoxicity to all treatments, but especially the bulb turnip at the last sowing time.

Insect control was gained by the application of Perfekthion S at 400 g *ai*/ha mixed with 3 l/ha of liquid boron fertiliser (2% N, 10% B). Application of insecticide-fertiliser mix took place on the 12 February for the first sowing date, 2 March for the second sowing date, 15 March for the third sowing date and the 5 April for the forth sowing date. Aphid damage was severe in the first sowing time due to a large mature brassica crop growing immediately adjacent to the experimental site. This caused the elimination of Green Globe turnip from the second harvest of this experiment.

Measurements

Plant populations were counted approximately 4 weeks after sowing to allow for any slow/delayed germination that is commonly observed in brassicas (Charlton and Stewart, 2000). Plant populations were also counted at the first and second harvest. A 66.5 cm long rod was used to measure plant populations along one drill row. With 15cm row spacing this is the equivalent to measuring a 1m^2 quadrat (15 cm x 66.6 cm = 997.5 cm^2). Two separate 66.5cm row lengths were taken from each treatment and averaged to give the plant population.

The main harvest was taken on the 15 July but excluded all Green Globe turnip treatments due to aphid and disease damage. Fresh weights were measured with 10 plants per treatment being taken for a sub-sample to measure dry matter percentages as well as leaf and stem yield.

Leaf appearance and senescence counts were taken weekly from each treatment using a mean of five marked plants per plot. Plants were selected for uniformity and marked with red paint.

Leaf counts ceased when plants started to branch at the stem or had become severely infected by disease as previous studies on legumes (Moot *et al.,* 2003) have shown that the number of leaves starts to increase exponentially once branching commences.

Meteorological data was collected from the Broadfields meteorological station situated opposite the research area.

Data Analysis

General analysis of variance tables (ANOVA) were used on all yield data to find treatment effects. Significant interactions and main effects were separated by 5% LSD. All analyses were performed using Genstat version 8 statistical package.

The base temperature section consisted of two methods of analysis:

a) Least-variable method – the correct base temperature is the one resulting in the lowest coefficient of variation of the total thermal time required for a particular stage of development over a period of time (Yang *et al.,* 1995). In the present study this was done using leaf appearance data. Leaf appearance was plotted at different base temperatures and regressed to find which base temperature would give the best fit or r^2 value for the data.

b) Regression coefficient – developed by Hoover (1955), this method consists of calculating a regression equation using the growth period mean air temperature as the independent variable and in the present study leaf appearance rate as the dependent variable (Yang *et al.* 1995). Leaf appearance (days per leaf) was plotted against mean air temperature. Leaf appearance (days per leaf) had an exponential decay curve fitted using SigmaPlot version 7.0. Leaf appearance was then inversed to give leaves per day. The data points were then regressed and extrapolated to find where the regression line cut the x axis.

All linear regression models were fitted using Minitab 14. Differences in regression lines were found by separation with 95% confidence intervals.

Results

Environmental conditions

A summary of weather data taken from Broadfields meteorological station (January – July 2004) showed below average rainfall for the growing period. The rainfall for the period was 270 mm with a calculated Penman evapotranspiration of 554 mm giving a potential deficit for the period of 282mm. February, March and April were warmer than the long term mean, however May and June were both colder than average. Over the months January to July there was 49 ground frosts with the lowest temperature recorded being -9.1°C.

Herbage yields

At the final harvest on 15 July both cultivar and sowing time affected total dry matter production but there was no interaction between these two treatments (Table 1)

Total dry matter yields ranged from 7,410 kg DM/ha for Goliath rape to 8,860 kg DM/ha for Gruner kale. The yield of Kestrel kale was not different (P>0.050) from either Gruner or Goliath but Gruner was higher than Goliath. The total yield for each cultivar was made up of almost equal yields of leaf and stem. The leaf yield was the same (P>0.050) for the three cultivars ranging from 3,940 kg DM/ha to 4,080 kg DM/ha. The yield of stem was similar ranging from 3,460 kg DM/ha for Goliath to 4,880 kg DM/ha for Gruner. The stem yield of Kestrel was 3,750 kg DM/ha which was lower (P<0.010) than Gruner but the same as Goliath. Successive delays in sowing significantly reduced yield (P<0.001). The highest yield was 10,910 kg DM/ha from the 16 January sowing (Table 1). The 3 February and 18 February sowing dates produced 9090 kg DM/ha and 7590 kg DM/ha respectively. The 8 March sowing only produced 4540 kg DM/ha, less than half that achieved with the earliest sowing (Table 1). The range in leaf yield caused by differences in sowing time was only from 3580 kg DM/ha to 4620 kg DM/ha the latter being produced by the 18 February sowing, this being greater than all other sowing times. However, as with total yield, stem yield declined sharply and significantly with each successive delay in sowing time starting at 6880 kg DM/ha for the 16 January sowing and dropping to 5230, 2970 and 960 kg DM/ha for the 3 February, 18 February and 8 March sowing times respectively (Table 1).

Table 1: The effect of cultivar and sowing time on final dry matter yield (kg DM/ha) on the 15 of July 2004.

