VG97019
Factors Influencing Carrot Size and Shape

Philip Brown and Alistair Gracie
Tasmanian Institute of Agricultural Research

Know-how for Horticulture™

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Final Report

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Project number: VG97019

September 2000

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Industry Summary

Carrot production in Australia has increased steadily over the past decade, with increased per capita consumption and expanding export markets supporting the increase in production. Carrot root quality has become a more important issue for the industry due to the change in consumer preference towards pre-packaged, sweet tasting carrots of uniform length and no shape imperfections on the domestic market and stringent quality requirements in the predominant export markets. Agronomic and crop protection strategies have been developed to increase crop yields, but little attention has been given to increasing the proportion of the harvested carrots that fit the target market quality specifications. This project has examined the major non-disease factors limiting packout of premium quality carrots: size variability, poor shape characteristics and harvest splitting. Research has been conducted in Tasmania with nantes and kuroda type carrots grown on heavy red ferresol (krasnozem) soils.

The size of a carrot root is an important quality attribute for the crop, particularly when carrots are grown for export markets with narrow size specifications. This project has identified the major factors influencing variability in root size within carrot crops and developed recommendations for minimising variability in carrot size. Under Tasmanian condition the yield of carrots is often high (70 tonnes/ha or higher), but it is not uncommon for packout to be low (e.g. approximately 60%) for fresh market carrots. An increase in the percentage packout of the carrots would substantially increase profit margins to both companies and growers. One of the major causes of low packouts in carrot crops is lack of size uniformity, that is, carrots failing to meet the stringent premium market size range. Project work has been undertaken to firstly identify the factors influencing carrot size uniformity and secondly strategies to minimise variability in size within commercial carrot crops.

Trials were conducted in commercial carrot crops, research plots at the Forthside Vegetable Research Station and under glasshouse conditions using Kuroda and Nantes varieties. The effect of seed grading, plant spacing, arrangement and density on size uniformity in carrots was examined. The trials demonstrated that seed quality in terms of uniformity of embryo sizes can have a large influence on uniformity of seedling establishment. Variability in embryo size was directly correlated with uniformity of carrot size until approximately 80 days after sowing. After this period competition appeared to be the main factor influencing uniformity of root size. Competition can be manipulated by changing planting density and uniformity of spacing between plants, but only small improvements in size uniformity were achieved using these treatments in kuroda crops planted in beds in a three double row arrangement. Size uniformity within the trials was likely to be close to the optimum possible for the varieties examined as best practice soil preparation, irrigation and fertilizer management were used. Under good crop management conditions, selection of carrot varieties with increased size uniformity when grown at target density is the most effective strategy to reduce size variability. Under less than ideal growing conditions, management of soil preparation and irrigation to promote uniform crop emergence is important for increasing the percentage of carrots in the crop in the target size range. In addition, seed grading to reduce seedlot variability and attention to planting systems to improve uniformity of spacing are likely to improve uniformity at harvest under low density conditions or for early harvested crops.

Planting density and evenness of spacing of the carrot seedlings at establishment also influence the distribution of taproot sizes at harvest and other important shape characteristics for marketing. Management of seed quality, plant spacing uniformity and plant density can be used to alter the average carrot root size even when size variability is not changed. Increasing density will reduce carrot root weight but may not result in a significant overall increase in total yield. Heavier and longer carrot roots can be produced by reducing planting density, increasing spacing uniformity and/or using larger or heavier seed. Seed grading and spacing treatments can therefore be used to increase packout in target size classes even when they do not result in a significant increase in root size uniformity. The effects of density are however site specific and trials need to be conducted on individual growers properties in order to establish optimum planting densities to maximise packout in target size classes.

The length of the carrot root at harvest appears to be determined early in crop growth and is influenced by soil strength or bulk density. Expansion of the storage tissue in the root begins at the top of the carrot and moves down until it reaches a portion of the root below which rapid expansion cannot take place. At this point the base of the carrot 'rounds off' and this stage signifies the conclusion of the rapid growth phase in the root and is a useful indicator of maturity. The length of the root at harvest thus appears to be linked to the rate of growth of the root following crop establishment and the timing of the initiation of expansion growth. High soil strength, which is linked to high bulk density and/or low soil moisture conditions, restricts the rate of root growth and results in a shorter potential root length at the point when root expansion commences. Factors controlling the timing of initiation of root expansion are unknown, but temperature during the establishment phase appears important as warmer temperatures promote earlier expansion and hence shorter root length. Further studies are required to understand the processes that control root length and to establish critical soil bulk density and soil moisture levels likely to reduce root length.

Soil conditions during the crop establishment phase influence carrot root shape development. The results from trials and observations made during the project suggest that soil conditions impact on the direction of root growth through the soil during the early stages of crop establishment. Localised areas of high soil strength within the soil (for examples, presence of clods or stones) may restrict root expansion and cause the root to grow around the obstruction. Alternatively, localised areas of lower soil water potential may stimulate root exploration in the soil towards areas of higher available water content. While more research is required to confirm the mechanism, the effect of non-uniform soil conditions is root growth that doesn't follow a straight path through the soil. The bends and twists in the primary root that occur as it grows around areas of higher strength or lower water content persist during the root expansion phase and ultimately lead to misshapen carrots. In heavier clay soils with high bulk density irrigation management during the establishment phase is critical as soil strength increases with lower water content leading to the development of localised areas that carrot root are unlikely to penetrate. Maintenance of high soil moisture content is necessary to reduce the risk of misshapen carrots on these soils. Even spacing of carrots in the crop can also reduce the proportion of misshapen roots. While the mechanism of interaction between closely planted carrots that results in twisting around each other is not known it is possible that water potential gradients in the soil associated with water uptake by one carrot will influence the growth of the second carrot root. The water potential gradients may impact on soil strength or may be sufficient to directly influence the direction of root growth.

Susceptibility of carrot roots to splitting during harvesting has been shown to be linked to daily changes in expansion of the root. The carrot root expands during the late afternoon, night time and early morning and the roots are most susceptible to splitting during these periods. The changes in susceptibility to splitting are not a direct result of changes in tissue temperature as similar splitting susceptibility scores were recorded for carrots held at a range of temperatures in the morning. It is likely that the processes that control tissue expansion are important in susceptibility to splitting. Tissue expansion is controlled by changes in cell wall properties (loosening of cell walls to allow expansion) and changes in the concentration of sugars and other chemicals in the cells (providing the gradient required for water movement into the cells to drive cell expansion). Cold night temperatures increase carrot susceptibility to splitting and have been shown to influence cell wall properties and cell expansion in other plant species. Losses due to harvest splitting can thus be minimised by avoiding harvesting early in the morning following low night temperatures, with the critical temperature lying between 0 and 8°C for kuroda crops in Tasmania. Carrot susceptibility to splitting also increases following maturity of the root (rounding of at the base of the carrot) and timing of harvesting during the day is critical for overmature crops. Trimming of outer leaves or undercutting of carrots on the day prior to harvesting can significantly reduce splitting susceptibility. Further work is required to fully characterise the physiological basis for splitting, but the research undertaken in this project provides evidence of the mechanism and therefore likely areas where control of splitting may be targetted.

Technical Report

I. Introduction

The regulation of carrot root growth and development is poorly understood at the tissue level and very few studies on carrot root physiology have been undertaken to support the agronomic practices used by industry. The basic agronomic studies undertaken by industry have focussed on optimising planting systems (bed or mound, row number and plant density), irrigation and fertilisation to maximise yield and a limited number of studies attempting to identify treatments to reduce the incidence of physiological disorders such as splitting. Recommendations from these studies have generally been broad and industry practice currently reflects this with similar agronomic practices used under a range of growing conditions (early and late season crops, different soil types) and different varieties. There is scope for further optimisation of agronomic practices at the individual farm or regional level but identification of the factors most likely to influence packout is important to permit selection of agronomic practices that should be altered. This study was undertaken to identify the factors influencing non-pathological causes of packout loss in carrot crops and to describe the physiological basis for carrot shape development including carrot susceptibility to harvest splitting.

The dominant cause of reduced packout in fresh market carrot crops grown on heavier soils is poor shape of the harvested root. In addition, a significant percentage of carrots that are not rejected do not conform to the size specifications of the premium markets. Rejection of carrots based on shape characteristics is also common in the processing sector. The variability in size and shape at harvest is influenced by four main aspects of carrot production: 1. Seed characteristics, 2. Planting methods/seed placement, 3. Crop establishment/field factors, and 4. Crop management practices.

1. Seed characteristics. Variation in germination rate and seedling vigour within seedlots may contribute to variability in carrot size and shape at harvest. A large volume of published information on carrot seed quality exists and suggests that seed quality can account for a large proportion of size variability in crops at harvest. In Tasmania, the small size of the industry and the specific varietal requirements of the export market (eg. Japanese market demand for Koyo 2) has lead to limited seed availability and the use of seedlots of variable quality, thus making seed quality an important issue to the industry.

2. Planting methods/seed placement. The spacing and depth of planting of seeds influence the timing of emergence and the competitive ability of seedlings after emergence. Variability in seed placement is a function of the seeder used, seed treatments (coating etc), and the soil characteristics at planting. While precision seeders are generally used in Tasmania, ground preparation for planting is not always ideal for uniform placement of seeds. The effect of uniform seed placement on crop establishment and subsequent growth has not been quantified under planting conditions prevalent in Tasmania. Improvements in management of planting operations can be made if seed placement is shown to be a major contributor to carrot size and shape at harvest.

3. Crop establishment/field factors. The so-called 'field factors' constitute the range of soil and microclimatic conditions that may influence seed placement, seed germination, seedling emergence and vigour, and plant growth rate. This area has been seen as a significant problem area by industry, with field plantings often revealing a very poor correlation between seedlot germination rates and actual field establishment rates. Both biotic (for example the effect of *Alternaria* infection, as demonstrated in South Australia by Coles and Wicks) and abiotic factors may be involved in field factor effects on crop establishment. The literature suggests that soil moisture characteristics are likely to contribute to variability in germination, emergence, and vigour in small seeded crops such as carrots, and may also cause pre- and post-emergence losses. Soil organic matter content and bulk density are therefore likely to be critical soil factors, particularly with respect to crop variability during the establishment phase.

4. Crop management practices. The interactions between soil conditions and crop management practices (particularly irrigation) need to be examined to determine methods to limit crop variability. Crop management practices have been shown to influence the development of physiological disorders such as splitting. An understanding of the mechanisms of root size and shape development, and physiological disorders such as splitting, is required in order to assess the impact of management practices on these mechanisms and to develop management strategies to improve packouts.