	Total Yield (kg/DM/ha)	*Leaf Yield (kg DM/ha)*	*Stem Yield (kg DM/ha)*
Cultivar			
Goliath	7,410 b	3,940 a	3,460 b
Gruner	8,860 a	3,980 a	4,880 a
Kestrel	7,830 ab	4,080 a	3,750 b
S.E.	260	120	180
Sowing Time			
16 January	10,910 a	4,030 b	6,880 a
3 February	9,090 b	3,770 b	5,320 b
18 February	7,590 c	4,620 a	2,970 c
8 March	4,540 d	3,580 b	9,60 d
S.E.	290	130	200
Interaction:			
Cult.*Sowing	ns	ns	ns

(Means with different letters within columns are significantly different using a 5% LSD)

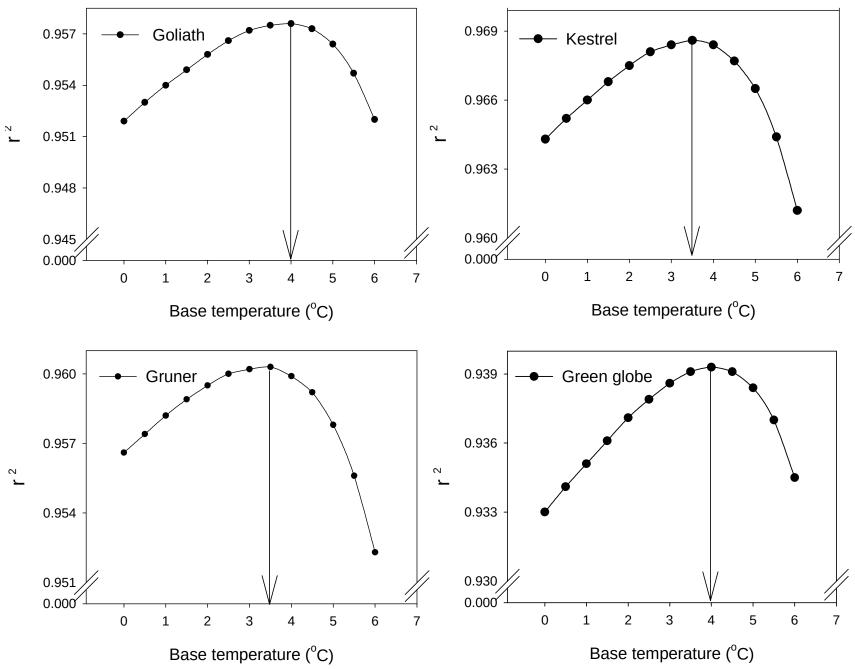

Figure 1: The plot of r^2 values for the regression of the number of leaves against thermal time at different base temperatures (arrows show the temperature at which r^2 is maximised).

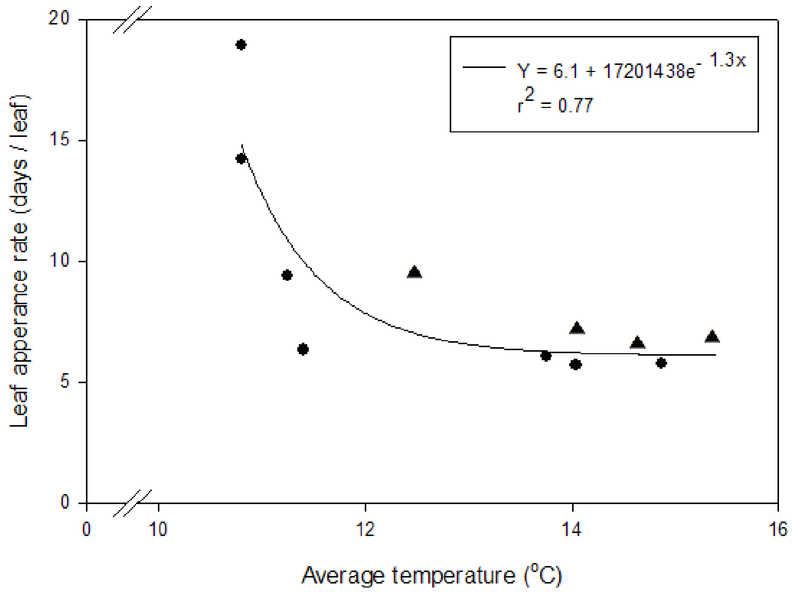

Figure 2: The leaf appearance rate (days/leaf) for Gruner kale measured from six sowing times (● Kimihia experiment, ▲ Crop and Food experiment data).

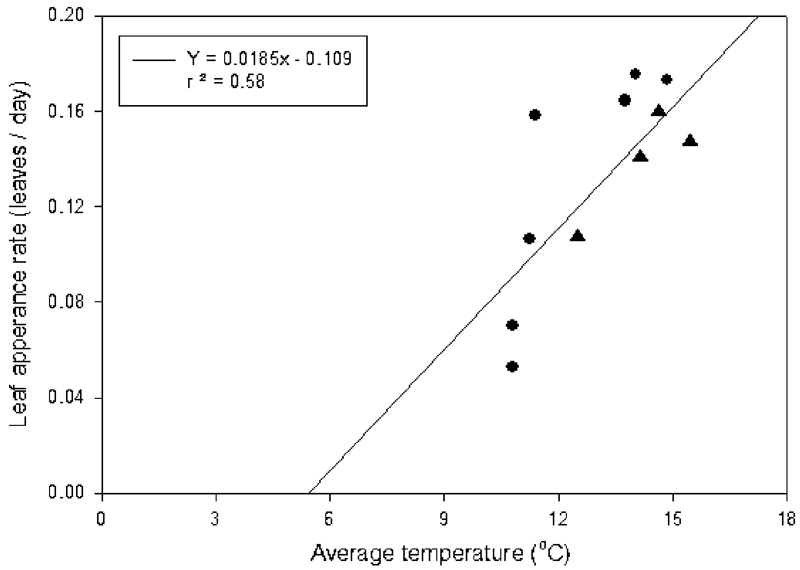

Figure 3: The regression of leaf appearance rate (leaves/day) for Gruner kale measured from six sowing dates (● Kimihia experiment, ▲ Crop and Food experiment data).

Determination of base temperature

The first method used to determine the base temperature (Tb) for leaf appearance rate was the least-variable method (Yang *et al.,* 1995). The number of appeared leaves was plotted at different base temperatures calculated using daily air temperature means. Leaf appearance rates were derived from data collected from the first three sowing times of 16 of January, 3 of February and 18 of February. This method relies on the variation in appearance rates for different sowing times to be minimised at the best estimate of the base temperature. The number of leaves was regressed against thermal time at a range of base temperatures to find which base temperature would give the best fit to the data. The r^2 value for each regression line fitted was then plotted on a series of graphs to find which base temperature gave the best fit Figure 1. This showed that the r^2 value was greatest at a 3.5 ^oC base temperature for Kestrel and Gruner. Goliath and Green Globe had an r^2 value that peaked at a 4 ^oC base temperature. It must be emphasised that the Y axis of the graphs in Figure 1 does not pass through the true zero, thus tending to visually overestimate the range in r^2 values, but with this limitation aside definite trends were visible. From this method based on minimising variation between sowing dates the base temperature was estimated to be 4.

The second method used to determine the base temperature was the regression coefficient method. This is a more traditional method commonly used in recent studies for pasture species (Moot *et al*., 2003). The number of leaves was first plotted against days after sowing to find periods of linear leaf appearance. These linear phases were then analysed to find an average temperature for the period. This enables a series of data points to be collected that show the leaf appearance rate (days/leaf) at different temperatures Figure 1. Figure 2 shows that the range of temperatures was small in the present study which limits the reliability of this method. In an effort to improve both the range of temperatures and hence the reliability of the estimate, data from a Crop and Food experiment with three other sowing times of 9 December, 23 December 2003 and 14 January 2004 were included to give six sowing times in total. An exponential decay curve was fitted to the data points and gave an r^2 of 0.77 to demonstrate the trend of the data points gathered Figure 2.

The leaf appearance rate (days/leaf) was then inversed to give leaves/day Figure 3. Leaves/day was then regressed against mean air temperature and extended out through the x axis to find the temperature at which leaf appearance would stop (Figure 3).

Figure 3 shows that the regression of leaf appearance (leaves/day) against temperature gave a base temperature of 5.5 ^oC. The regression line was however, a poor fit with an r^2 of 0.58. Figure 3 also shows that even with the extra sowing times there was a lack of data points below 10 ^oC. Extrapolation of the regression line into temperatures well below those in the data set is at best a questionable practice.