The research presented in this report is divided into three sections; examination of size variability, shape development and harvest splitting. Each section contains a brief review of pertinent literature, description of the research undertaken ion the project, and summary of the major findings.

I. Carrot Size

LITERATURE REVIEW

Variability in carrot root size is one of the most important determinants of crop packout, particularly for fresh market carrot production, and has therefore been examined in some detail in the literature. There are many factors that have been shown to influence the final variability of individual carrot root weight at harvest in a crop. These include; cultivar/carrot type, seed quality, uniformity of seedling emergence, plant spacing and time after sowing. Most of the scientific literature focuses on seed quality and crop emergence under cold climate, long growing season conditions in Europe. No work has been published on size variability in kuroda type carrots that are grown extensively in Tasmania for export to the Asian region.

The spread in time of emergence and size of seedlings, at, or soon after, emergence has been shown to be important in influencing the variability of mature carrot root weights (Benjamin, 1984; Salter *et al*, 1981). Salter *et al* (1981) found in field experiments that 40% of the root weight variation was accounted for by the time of seedling emergence. Others have reported 5-45% (Benjamin, 1982) and 61% (Benjamin, 1984) of the carrot root weights at or only weeks prior to harvest as being attributed to seedling emergence. The spread in time of emergence may be attributed to variability in seed (Gray *et al*, 1991), seedbed condition (Finch-Savage and Pill, 1990) and evenness of planting depth. The variability of seedling weights soon after emergence is largely related to the variability in embryo sizes within the seed (Gray *et al*, 1988).

The density of a carrot crop has also been shown to influence the final variation in carrot root weights. With increasing densities Gray *et al* (1991) found that the coefficient of variation (a measure of variability that is independent of plant size) increased and was largely due to increased competition between plants. However, Salter (1981) found that competition *per se* was not a prime source of variation in root size but magnified any initial variation within the crop at the time of seedling emergence. This impact of high densities associated with asynchronous emergence causing higher variations in carrot root weights than synchronous emergence has been widely demonstrated (Li *et al*, 1996; Wiener and Thomas 1986), thus highlighting the need for cultural practices and high quality seed that lead to even emergence of seedlings.

The spacing and arrangement of carrots in the field also influences the variability of carrot roots in a crop. Benjamin (1984) recorded that up to a fifth of the weight variation in carrots is associated with the position of the row in which the plants are growing. It has been known for a long time that the outer rows of carrots planted in multi-row beds will produce larger carrots than carrots in the inner rows if planted at the same density. In fact carrots in edge rows can be 10 to 100% heavier than those growing in inner rows (Salter *et al*, 1980). The recommendation to reduce this edge effect is to increase the seeding rate in the outer rows 1.5 to 3 times that in the inner rows whilst holding the overall density constant (Benjamin and Sutherland, 1992).

Seed Quality

Seed quality is an important part of crop establishment in terms of percentage emergence, uniformity of emergence and rate of growth in the field. Many assessments have been

undertaken in order to predict the performance of seed lots under field conditions using laboratory tests. The International Seed Testing Authority (ISTA) procedure for carrots is to germinate seeds at 20°C, however, some researchers have found better correlations between seed germination under cold temperature (10°C) (Hegarty, 1971) or controlled deterioration (Mathews, 1980) and the establishment of the crop in the field.

Treatments such as priming, osmoconditioning, and hardening have been shown to result in faster emergence, increased uniformity in root size and higher yields of carrot. However, the advantage often diminishes when ambient air temperature increases and conditions become more favourable to germination (Currah *et al,* 1974; Murray, 1989; Szafirowska *et al*, 1981; Finch-Savage and McQuistan, 1989; Bodsworth and Bewley, 1979).

Gray and Steckel (1983b) undertook a comprehensive comparison of methods for evaluating seed quality in carrots. Their findings confirm previous reports (Gray and Steckel 1983a) that the coefficient of variability (CV) (uniformity) of seedlings weight is closely correlated with the CV of embryo length. Hence the CV of embryo length could be a useful tool to be used by seed producers to identify seed lots with high or low seedling variability. Also measuring the root length of seedling in the slope test provided a good potential measure of variability of seedling size, though not as good as the embryo test.

Since the isolation of the embryo from the seed is a tedious process, faster methods of extraction of embryos have been designed (Keefe and Draper, 1986). The use of these methods to measure the variability combined with vigour tests could prove valuable information as to the sowing time and soil conditions appropriate for different seed lots.

While some attempts to grade carrot seeds by size has successfully improved uniformity and yield in seedling emergence (Salter *et al,* 1981 Benjamin, 1982), not all have been successful since carrot embryo size is not closely correlated with seed size or weight (Gray and Steckel 1986). Testing of carrot embryo size variability, and the relationship between embryo size and seed size, therefore need to be tested prior to grading of seed lots. Based on the evidence presented in the literature, grading of seed lots with high CV of embryo length and a strong correlation between embryo size and seed size could be expected to reduce variability in seedling size and hence final root size in carrot crops.

RESEARCH TRIALS

Field trials examining carrot root size variability were conducted in the 1997/98, 1998/99 and 1999/2000 seasons. The trials in the first season involved detailed examination of carrot development in 13 commercial crops, six of which were kuroda type and seven nantes (cultivar Hi Pak), and a survey of all carrot paddocks grown under contact for Field Fresh, Harvest Moon and Simplot Australia. This work aimed at identifying the relative contributions of seed and field factors to carrot root size variability at harvest. Trials in 1998/99 examined the effect of seed grading on size uniformity, and aimed to evaluate the effectiveness of seed grading as a strategy to increase packout in commercial carrot crops. Laboratory evaluation of carrot seed quality supported the field research. In 1999/2000, the interaction between plant spacing, plant density and seed quality was investigated in replicated field trials. Data from this trial allowed the relative contributions of seed variability and between plant competition to root size variability at harvest to be assessed.

(1) 1997/98 Surveys of commercial crops

Crop growth and development patterns

Uniformity of carrot weight in 13 fresh market carrot crops was monitored over the duration of the season. All crops were located on the North West Coast region of Tasmania and were grown on krasnozem (red ferresol) soils. The crops were selected to represent a range of planting dates and management practices (average to high performing growers were selected based on previous experience of field officers for contracting companies). The six kuroda crops were planted in 3 double rows in beds. The seven nantes crops were planted in two single rows in mounds. Samples were collected from each crop at three dates, 40, 80 and 120 days after planting. At each sampling date three replicate samples of 100 carrots each were collected from pre-assigned, randomly selected positions within the paddock. All carrots within a 1 metre length of bed or mound were harvested to collect each sample. Carrots were washed, dried and individually weighed. Root length was also determined at each sample date. Entire carrots were used for the 40 and 80 day samples while only the root was weighed at 120 days. Weight data was used to calculate coefficient of variation (%CV) from the following formula:

$$\%CV = (\text{standard error}/\text{mean}) \times 100$$

Uniformity, measured as coefficient of variation (%CV), ranged from 35-45% 40 days after sowing and increased to 45-55% by harvest at day 120 (Figure 1).

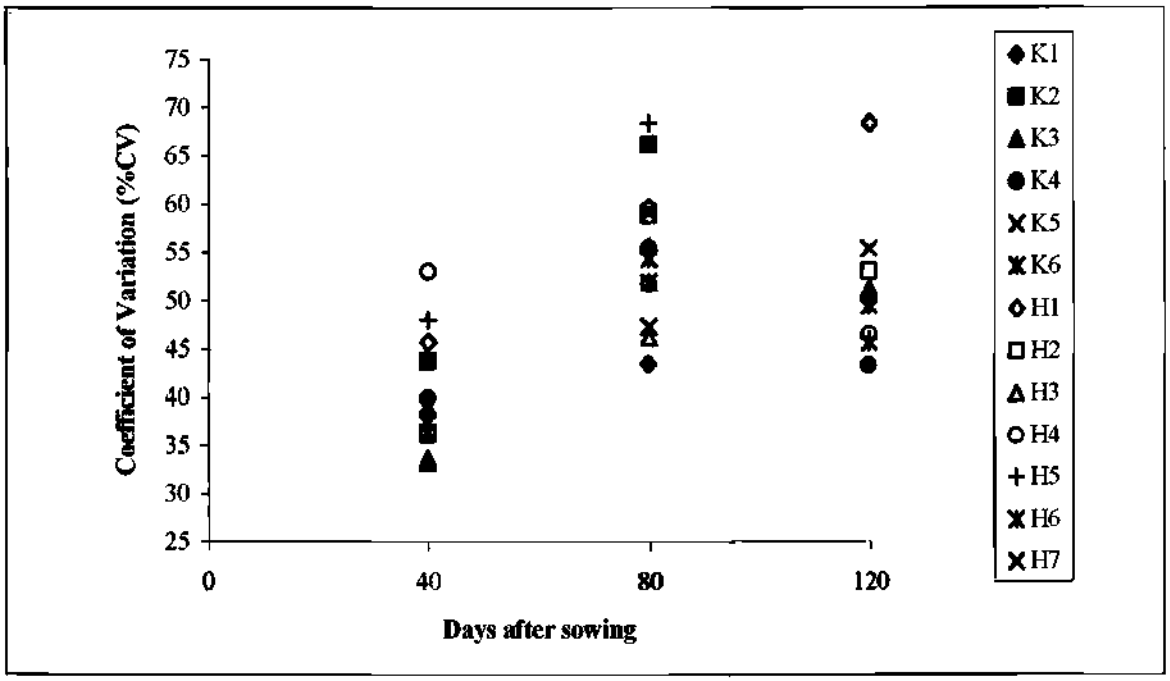

Figure 1. *Changes in coefficient of variation (%CV) of carrots from 13 commercial crops. K1 to K6 are Kuroda type and H1 to H7 are Hipak variety.*

Obvious differences existed between crops in variability at each sample date and in the pattern of change over the duration of crop growth. These differences are likely to reflect variations in paddock preparation and crop management. Careful attention to seedbed preparation and good management of irrigation during crop establishment were considered critical to obtaining minimum variability at day 40, while disease problems and poor management of irrigation and nutrition were likely to contribute to variability following establishment. While there were distinct differences between the crops, the pooled data suggested that the establishment phase was critical in determining crop variability. The overall pattern was for a relatively high level of variability to be present at the establishment phase (day 40), increasing slightly prior to root bulking (day 80) before decreasing prior to harvest (day 120) (Figure 2).

There was little difference in the %CV between crops of each variety at day 40, with the mean %CV for kuroda crops being 38 and %CV of 42 for Hi Pak. Mean %CV between varieties at day 40 was significantly different but no significant difference was observed between sites. The uniformity within variety over six sites indicated the importance of seed characteristics in determining carrot size variability. Variability increased between day 40 and day 80, with significant differences between sites. This increase in variability is likely to be linked to competition between plants and will be influenced by crop management practices and soil conditions. Variability decreased between days 80 and 120 due to slowing in growth rate of early emerging, larger carrots reaching mature size while later emerging, smaller carrots continue to expand at a greater growth rate. This confirms the industry observation that smaller carrots 'catch up' to larger carrots in the later stages of crop growth.

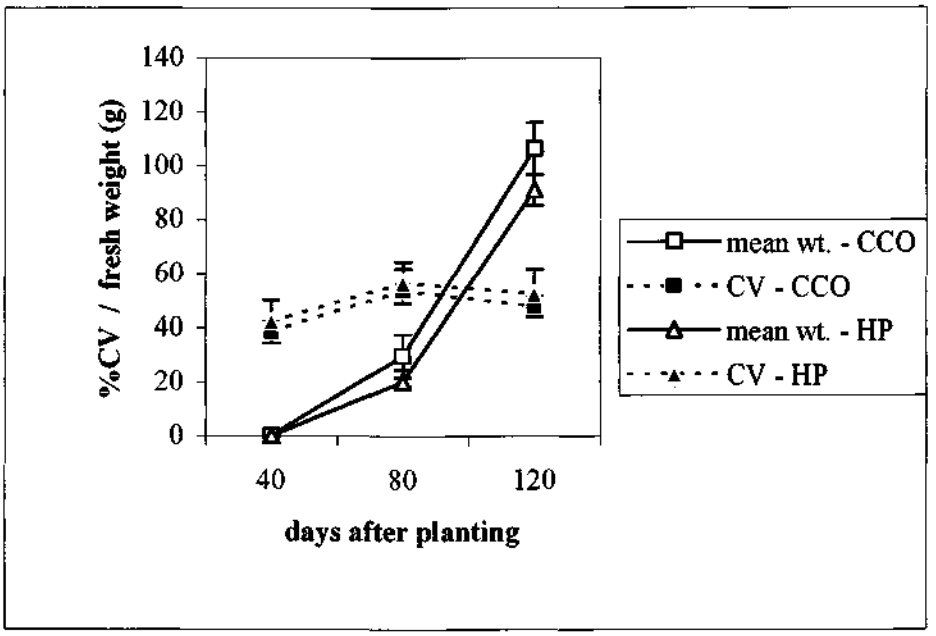

Figure 2. *Changes in root weight and Coefficient of Variation (%CV) during carrot crop development for kuroda (CCO) and Hi Pak (HP) varieties.*

The growth curves of carrots in Tasmania, constructed from the mean weight data collected in the field trial, were similar to data reported in the literature. The kuroda type and Hi Pak have slightly different growth curve characteristics, with the kuroda type displaying a more rapid increase in weight and a higher mean weight at harvest (Figure 2).

The initiation of carbohydrate storage in the carrot root occurs at around 40 days after planting, at which point root elongation slows or ceases. The rate of storage is initially faster in kuroda than nantes (Hi Pak), but similar rates are maintained between days 80 and 120. Examination of the weight changes on a weight category basis (comparison between largest and smallest carrots at each sample date) indicated that the rate of deposition of carbohydrates in larger carrots in later stages of growth was lower than smaller carrots. This indicates some limit to storage capacity that is being met at around day 120. The two most important stages in development are therefore the initiation of carbohydrate deposition (at around day 40) and the attainment of optimum size or storage capacity, which varies within a crop according to size variability but is averaged as the stage of crop maturity at approximately day 120. This stage is likely to be particularly significant in the development of splitting susceptibility in carrots.

Survey of field and production factors

A survey of carrot growers was conducted to identify soil factors and production practices in all carrot crops grown for Field Fresh Tasmania, Harvest Moon and Simplot in Tasmania. The one page survey form was distributed to field officers at each company in order to collect the required data. The completed surveys were returned at the end of the season. Yield and packout data for all crops was also obtained, and the information used to identify possible field and production practices linked to size variability and root shape characteristics at harvest. Due to the nature of the survey, the data collected was subjective and could only be used to identify possible areas for further investigation. The survey form used in the study is shown in appendix 1.

Analysis of the crop survey forms also indicated some links between soil conditions and carrot size and shape characteristics. The information requested in the survey was of a less specific nature than the detailed measurements taken in the 13 crops, but did provide some insights into the factors of greatest importance in size and shape development. Examination of the data indicated that soil preparation, soil type and irrigation management were key factors in carrot shape development (and also yield through average carrot length) while seed characteristics may have contributed to size variability within crops. Differences existed between cultivars in the level of variability at harvest, and these differences could be attributed to either genetics or to variability in seedlots.

(2) 1998/99 Seed vigour testing and effect of seed grading on uniformity

Preliminary seed evaluation

Seed size variation, germination rates and seed vigour characteristics were determined for samples of kuroda and Hi Pak seed. Seed was divided into three weight classes and germination percentages and times determined at 20□C (following International Seed Testing Organisation protocols) and 10□C. Seedling vigour was also assessed by germinating seeds in potting mixture at 10□C and measuring seedling weight four weeks after planting.

Both seedlots gave similar germination and vigour results, although the kuroda seed was significantly heavier than the Hi Pak seed. No significant difference in germination characteristics between the three weight classes was found at 20□C, but at 10□C the germination rate was significantly slower for the small seed class. Similarly, there were significant differences in mean seedling weight between the three weight classes when germinated and grown at 10□C for four weeks, with the heavier seed giving rise to heavier seedlings. This finding has some support in the literature, but other workers have not found a correlation between seed size of weight and seedling performance in carrots. The relationship between seed size and embryo size recorded in the seedlots suggests the seed grading may be used to reduce variability in the commercial seed lines planted in Tasmania.

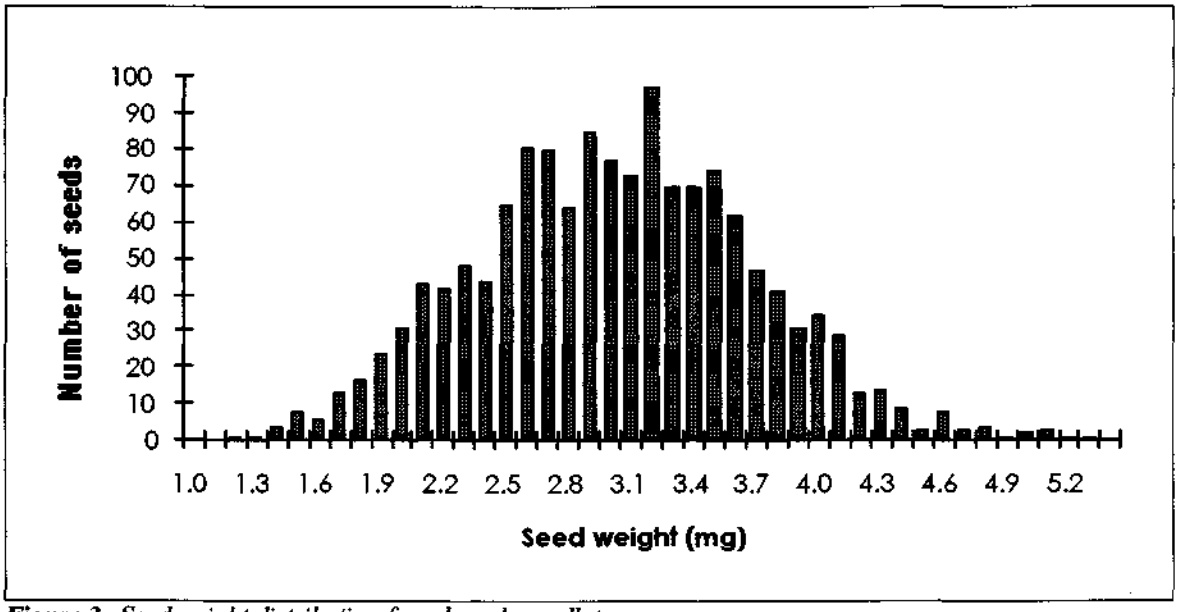

Figure 3. *Seed weight distribution for a kuroda seedlot*

Analysis of all seedlots revealed significant variability in seed weight (Figure 3). When the seedlots were graded into light, medium and heavy seed classes (weight rages in each class chosen in order to obtain approximately equal numbers of seeds in each class), germination testing revealed significant differences in germination percentage and timing (Figure 4).

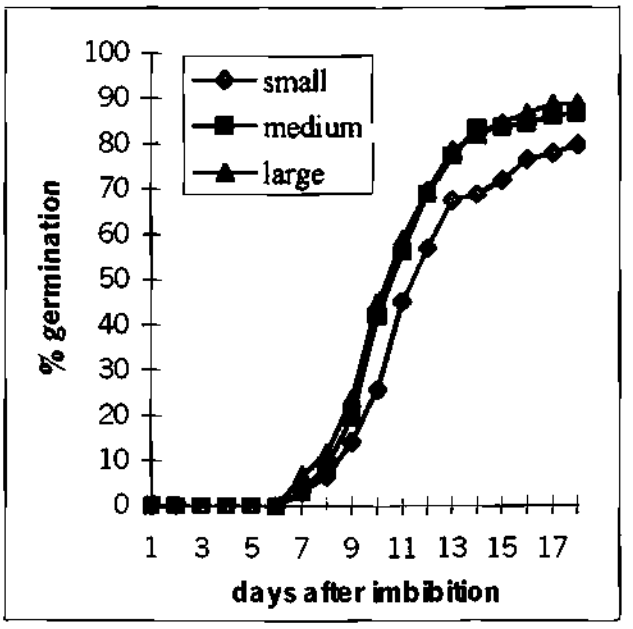

Figure 4. *Germination curves for weight graded Hi Pak seedlots*

At 10°C the germination rate, the reciprocal of the mean time to complete germination, varied between seed weight classes and seedlots. For four of the six seedlots tested, heavier seed classes displayed higher germination rates than lighter classes, indicating that lighter seed classes may be slower to emerge in the field.

Field trials and preliminary laboratory seed assessment

Results from the previous seasons field trials and UK research work indicated that variability within the seedlot prior to planting contributed significantly to variation in carrot size at harvest. Preliminary seed evaluation indicated that grading of Hi Pak and kuroda seedlots may reduce variability within seedlots. A trial was undertaken to assess the effects of seed grading on weight variability at harvest in commercial carrot crops. Seed of the Kuroda and Hi Pak cultivars used throughout this project were graded by density and size using a commercial seed cleaning service. Assessment of seed variability confirmed that the grading had reduced variability significantly (from approximately 30%CV for ungraded to 17%CV for large sized/high density seed). The graded seedlots were then planted in commercial carrot paddocks using conventional planting equipment and crop management practices.