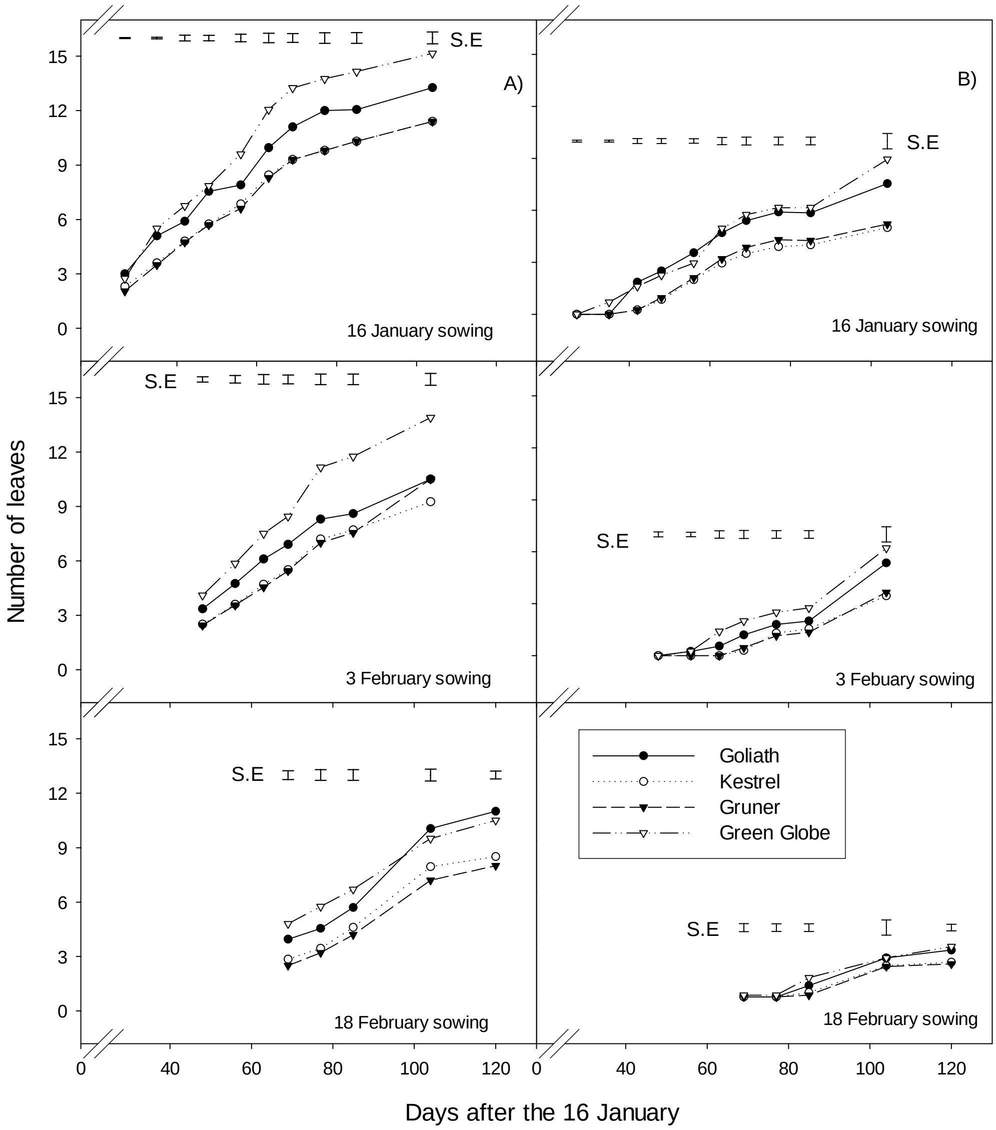

Figure 4: Interaction between cultivar and sowing time for total amount of appeared leaves (graph A on the left) and senesced leaves (graph B on the right).

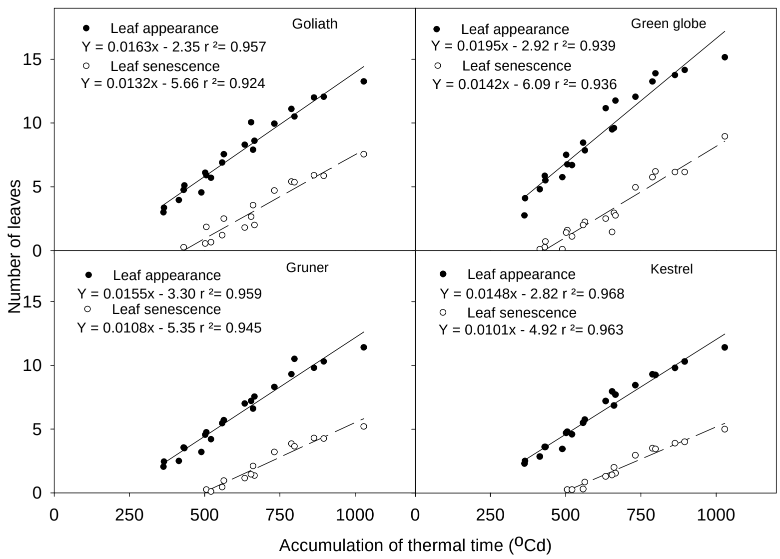

Figure 5: Leaf appearance and senescence rates for four cultivars of winter brassica grown over three sowing times (16 January, 3 February and 18 February) plotted against thermal time (base temperature 4 °C).

Leaf appearance and senescence

The interaction between cultivar and sowing time for the total number of appeared and senesced leaves is shown in Figure 4. For each of the 3 sowing times there was an approximately linear phase of leaf appearance where the total number of leaves increased from 3 to 12. After 70 days post January 16, there was a decrease in the rate at which leaf numbers where accumulating for the 16 January and 3 February sowing times Figure 4. Of the four cultivars measured, Green Globe turnips had the most ($P<0.050$) leaves appearing for the 16 January and 3 February sowing times with 15 and 14 respectively. Gruner and Kestrel had the same ($P = 0.050$) number of leaves for all sowing dates. The number of leaves for Goliath at the final measuring date for the 16 January sowing was the same for all other cultivars. Goliath however, had the highest ($P<0.050$) number of leaves along with Green Globe for the 18 February sowing time Figure 4.

The interaction for the number of senesced leaves was only significant for the 16 January and 3 February sowing times Figure 4. At the final measuring date, cultivars within the third sowing time (18 February) had only of 2.5 to 3 senesced leaves. The two earlier sowing times, 16 January and 3 February produced proportionally more senesced leaves (3 and 6 respectively) 85 days post January 16. For these latter two sowing times there was an increase in the rate of leaf senescence after day 80, particularly the earliest sowing of Green Globe turnips Figure 4.

Figure 5 shows that the appearance of leaves (phyllochron) for brassicas was linear in relation to thermal time. The data presented in Figure 5 are a combination of three sowing times (16 January, 3 February and 18 February) plotted against thermal time at a base temperature of 4 °C. Of the four cultivars Kestrel and Gruner kale had the slowest ($P = 0.050$) phyllochron with a leaf appearing every 67.5 °Cd and 64.5 °Cd respectively. Goliath was faster ($P = 0.050$) than Gruner and Kestrel with a phyllochron of 61.3 °Cd. Green Globe was the fastest ($P = 0.050$) cultivar to produce leaves with a leaf appearing every 51.2 °Cd.

Leaf senescence was also linear in relation to thermal time. All cultivars were losing leaves at a slower rates than there phyllochron. Green Globe had the fastest (P = 0.050) rate of leaf senescence with leaves dying every 70.4 °Cd. Kestrel had the slowest (P = 0.050) rate of senescence at 99 °Cd. Gruner had the second slowest (P = 0.050) senescence rate at 92.5 °Cd followed by Goliath with 75.7 °Cd (Figure 5).