The trial involved three commercial paddocks of kuroda and Hi Pak carrots. Each site consisted of three blocks planted with four graded seed treatments, with randomisation within each block. Approximately 7kg of seed from each cultivar was graded into three density grades, each of which was subsequently graded into three size grades to give a total of nine graded seedlots. Three of the graded seedlots (low density/small size, medium density/medium size, and high density/large size) and an ungraded seedlot were planted at each site, with each block approximately 30m in length and each replicate consisting of three double rows of carrots. Measurements of time of emergence (measured three times a week), emergence percentage, and variability at days 40, 80 and 120 were taken.

Seed lots were graded in a 3 x 3 factorial design (Figure 5). Each seed lot was graded on a density table into three densities, which were referred to as low, medium and high density.

Each density grading was then graded by size using square sieves. The corresponding sizes were recorded as small, medium and large seed. This resulted in a total of 9 different seed groupings from each seed lot.

The density grading for Kuroda seed lot was low 142 (g/ml), Medium 165 (g/ml) and large 185 (g/ml) and size grading of Small <1.6mm, Medium 1.6mm – 2mm and Large > 2mm.

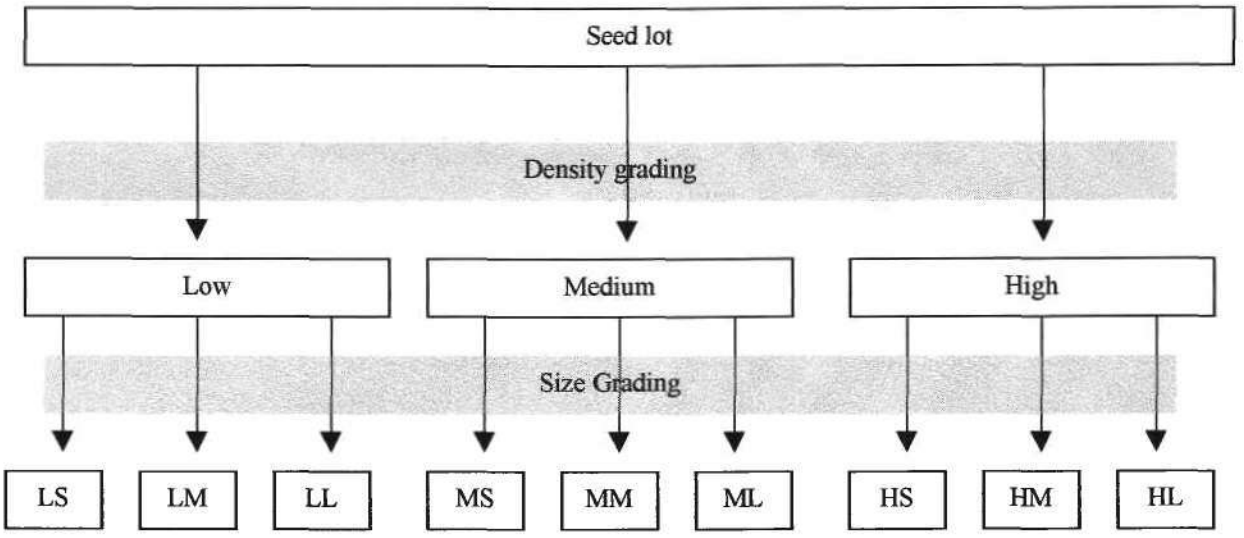

Figure 5. *Grading of carrot seed in a factorial design. Grading by density into Low, Medium and High density groups, and then size into Small, Medium and Large. Hence LS refers to Low density Small seed so that the density grading proceeds the size grading.*

Sub-samples of each graded seedlot were examined to determine seed quality attributes and seedling vigour. Germination characteristics were assessed at 10°C and 20°C. The seeds were germinated on double Whatman No. 1 filter paper in 100mm diameter lidded plastic petri dishes in the dark. One hundred carrot seeds of the same group were placed in each petri dish. Each seed weight class was replicated 4 times for both temperatures in a randomised complete block design. The filter paper was saturated with 4 mls of distilled water. The wetting of the filter paper was taken as day 0 and the number of germinated seeds was recorded daily. Germination was taken as the point when the radicle had pierced to seed coat. Percentage germination, mean time to complete germination and uniformity of germination was calculated.

Mean time to complete germination $t = \Sigma(t_x.n_x)/ \Sigma n$

Coefficient of Uniformity of Germination (CUG) = $\Sigma n/[(t\text{-}t_x)^2.n_x]$

t_x – time in days, starting from day 0 the day of sowing
t - mean time to complete germination
n_x – number of seeds completing germination on day x
n – total number of seeds germinating

The percentage of seed germinating 20 days after imbibition was between 85% and 91% for seed germinated at 20°C and between 84% and 91% for seed germinated at 10°C. Grading had no significant impact on the percentage of seed germinating.

Germinating seed at 20°C resulted in a shorter mean time to complete germination and a more uniform germination pattern than at 10°C. Temperature effects on germination of vegetable species have been extensively published. Under conditions that are less favourable to germination, lower rates of germination and greater spread in germination time is common.

Though the temperature at which seeds were germinated influenced the uniformity of germination, no significant differences in uniformity of germination between seed grading were observed. This result was surprising considering that that %CV of embryo length has been shown to be linked to the spread in germination of carrot seed (Salter *et al,* 1981).

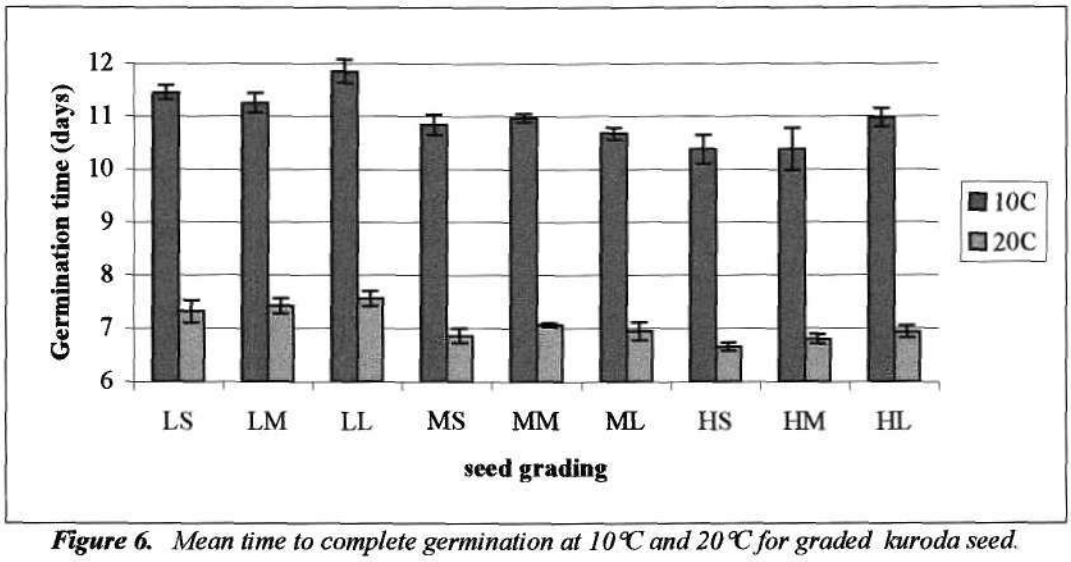

Figure 6. *Mean time to complete germination at 10°C and 20°C for graded kuroda seed.*

Significant differences in mean time to complete gemination between seed grading at both 10°C and 20°C were observed. This result is consistent with findings by Salter *et al* (1981) who found that mean time to complete germination was shorter with increasing embryo sizes. However, the time difference between the seed grade with the fastest mean time to complete germination and the slowest was approximately 1 day at 20°C and 1.5 days at 10°C (Figure 6).

Sub-samples of each graded seedlot were also examined to determine size and variability characteristics. The results presented are for the kuroda seedlots. Hipak seedlots had similar characteristics to kuroda and so the results are not presented here. Grading according to density and size had an expected effect on seed weight within seedlots. The 1000 seed weight results demonstrate the effects of grading on seed weight characteristics (Figure 7).

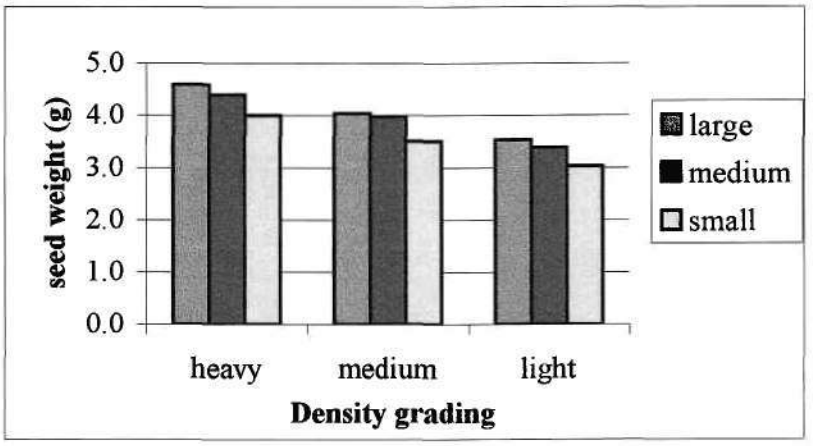

Figure 7. *Effect of seed grading on kuroda seed weight within graded classes*

The grading system firstly separated each seed batch into thirds according to density using a gravity table system. Each batch was then separated into three size categories using sieves, with the majority of seed in each density class falling into the mid size range. The same size grading was used in each density class, and it is interesting to note that size and density were not closely related, such that there were a similar proportion of large sized seeds in each density batch. The size distributions within density classes are shown in Figure 8.

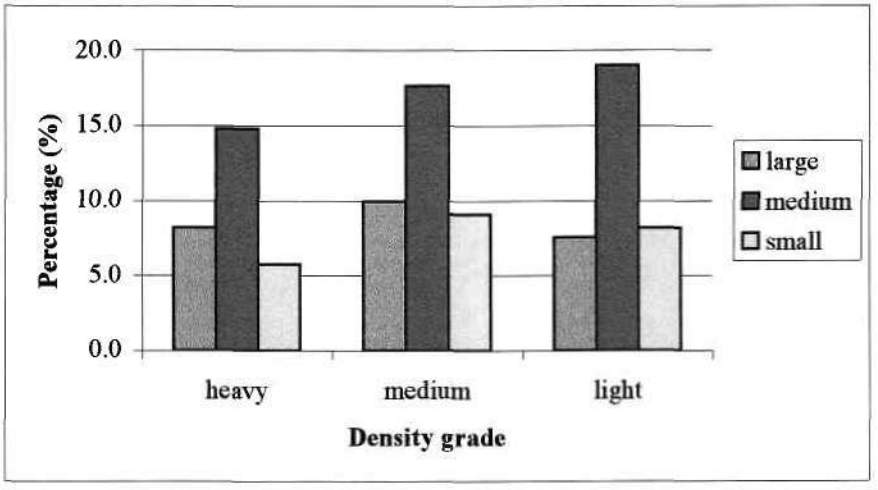

Figure 8. *Seed number in each graded class*

Embryo length of 100 seeds per graded class was recorded after fixing seeds by soaking them in FAA for a minimum of 48hours. Embryos were carefully removed from individual seeds using a scalpel. Embryos were examined under dissecting microscope to measure length. The length of each embryo was recorded by measuring the distance from the base of the hypocotyl to the tip of the longest cotyledon (cotyledons are usually similar is size for individual embryos). For both kuroda and hi pak seedlots used in the trial there was a positive relationship between seed size and embryo length, and also seed density and embryo length. This relationship in kuroda is shown in Figure 9.

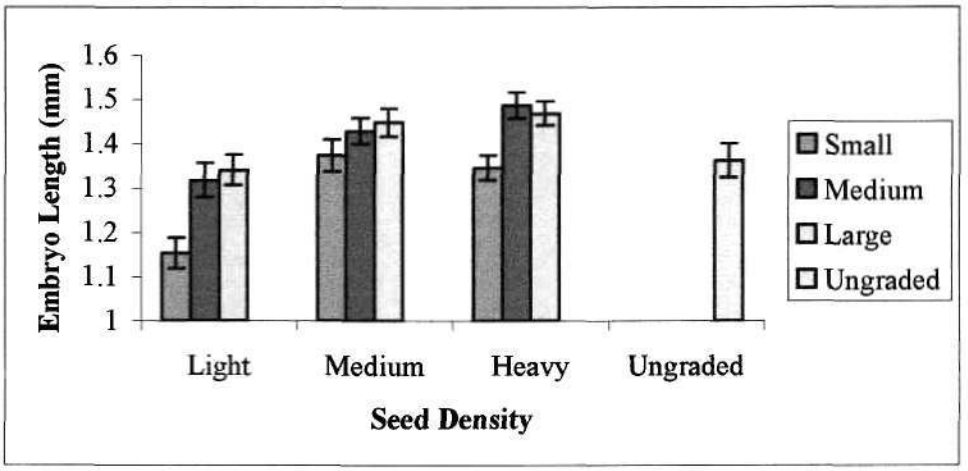

Figure 9. *Relationship between seed size and embryo length in graded kuroda seedlot.*

The presence of a relationship between seed size/density and embryo length makes it possible to reduce variability in embryo length within the seedlot through grading. Examination of the variability in embryo length within each graded seed group revealed a significant reduction in coefficient of variation (%CV) with grading for all but the small and light seed fractions. As these represent only a small proportion of the total seed weight, the effect of grading is to significantly reduce variability compared to ungraded seedlots. Variability within kuroda seedlots is shown in Figure 10. The mean embryo length in LS seed was lower and the CV (30%) slightly higher than ungraded seed (28%), while the mean embryo length in HL seed was higher and the CV lower (18%).

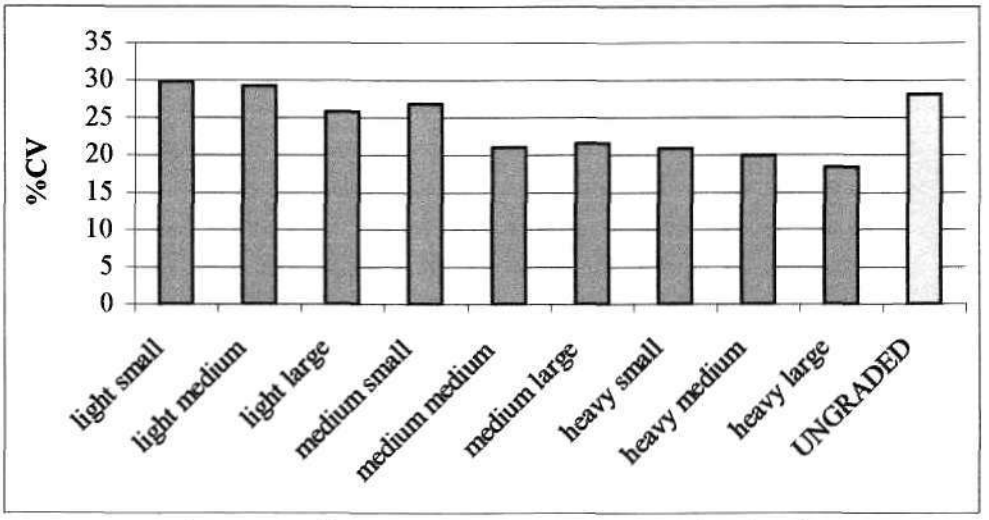

Figure 10. *Effect of seed grading on %CV of embryo length*

The results of the preliminary seed examinations were quite encouraging as grading had resulted in a significant decrease in embryo size variability in the carrot seedlots. As the literature suggested that between 30 and 60% of final size variability in carrots could be attributed to embryo size variability (Benjamin 1982,1984), seed grading using the commercial seedlots of kuroda and hipak selected this season may increase size uniformity at harvest. Variation in embryo size is an important component of seed that influences the initial variation in plant size in a crop. Gray *et al* (1986) undertook an extensive assessment of the embryo length of seed used in commercial production and its relationship to %CV of

seedling and mature carrot roots. They suggest an embryo %CV classification of: <20% low, 21%-30% medium and >30% high variability. The %CV for ungraded kuroda was 28%. This just falls within the medium range in the classification.

Assessment of graded seed in the field

Three graded seed classes and a control (ungraded) seed class were selected for field trials; LS (Low density Small size, MM (Medium density Medium size) and HL (High density Large size). The three graded seed groups and the ungraded control were replicated three times in a randomised complete block design. Each replicate consisted of one bed of 20 to 40 metre length. Each bed was planted with three double rows of carrots.

A 1m length of the bed was marked out for each replicate. Within this marked area seedling emergence and development was recorded. Carrot seedlings were recorded as having emerged when the cotyledons were upright and had separated. The number of seedling reaching 1st leaf stage was also recorded on given days. Seedling emergence and development was assessed every 2nd/3rd day.

40, 80 and 120 days after sowing the trial, carrots were carefully harvested from a 0.5m length of bed and washed free of soil. The stages of development and dry weights were recorded for each carrot. The number of leaves that had fully developed was used as a measure of stage of development (a separate scale was used for day 40). The %CV of carrots was calculated using the dry weight measurement of individual carrots. Dry weights were determined after drying at 70°C until no further weight change occurred. Fresh weights of carrots at day 120 were weighed with sub samples being dried in order to determine %DM content.

No significant difference in number of seedlings that emerged, uniformity of emergence, or time to reach 1st leaf stage was observed between seed treatments LS, MM, HL or ungraded. However, a large block effect resulted in this trial (Figure 11). In one block seedling emergence was later with the number of seedlings emerging being 13% less than the other blocks. This indicates the importance of the 'field factor' in influencing seedling establishment. The 'field factor' is a term that is readily used to encompass a range of field variables such soil condition and water availability.

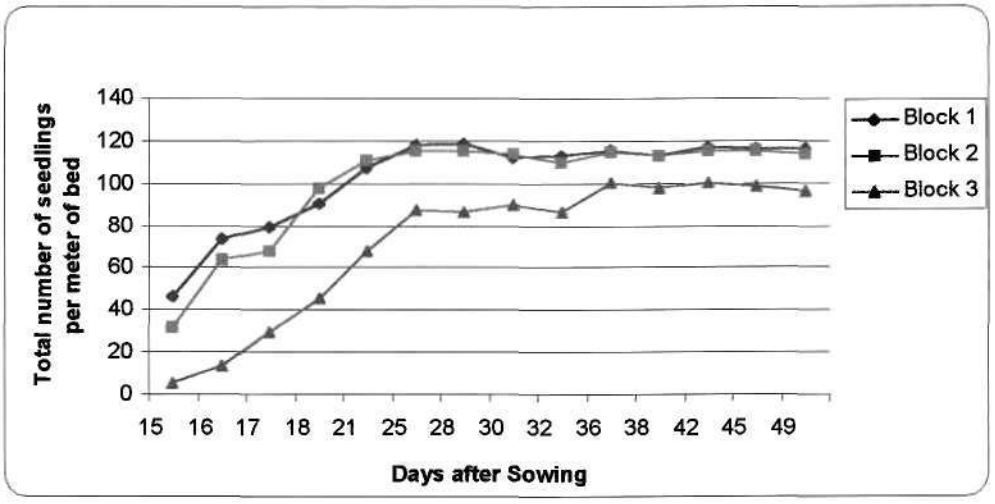

Figure 11. *Emergence of seedling from the different blocks.*

No significant difference in number of seedlings that emerged, uniformity of emergence, or time to reach 1st leaf stage was observed between seed treatments LS, MM, HL or Ungraded. Although no differences in seed emergence pattens between seed treatments were recorded, 40 days after sowing significant differences in the dry weight (Figure 12a) of seedlings and the %CV of seedling weight (Figure 12d) between seed gradings were observed. No significant differences in stage of development were recorded. The %CV of seedling weight 40 days after sowing reflected the %CV of embryo lengths prior to planting for each seed treatment.

The effect seed grading on the mean dry weight of carrots continued through until 80 days after sowing (Figure 12b). 80 days after sowing, carrots growing from LS seed had lower weights than MM and HL. Though not significant the %CV maintained a similar trend as found at 40 days after sowing (Figure 12e). No significant differences in stage of development were observed. 120 days after sowing differences in the mean dry weight (Figure 12c) and %CV (Figure 12f) of carrots between seed treatments no longer existed between seed gradings.