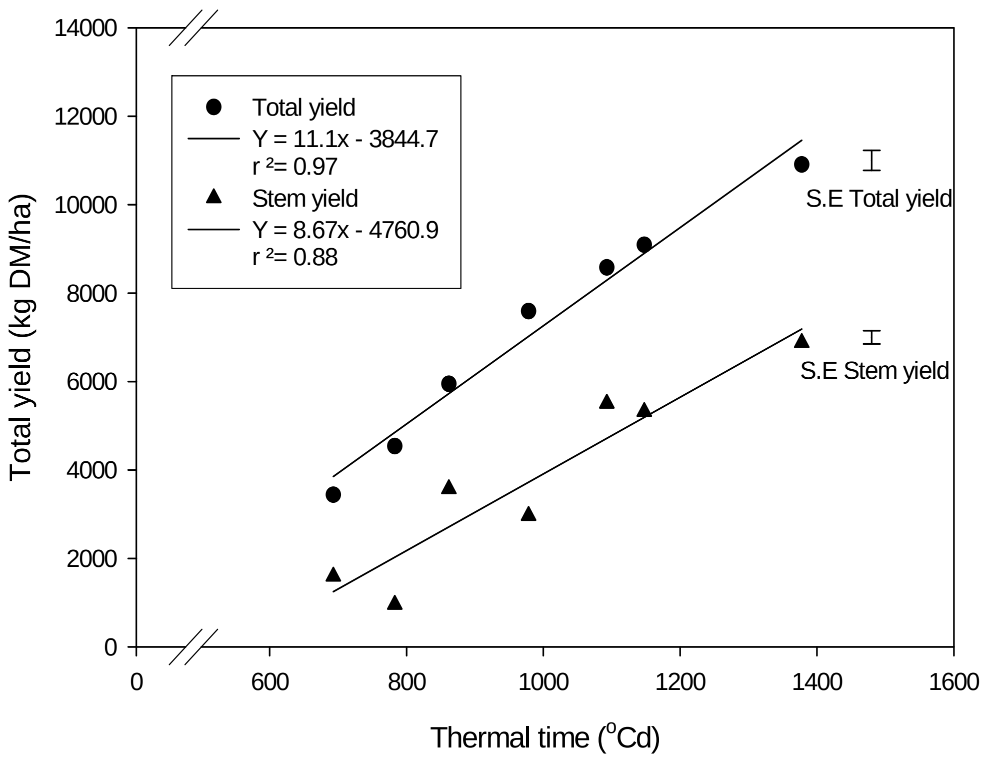

Figure 6: **The accumulation of total yield and stem yield with increasing thermal time (mean of 3 sowing times and four cultivars).Thermal time relationships**

Thermal time is not the driver of growth but it does drive development and leaf appearance. Leaf appearance and expansion in turn influence light interception which is the main driver of growth (Hay and Walker, 1989). Thermal time when plotted against yield give a close relationship, r^2 = 0.97 (Figure 6). This relationship is relatively simple and can be used in different districts to predict yields based on local meteorological data (Figure 6). The increase in total yield is explained by the equation Y = 11.1x – 3844.7. This means that for every 100 °Cd the crop accumulated 1,100 kg DM/ha. The yields of stem followed a similar trend with and increase of 870 kg DM/ha for every 100 °Cd. The yield of leaf increased slightly over the growing season. This can be deduced from Figure 6 where the slope of the two regression lines varied little. This resulted in little variation observed in leaf yield as previously presented in Table 1.

Discussion

Plant Populations

Plant populations were taken one month after sowing and at the harvest on 15 July 2004. None of the sowing times reached their target population of 80 plants/m^2 at any of the harvest dates. Plant populations at establishment ranged from 53 to 74 plant/m^2 for the 3 February and 8 March sowing times respectively. By the final harvest (15 July) plant populations had decreased, ranging from 39 to 65 plants/m^2 for the 3 February and 8 March respectively. The cultivars Goliath rape, Gruner kale and Kestrel kale were sown to a target population of 90 plants/m^2, while Green Globe turnip was sown to reach 55 plants/m^2. Of the four cultivars Green Globe was the closest to reaching its target population at establishment with 41 plants/m^2.

Robinson and Frame (1966) found that decreasing the kale plant population from 100 to 9 plants/m^2 caused little variation in yield. They however noted that stem size of the 9 plants/m^2 treatment were large and tall (1.5 m) with leaves spread over the top half of the plant. This is compared with relatively small stem sizes (1 to 1.3 m) for the higher (100 plants/m^2) populations.

Brown (1996) found that maximum turnip yield was produced from a plant population above 45 plants/m^2, which is almost double that recorded in the present study. It is therefore concluded that the large variation observed in plant population for Gruner, Kestrel and Goliath had little effect on final dry matter yields but for Green Globe turnip the plant population was sub-optimal for yield (Brown, 1996).

Dry Matter Yields

The experiment demonstrated the dependence of dry matter yield on the time available for growth between sowing and harvesting. The yield of all brassica cultivars was characterised by a decrease in yield with delayed sowing time. However the effect of sowing date was less pronounced in early than late sown crops (Table 1). A delayed sowing from 16 January to 8 March caused a 60% decrease in yield (11,000 to 4,500 kg DM/ha). The yield from the 3 February and 18 February sowing times was 9,000 and 7,600 kg DM/ha. Stephen (1976) also found that a delayed sowing from November to January caused a 50% yield decrease for kale. Banfield and Rea (1986) found that a delayed sowing of Rape from January to February caused a 40% decrease in yield.

Sowing time had little effect on leaf yields ranging from 3,580 kg DM/ha to 4,620 kg DM/ha for the 8 March and 18 February sowing respectively. This also confirmed the results of Stephen (1976) who found that kale accumulated leaves until a leaf yield of 4,000 kg DM/ha was reached. He observed that leaf yields then stabilised at 4,000 kg DM/ha with no apparent increase or decrease in yield. It is possible that the higher leaf yields from the 18 February sowing compared with earlier sowings, may have been in response to more favourable temperature and moisture regimes during early growth; the decline thereafter may have been partly due to less favourable climatic conditions and decreasing light levels. The decline in early sowings may also be partly due to the tendency for shedding of leaves as the plant matures (Calder, 1939).