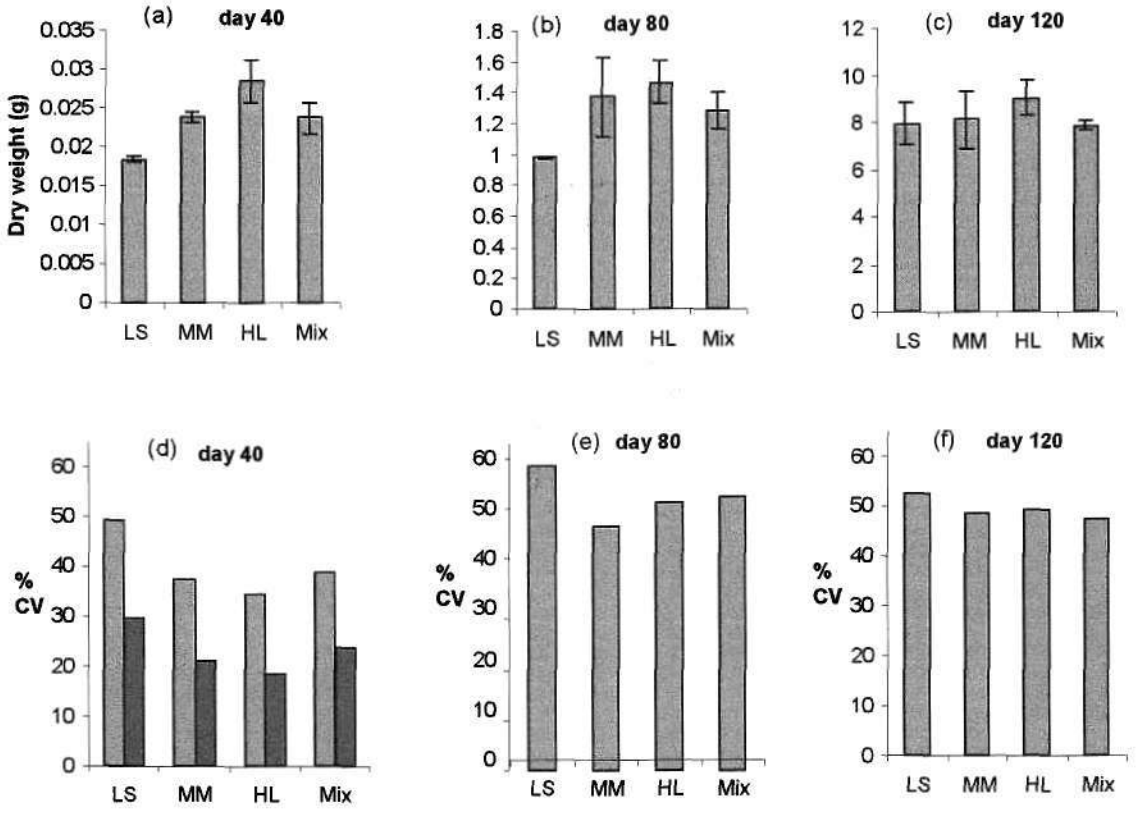

Figure 12. *Mean dry weight (a), (b) and (c) and %CV (d), (e) and (f) of carrot plants 40, 80 and 120 days after sowing respectively. Red bars in (d) indicate %CV of embryo size in the seedlots.*

The increased crop uniformity following seed grading was clearly evident in the medium and large seed grade treatments early in the growth of the crop. It is interesting to note that the average size of plants grown from the medium and large seeds was greater than for ungraded (mix) or small seed even though the stage of development (leaf number) was not different. Thus bigger (size and density) seed gave rise to bigger seedlings, so grading of

seed reduced variability in seedling size within the crop. This effect was, however, lost during the rapid filling stage of carrot crop development, suggesting that competition between plants for available resources (light, nutrients, water, etc) was more important in determining size variability than initial variation in seedling size. Plant spacing and arrangement have the greatest influence on plant competition, so factors such as operation of planters (ability to evenly space seed), density and row arrangement and number in beds will contribute to size variability. This area was investigated in field trials in the 1999/2000 season.

The effect of row position on plant growth rate was monitored in the 1998/99 trial. The crop was sown in a bed using a three double row arrangement. Average plant size was assessed 40, 80 and 120 days after planting. Carrots in the inner lines (rows) in the bed grew faster than the edge (outer) lines for the first 80 days, but by 120 days after planting carrots in all lines were similar weight (Figure 13).

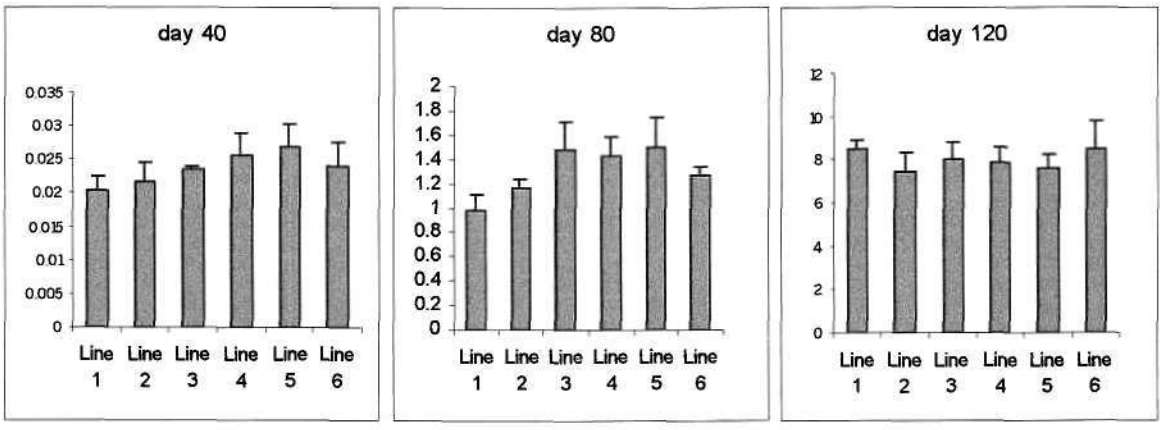

Figure 13. *Plant dry weight in the 6 lines (rows) in a bed. Bed orientation was approximately east-west, and line 1 was on the southern side of the bed.*

Reduced growth rate in the outer lines prior to the bulking stage may have been due to lower water availability as the edge of the beds tended to dry out faster than the middle of the bed. Rapid growth of plants in the outer lines between days 80 and 120 suggest that competition for light is important during the later stages of crop growth. The trend for plants in lines on the northern side of the bed to grow faster than those on the southern side provides further evidence that growth rate is linked to light interception. These findings further demonstrate the importance of competition in determining growth rate and hence size variability within the crop.

(3) 1999/2000 Effects of plant arrangement and density

The effect of competition between plants on carrot root size variability was examined in a field trial incorporating plant spacing/arrangement and density treatments. The trial was located at the Forthside Vegetable Research Station, NW Tasmania, and used kuroda seedlots. Three density treatments and three between plant spacing treatments were imposed in a randomised complete block design involving four replicate blocks. Each replicate treatment consisted of a six metre bed length with three double rows planted in the beds. The density treatments were current commercial standard density (in the range 100 – 140 plants per metre of bed, exact figure commercial in confidence), low density (80 plants per metre of bed) and high density (210 plants per metre of bed). The plant spacing/arrangement treatments were standard (plant spacing following precision drilling), even spacing (planted at high density, then thinned down to standard density leaving even spacing between plants) and random spacing (planted at high density, then thinned down to standard density randomly). Standard density was used for all spacing/arrangement treatments. The effectiveness of hand thinning in changing spacing patterns between plants was assessment by measuring between plant distances in the treatments (Figure 14).

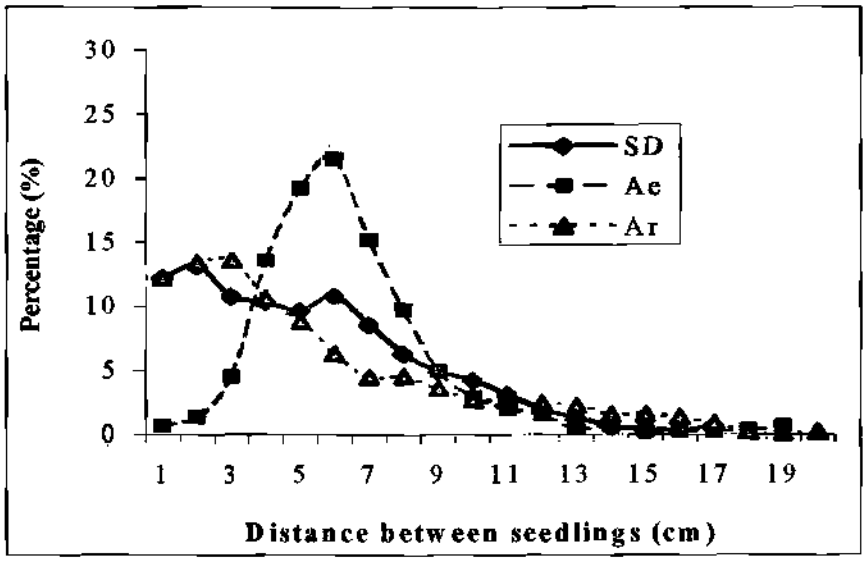

Figure 14. *Distance between plants for standard planting (SD), even spacing (Ae) and random spacing (Ar).*

The results demonstrate the variability in between plant spacing achieved with the conventional precision drilling practices. Thinning to even spacing resulted in 80% of plants being spaced between 4 and 8cm away from their nearest neighbour, while precision drilling resulted in less than 50% of seedlings between 4 and 8cm from their nearest neighbour and over 30% being 1 to 3cm away from the nearest seedling. Hand thinning to random spacing resulted in a higher percentage of seedlings being located close to their nearest neighbour.

The between plant spacing in the density treatments were also determined for comparison (Figure 15). As expected, the percentage of plants located within three centimetres of the nearest neighbour increased significantly from low density to standard density and high density.

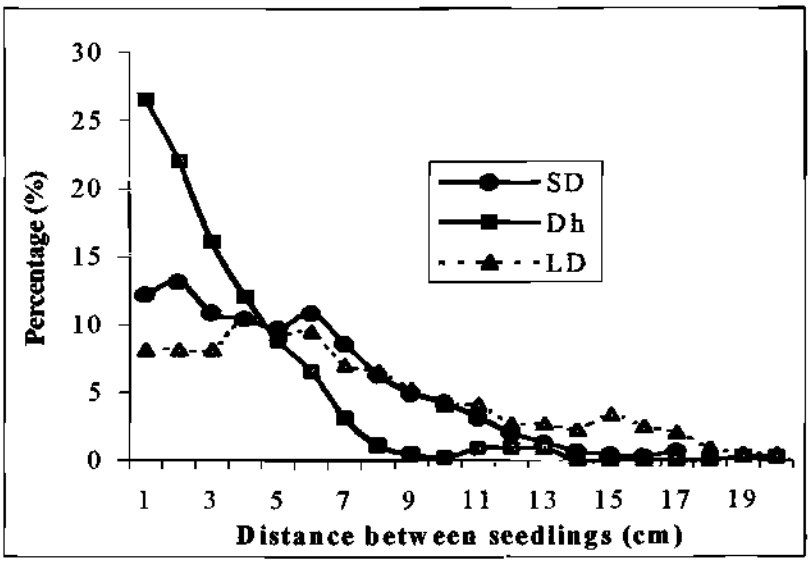

Figure 15. *Distance between plants for standard density (SD), high density (Dh) and low density (LD).*

The variability in carrot size was assessed at three points (seed, 40 and 120 days after planting) during the development of the crop. The sampling strategy and assessment of samples was as described previously. In order to compare the effects of competition and seed variability on carrot size variability the changes in size variability in crops grown from graded seedlots has been included (Figure 16). As discussed previously, seed grading can reduce size variability early in crop development but the effect of grading is not significant at harvest.

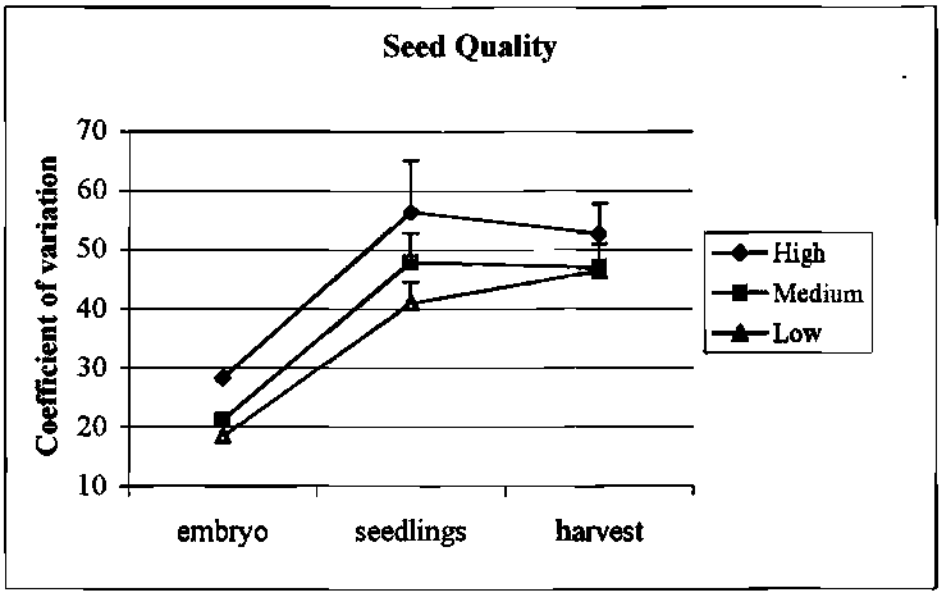

Figure 16. *Size variability (%CV) in the seed (embryo), 40 days after planting (seedling) and 120 days after planting (harvest) in graded seedlots with high, medium and low seed variability.*

Both density and spacing/arrangement treatments resulted in small but not significant differences in carrot size variability 120 days after planting. Increased uniformity was recorded in the low density treatment (Figure 17) and the even spacing/arrangement treatment (Figure 18).

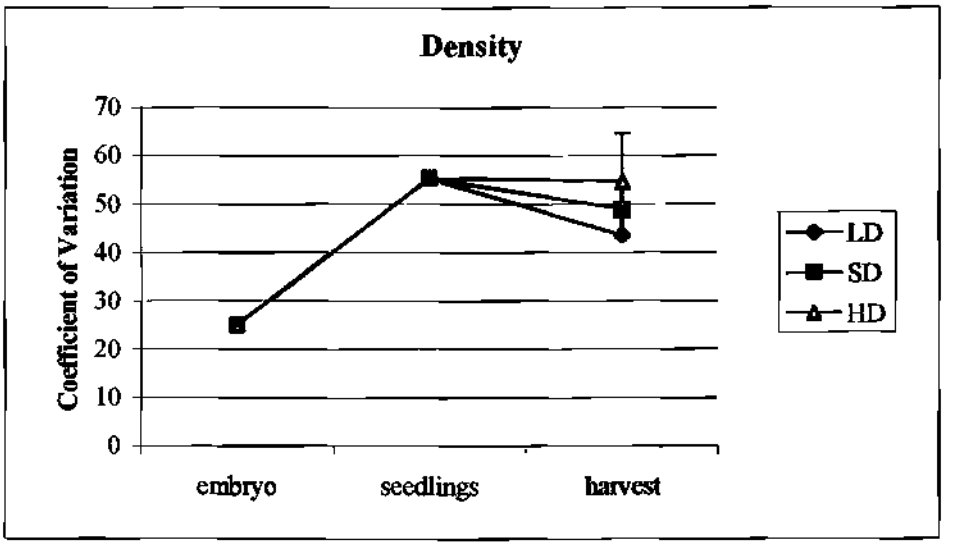

Figure 17. *Size variability (%CV) in the seed (embryo), 40 days after planting (seedling) and 120 days after planting (harvest) in low (LD), standard (SD) and high density (HD) treatments.*

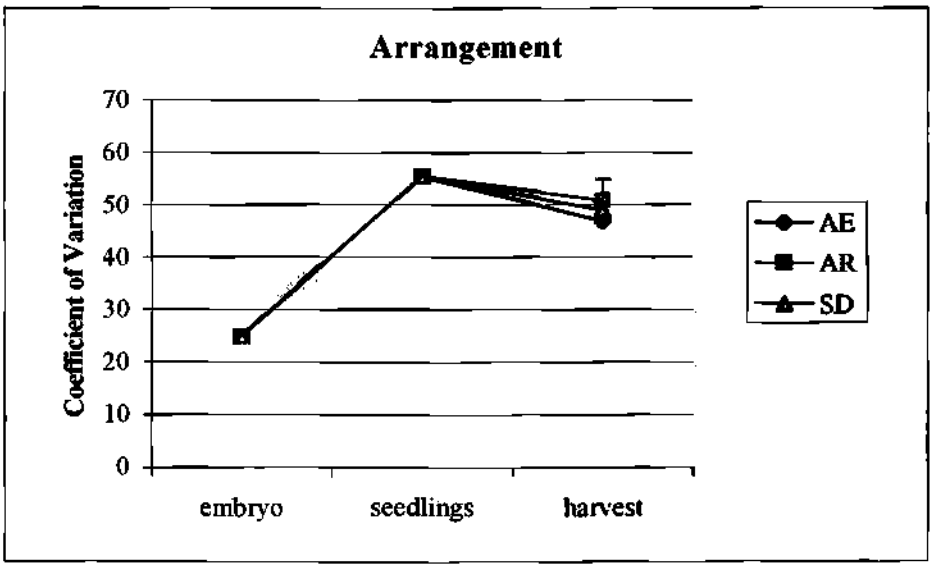

Figure 18. *Size variability (%CV) in the seed (embryo), 40 days after planting (seedling) and 120 days after planting (harvest) in even (AE), random (AR) and standard (SD) spacings at the same density.*

In all cases the variability in root size declined in the final stages of root filling, suggesting that the rate of increase in root size decreased at maturity allowing the smaller, less mature carrots in the crop to 'catch up' to the larger, more mature plants. The decrease in variability during filling was greatest at low density and at even spacing, indicating that either the uniformity in stage of growth or maturity was higher or the growth rate of the smaller carrots in the crop was faster than in the other treatments.

It is unlikely that any increase in uniformity resulting from more precise placement of seed could significantly improve the packout of carrots of the kuroda type used in these trials. The combination of seed grading to reduce variability in seedlots and precision placement to decrease competition between plants may result in significant reductions in size variability, but underlying processes related to cultivar genetics are likely to always predispose the crop to the level of variability recorded in the project. Genetic variability within the seedlot, and/or inherent variability associated with different responses of

individual plants to the environment, could explain the small effect obtained by the treatments imposed in this project. Thus, a certain level of variability in a crop would be expected due to genetic factors regardless of the uniformity of embryo size within the seedlot and the environment under which the plants develop.

While uniformity in carrot root size was not increased by a level that would confer commercial significance by the density and spacing/arrangement treatments, packout can be increased by the treatments. The impact of the treatments on shape characteristics is discussed in the following section, but significant decreases in rejection due to shape characteristics were recorded in the even arrangement and lower density treatments. In addition, average carrot size could be manipulated by changing density while overall yield (tonnes per hectare) changed little within the density range investigated. It is therefore possible to increase the percentage of large sized carrots in the crop by decreasing density without sacrificing yield. Relationships between planting density and yield were established at two field locations and revealed only slight yield increases with a doubling of density (Figure 19).

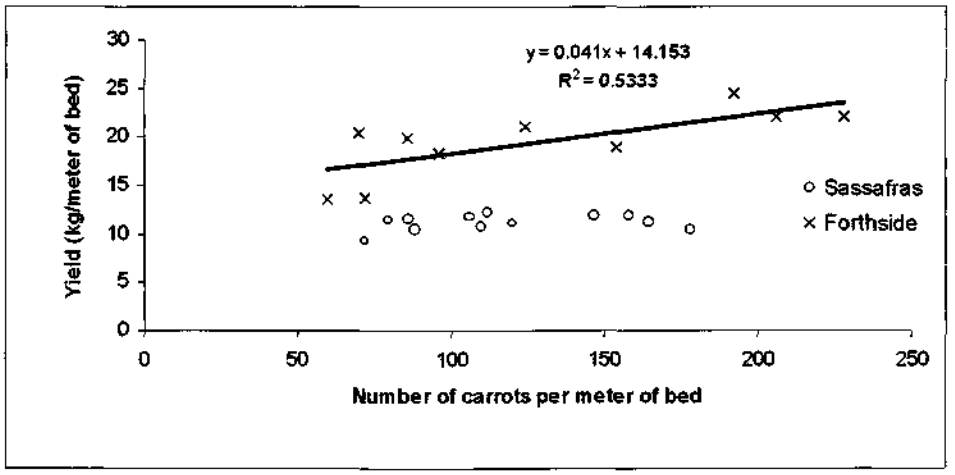

Figure 19. *Relationship between yield (kg/m bed) and density (plant number/m bed) at two field locations.*

In contrast to the weak relationship between yield and density, average carrot size was inversely related to planting density (Figure 20).