The yield of stem was directly related to sowing time. The 16 January, 3 February, 18 February and 8 March sowing times yielded 6,880, 5,320, 2,970 and 960 kg DM/ha respectively (Table 1). Stephen (1976) found stem yields in kale increased steadily during growth. He found with early sowings (November) that stem yields plateaued, presumably because there was sufficient time for these crops to reach maturity. The stem yields observed in this present experiment were higher than those of Stephen (1976). He found that a January sowing produced 5,000 kg DM/ha when harvested on the 16 July. Because of the later sowing dates used in this experiment no obvious plateau in stem yield was observed.

The yield of each sowing time is a reflection of the amount of radiation available to the crop. The month of January had approximately 700 MJ/m^2/day of radiation was available to the crop. The amount of radiation available to the crop then decreased approximately linearly until May when only

200 MJ/m^2/day of radiation was available. The decreased yield from delayed sowing time was less pronounced in the three early sowing times. Other extraneous factors influenced the yield of the crops sown on 8 March. The application of Frontier herbicide caused significant damage and deformation of plants in the last two sowing dates (18 February and 8 March), and therefore, reduced potential growth rates. This seems to be the main reason for lower leaf yields from the 8 March sowing date. The application of Cropmaster 15 at 250 kg/ha at the beginning of the experiment meant the earlier sowing times had more access to nitrogen. By the last sowing time (8 March) most of the nitrogen had probably been lost from the soil, thus decreasing the potential yield of the 8 March sowing time. The last sowing time (8 March) was however less affected by aphids than the 16 January and 3 February sowing times.

The highest yielding cultivar on the 15 July was Gruner kale (8,860 kg DM/ha). Gruner produced the same leaf yield as Kestrel kale and Goliath rape but produced 27% more stem (Table 1). Goliath rape and Kestrel kale produced the same total yield, leaf yield and stem yield. Gruner kale is classified as a "tall" kale, while Kestrel is classified as a short kale thus the contrasting yield between these two cultivars was expected (Stewart and Charlton, 2003). Kestrel kale was breed by Wrightson to produce less stem to increase animal performance, whereas Gruner was bred for high yields. Goliath rape was bred as a high yielding giant-type rape. The results of these cultivars confirm work conducted by Anon. (2003) who conducted the initial work on these cultivars. The results are also confirmed by Mortlock (1975) who found that Giant-type kale planted in January yielded 10,000 kg DM/ha of which 34% was leaf. He also found that Kestrel kale yielded less total dry matter at 9,000 kg DM/ha but more leaf (41%).

Base Temperature

Base temperature was calculated using two methods that are described in full by Yang *et al.* (1995). The first method used was the least-variable method, where the correct base temperature is the one resulting in the lowest coefficient of variation of the total thermal time required for a particular stage of development (Sharratt *et al.*, 1989). The variation (r^2) of each regression line is plotted against base temperature and indicates a base temperature of 3.5 ^{o}C for Gruner and Kestrel kale and 4.0 ^{o}C for Goliath rape and Green Globe turnip. The range in r^2 values observed between base temperatures was small but clear-cut trends were apparent.

The above method of base temperature calculation is empirical. To obtain a base temperature, which generates the least variation in thermal time or days, a range of candidate temperatures must be selected to calculate thermal time or days and their associated variation. The main disadvantage is that if the base temperature is below zero it is possible to miss it in the process of selecting candidate base temperatures (Yang *et al.*, 1995). Because this method is empirical it is difficult to select the correct base temperature with the least amount of variation.

To overcome the shortcomings of the previous method, Hoover (1955) developed a regression coefficient method to estimate the base temperature. Figure 2 shows the leaf appearance rate (days/leaf) against mean temperature. Leaf appearance rate (days/leaf) was then inversed to give leaf appearance rate (leaves/day) and regressed against mean air temperature to find the temperature at which leaf appearance would cease. The extrapolation of the regression line through the x axis gave a base temperature of 5.5 ^{o}C. The regression line was however a poor fit with an r^2 value of 0.58. The main problem encountered with this method was the lack of data points below 10 ^{o}C resulting in the regression line being extrapolated into temperatures well below those in the data set.

An extra three sowing times from Crop and Food research were included to try and overcome this problem but these sowing times also had a similarly restricted temperature range. Because of the need for extra sowing times only Gruner kale was analysed using this method.

The range of base temperatures (4 to 5.5 ^{o}C) found from the methods described above are similar to that found by Morrison *et al.* (1989) who found the base temperature of Westar summer rape was 5 ^{o}C. This was determined using the regression coefficient method with data gathered from growth cabinets. Results were then confirmed using the least-variable method based on field data. Morrison *et al.* (1989) found that there was no significant difference between the two methods and concluded the base temperature for summer rape was 5 ^{o}C.

One possible reason for the variation observed in base temperature calculations, was the location of temperature measurements. Daily temperature means where taken from Broadfields meteorological station which was approximately 1 km away from the experimental area. This may have resulted in data that was not fully representative of the temperatures experienced by the crop. Temperature for leaf appearance was measured as mean air temperature 1.5 m above ground. Where the growing point is above ground air temperature is suitable for thermal time calculations (Hay and Walker, 1989). However for Green Globe turnip where the growing point is just above the ground, soil temperature may have been more appropriate.

The reason for the lack of data points below 10 ^{o}C was because leaf counts ceased on the 6 May. This was due to the initiation of axillary branching (January 16 and 3 February sowing times) and damage caused to cultivars by aphids (all sowing times). Hay and Walker (1989) reported that both these effects can cause accelerated development rates and change the temperature relationship for leaf appearance. The last two sowing times (18 February and 8 March) were also affected by herbicide application. The worst affected sowing time was the 8 March with severe deformation of leaves so no leaf counts were taken from this sowing time.

From the two methods used to determine base temperature (Tb) it was concluded that the base temperature for the cultivars used in the present study was 4 ^{o}C and this figure was used in the determination of leaf appearance and senescence rates and dry matter accumulation results.

Leaf Appearance and Senescence

Leaf numbers per plant was shown to vary between sowing dates and between cultivars (Figure 4). For the 16 January and 3 February sowing times leaf numbers accumulated linearly until 80 days post January 16. Leaf appearance rates then decreased for all cultivars except Green Globe in the 3 February sowing time. The 18 February sowing time had a liner phase of leaf accumulation until 100 days post January 16, the rate thereafter decreased until leaf counts ceased on the 6 May. Of the four cultivars measured Green Globe turnip produced the most leaves for the 16 January and 3 February sowing times (15 and 14 respectively). Gruner and Kestrel kale were not significantly different for any of the sowing times. Goliath produced more leaves than Gruner and Kestrel but less than Green Globe for the 16 January and 3 February sowing times (Figure 4). Wilson *et al.* (2004) found with earlier sowings (November and December) of kale that leaf numbers accumulated linearly with days after sowing. Similar results have been found by Nanda *et al.* (1995) in kale, where sowing date had little effect on the rate of leaf appearance or pattern of appearance. The linear rate of leaf appearance over chronological time is probably a reflection of the small temperature ranges experienced by the crop. Wilson *et al.* (2004) ceased leaf counts in March when temperatures were warm (15 ^{o}C) and only 2 ^{o}C lower than January and February. This small range in temperature would only result in small variations in the rate of leaf appearance. The decrease in leaf appearance rates after 80 days post sowing in the present study were probably due to decreased temperatures. The average temperature at the final measurement date was 10 ^{o}C, 5 ^{o}C lower than the beginning of the experiment.

Nanda *et al.* (1996) reported that brassica species exhibit delayed development under conditions of reduced (below 12 hours) photoperiod. Hodgson (1978) found that lower night temperatures accelerated brassica development and hence the onset of flowering. Reduced night temperatures can be used to explain the apparent increase in appearance rates observed in the 18 February sowing between day 70 and 100. Hay and Walker (1989) reported that there is evidence suggesting that the base temperature of cereals can vary with sowing date and that, in some cases the temperature relations of leaf appearance can be modified by stage of development. Therefore it is possible that there was a different base temperature between sowing dates in the present study which altered leaf appearance rates.

Leaf senescence also varied between sowing dates and cultivars (Figure 4). The two earlier sowing times (16 January and 3 February) produced proportionally more senesced leaves (3 and 5 respectively) 85 days post January 16. After day 85 there was an apparent increase in senescence rate for the 16 January and 3 February sowing times, particularly for the earliest sowing of Green Globe turnip. The 18 February sowing time had only 2.5 senesced leaves 120 days post January 16. Of the four cultivars, Green Globe turnip produced the most senesced leaves followed by Goliath rape.

Senescence rates were related to the total number of appeared leaves. Green Globe turnip which had the greatest number of appeared leaves also senesced the greatest amount of leaves. This pattern held true for all cultivars and sowing times.

Leaf senescence is poorly documented in the literature, partly due to the difficulty in recognising the time at which a given leaf has begun to senesce, or more importantly ceased to contribute to the dry matter production of the plant (Hay and Walker, 1989). In the present study leaf senescence was defined as when the leaf had turned completely brown or dropped of the plant. The increase in leaf senescence after day 85 for the first two sowing times can be explained by a number of factors. Hay and Walker (1989) stated that leaf senescence can be accelerated by herbivory from pests. The first two sowing times were severely affected by aphids. This explains why Green Globe turnip and Goliath rape had increased rates of senescence after day 85 compared with the aphid resistant kale cultivars.

Stephen (1976) observed with kale that earlier sowings (November and December) had the tendency to lose more leaves during autumn than later sowings, but no data was presented. This agrees with the findings of the present study where earlier sowings had higher senescence rates than later sowings. Hay and Walker (1989) stated that colder temperatures and frost also accelerate leaf senescence rates. Lower radiation levels also means there is a smaller requirement for leaves lower in the canopy. Because the upper canopy is capturing all the available light there was increased competition between leaves, therefore increasing the rate of senescence. Senescence rates before day 85 can be explained by sequential leaf senescence (Hay and Walker, 1989). Newly-expanded leaves compete with older leaves for solar radiation, mineral nutrients and assimilate, with the result that the leaves begin to senesce according to age.

It has been demonstrated for a range of crop species under controlled conditions and in the field that the rate of unfolding leaves is controlled solely by air temperature, provided that the growth is not limited by severe water or nutrient stress (Black *et al.*, 2002; Hay and Walker, 1989; Nanda *et al.*, 1995). Using thermal time and a base temperature of 4 ^oC the mean leaf appearance or phyllochron was calculated for the four cultivars (data is average of three sowing dates). Green Globe turnip had the fastest phyllochron with leaves appearing every 51.2 ^oCd. This is supported by Collie and McKenzie (1998) who found that the phyllochron of Green Globe turnip was 53.2 ^oCd, but they used a base temperature of 0 ^oC compared with 4 ^oC in the present study. Gruner and Kestrel kale had a similar phyllochron of 64.5 and 67.5 ^oCd respectively. Goliath had a slightly faster (61.3 ^oC) phyllochron than Gruner and Kestrel but slower than Green Globe (Figure 5). This agrees with work conducted by Nanda *et al.* (1995) who found the leaf appearance rates of *B. campestris, B. juncea, B. napus* and *B. carinata* were 59.9, 64.9, 82.6 and 63.7 ^oCd respectively. Again however, these were calculated using a base temperature of 0 ^oC. Wilson *et al.* (2004) found that the phyllochron of kale assuming a base temperature of 0 ^oC was 108 ^oCd, this was very similar to appearance rates in the present study when calculated with a base temperature of 0 ^oC (not reported in the present study). Past phyllochron studies have been calculated with a base temperature of 0 ^oC making it difficult to compare the findings with those from the present study. However appearance rates are similar for practical purposes and within the range that has been reported in the literature.

Leaf senescence was also linear in relation to thermal time. All cultivars were losing leaves at a slower rate than their phyllochron resulting in an ever increasing number of leaves per plant. Green Globe had the fastest rate of leaf senescence losing leaves every 70.4 ^oCd. Goliath senesced leaves every 75.7 ^oCd while Gruner and Kestrel kale senesced leaves every 92.5 and 99 ^oCd respectively. The main reason for the leaf senescence rates being slower than the appearance rate was because of high radiation receipts and warm temperatures. It is apparent in Figure 4 that the leaf senescence rates started to increase faster than leaf appearance rates 85 days after sowing. This was probably due to decreased temperatures and decreased radiation receipts. Therefore the data used in the calculation of leaf senescence rates in relation to thermal time have been derived from crops experiencing favourable conditions for crop growth, where the rate of leaf senescence is lower than the rate of leaf appearance (Hay and Walker, 1989).

Thermal Time

The pattern of crop production may be dependent on the efficiency of utilisation of resources during periods of active growth (Green, 1984). Factors such as biomass yield, seed yield, harvest index, canopy development and light capture, radiation use efficiency, water use efficiency and environmental effects will determine the yield of crops (De Ruiter, 2001). De Ruiter (2001) however, found the growth response to temperature was a more useful indicator than radiation use efficiency for selecting cultivars with improved productivity. It is also a very simple parameter to calculate as it only requires DM yield and standard meteorological data. This concept was therefore used in the present study to determine the rate of dry matter accumulation and the effect of delayed sowing on final yield.

The yield of brassicas (average of four cultivars) was found to be linear in relation to thermal time (base temperature 4 ^oC). Figure 6 shows that brassica cultivars accumulated 1,110 kg DM/ha/100 ^oCd. This is close to the figure used by Scott and Pollock (2004) for brassicas around 1,000 kg DM/ha/100 ^oCd. The value Scott and Pollock (2004) used was considered conservative compared with the 1.08 to 1.77 t DM/ha/100 ^oCd found be De Ruiter (2001) in cereals. Scott and Pollock (2004) used a conservative figure because brassicas are sown at low sowing rates limiting early canopy development and growth rates compared with cereals. The stem yield was also found to increase at a linear rate with thermal time (Figure 6). Stem yield accumulated at 867 kg DM/ha/100 °Cd. Stem yield has not been previously analysed in terms of thermal time but it does support the suggestion from Stephen (1976) that stem yield increases approximately linearly with days after sowing. The difference in the slope of the regression lines for total yield and stem yield varied little.

The rates measured in the present study were from the linear phase of development, and extension or extrapolation of these regression lines would not be valid. The yield data shown in Figure 6 were derived from crops that had all reached canopy closure. Below these points it is possible that growth rates are decreased due to limited amounts of PAR intercepted. For yields above those presented growth rates have been shown by Stephen (1976) and Nanda *et al.* (1996) to decrease due to a shorter photoperiod, lower temperatures and decreased daily radiation receipts. In very extreme cases of prolonged and sever frosts yields may actually decline. These factors cause leaf senescence rates to increase which causes a decreased leaf area. This combination of factors reduces growth rates in mature crops carried well into the winter.

Conclusions

From the experiment conducted the following conclusions can be made:

1. The optimum sowing time for winter brassicas in Canterbury was found to be mid January, giving a yield of 11,000 kg DM/ha.
2. The highest yielding cultivar was Gruner kale (8,800 kg DM/ha). Kestrel kale and Goliath rape produced the same amount of dry matter (8,000 kg DM/ha), while green Globe turnip only yielded 5,000 kg DM/ha.
3. Data collected from the months January to February was used to determine a base temperature for leaf appearance of 4 °C using the least-variable and regression coefficient methods. The reliability of this estimate was limited by the small range of temperatures (5 °C) experienced by these crops.
4. Leaf appearance rates for Gruner and Kestrel kale, Goliath rape and Green Globe turnip were 64, 68, 61 and 51 °Cd respectively at a base temperature 4 °C.
5. Leaf senescence rates for Gruner and Kestrel kale, Goliath rape and Green Globe turnip were 93, 99, 76 and 70 °Cd respectively at a base temperature 4 °C. Leaf senescence rates were increased by aphid damage, resulting in reduced light interception.
6. A thermal time model was developed to predict brassica yields base on meteorological data. The model found that brassicas accumulate total yield at a rate of 1,100 kg DM/ha/100 °Cd. It also found that stem yield increases at a rate of 900 kg DM/ha/100 °Cd. This resulted in leaf yields of around 4 t DM/ha for all treatments.

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