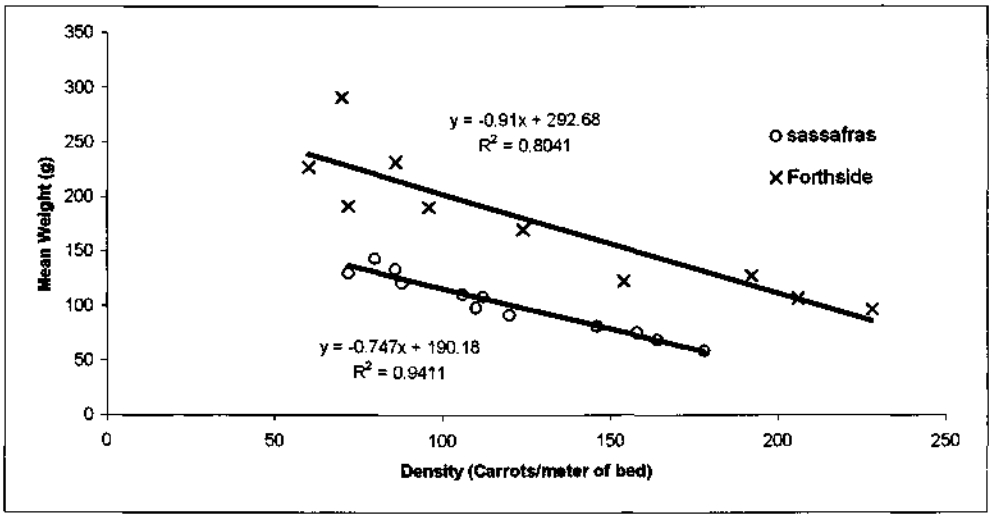

Figure 20. *Relationship between carrot root weight and density (plant number/m bed) at two field locations.*

At both field sites a significant reduction in average carrot root weight was found with increasing plant density. Planting at less than the current commercial plant density would have increased the packout in the larger size grades at both sites with an overall yield reduction at the Forthside trial of approximately 10% and no yield reduction at the Sassafras site. The commercial yield reduction is likely to be less significant as a proportion of the increased yield at higher densities will be due to carrots of less than marketable weight.

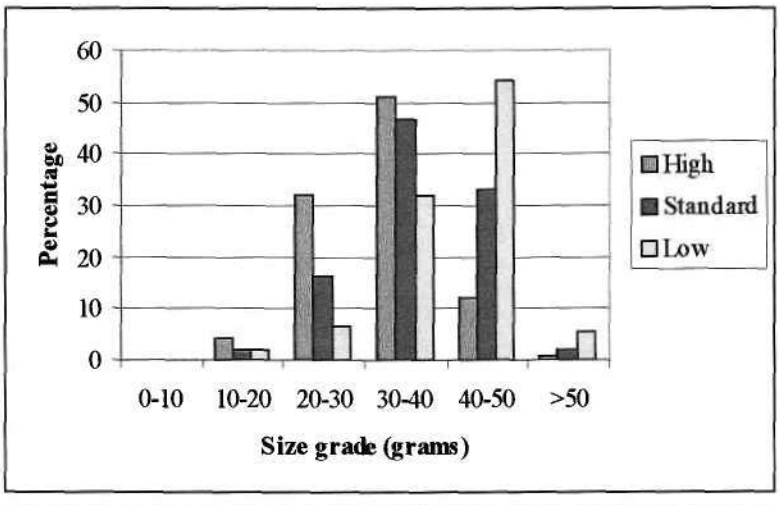

Figure 21. *Proportions of harvested carrots in size grades under high, standard and low density treatments.*

The effect of plant spacing on carrot size distribution was not as dramatic as that of density, but even spacing of plants did result in a significant increase in the percentage of carrots in the larger size classes and reduction in the number of small carrots (Figure 22).

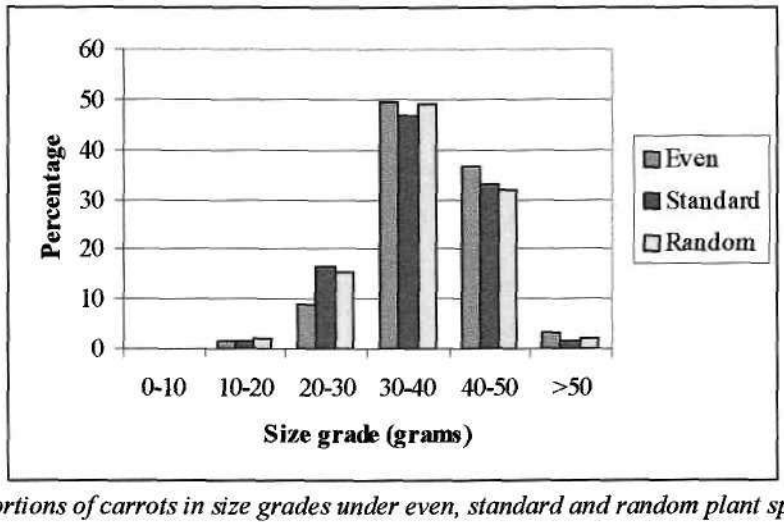

Figure 21. *Proportions of carrots in size grades under even, standard and random plant spacing treatments.*

The results indicate that improvements in planting precision to ensure even distances between plants, and selection of appropriate plant density can be used to maximise the proportion of carrots in target size ranges. While these treatments may have little effect on the size variability within the crop they can influence mean carrot weight and therefore packout in export weight classes.

DISCUSSION

The results presented in this section of the project report show that much of the variability existing in carrot crops during the first 80 days of growth is due to variability in embryo size within then seedlots used. This finding supports the conclusions from a number of previously published projects in the UK. Salter *et al* (1981) and Benjamin (1984) both found strong relationships between variation of seedling weights soon after emergence and variation of mature root weights. Since CV of embryo length is strongly correlated with CV of seedling weight (Gray *et al* 1986, Gray and Steckel 1983a, Gray and Steckel 1983a b) it seems reasonable that there should be a relationship between CV of embryo size and the CV of mature carrot root. Gray *et al* (1986) tested this and did not find a significant relationship between CV of embryo and root weights at harvest. However, they did obtained a strong relationship between CV of embryo size and CV of seedling weight.

Salter *et al* (1981) found in field experiments that 40% of the root weight variation was accounted for by the time of seedling emergence. Others have reported 5-45% (Benjamin, 1982) and 61% (Benjamin, 1984) of the carrot root weights at or only weeks prior to harvest as being attributed to seedling emergence. The variability of seedling weights soon after emergence is largely related to the variability in embryo sizes within the seed (Gray *et al*, 1988). The spread in time of emergence may be attributed to variability in seed (Gray *et al*, 1991), seedbed condition (Finch-Savage and Pill, 1990) and evenness of planting depth.

Variability in embryo size within seedlots did not explain variability in root weight at harvest for the kuroda and nantes type carrots examined in this project. Thus, while seedling weight was strongly correlated to embryo size, other factors such as competition between plants, genetic variability, and differences in timing of maturity must have impacted on size variability. The difference in growth rates of carrots in different rows within a bed demonstrated the competition between plants occurred in the carrot crops. The effect of plant spacing and crop density on root size variability at harvest was shown to be small, suggesting that competition could account for only a fraction of the crop variability. It appears that carrot growth rate decreases close to maturity, resulting in decreased size variability in crops approaching harvest as larger, more mature carrot growth slow while smaller, less mature carrots continue to grow rapidly. Factors influencing the variability in growth stage within a crop, as well as factors influencing the size potential of individual plants, would therefore affect the size variability in the crop at the harvest date. Field factors such as soil type and ground preparation, along with management of irrigation and seed sowing, have been shown to influence emergence time and would therefore be expected to contribute to variability in maturity. These factors, along with genetic variability, are also likely to determine the size potential of the plants. Treatments that reduce variability in emergence, and subsequent stage of growth as the crop develops, as well as limiting genetic variability will reduce variability in root size at harvest. Management of crops to ensure even emergence is likely to be a critical determinant of size variability in carrot crops, but even under optimum conditions variability due to genetic and competition factors will be present.

While treatments to significantly reduce size variability were not demonstrated in the project, management of plant spacing and density was shown to influence root size distribution within the crop. The results indicate that improvements in planting precision to ensure even distances between plants, and selection of appropriate plant density can be

used to maximise the proportion of carrots in target size ranges. These treatments may also reduce packout losses due to poor shape characteristics.

III. Carrot Shape

LITERATURE REVIEW

The aspects of carrot root shape that are important to commercial packout rates are shape defects such as bending, forking, splitting and twisting, and root length and diameter relationships. Despite the importance of shape defects, there has been very little research published concerning shape developments such as bending or twisting. Forking has been examined in some detail, particularly in respect to biotic factors associated with root damage, but very little information has been published on non-pathogenic influences on forking. Carrot splitting and cracking has been examined in detail recently, and the literature on this disorder is reviewed in the next chapter in this report.

The majority of literature associated with carrot shape is concerned with shoulder diameter and length. Bleasdale and Thompson (1963) derived an objective measure of shape by measuring the cylindricality of carrots using the carrot dimensions of diameter, length and weight. Cultivars are known to vary in shape and hence can be matched with market requirements. However, planting density, soil conditions and environmental factors are also known to influence the shape of carrots. Within a cultivar, increasing soil densities generally results in decreasing carrot lengths with a more conical shape (Thompson, 1969). At high soil bulk densities carrots that are typically conical in shape become shorter and sharply conical in shape (Sri Agung and Blair, 1989, Strandberg and White, 1979, Olymbios and Schwabe, 1977).

RESEARCH TRIALS

Investigation of carrot root shape development was conducted in both field and glasshouse experiments. Field measurements were undertaken in conjunction with field trials examining carrot root size variability in the 1997/98, 1998/99 and 1999/2000 seasons. An initial investigation of field factors influencing carrot shape was undertaken in 1997/98 and involved analysis of data collected in the field survey described in the previous chapter. In addition, data on soil characteristics in each of the thirteen crops examined in detail in the first season was collected in order to identify relationships between soil factors and carrot root shape development. Patterns of root filling were examined in glasshouse grown plants and linked to length and shape determination. In 1999/2000, the effects of plant spacing and plant density on carrot root shape were investigated in replicated field trials.

(1) 1997/98 Surveys of commercial crops

Changes in carrot shape during crop growth

Examination of carrot shape at 40, 80 and 120 days after planting in 13 crops revealed that the percentage of misshapen carrots did not change significantly between day 80 and day 120. The data indicated that carrot shape is determined early in the crops growth, with the pattern of growth of the tap root being more important than the cell division and expansion processes during storage tissue formation.

Day 80

	%Bent			%Forked			%Dented			%Twisted	
	B1	*B2*	*B3*	*F1*	*F2*	*F3*	*D1*	*D2*	*D3*	*T1*	*T2*
Kuroda	12.2	14.7	1.3	0.6	0.6	0	9.6	13	0	2.6	1.9
	2.4	8.3	1.8	2.4	1.8	0	4.2	4.8	3	0	1.2
	2.8	5	4.4	0	0	0	5.6	5	0.6	0.6	0.6
	4.4	4.4	11.7	0.6	0.6	3.9	2.8	2.8	0	1.7	1.1
	10.6	7.2	1.1	1.1	0	0.6	3.3	2.2	0.6	1.1	1.1
	22.8	13.9	1.7	1.1	0	0	10.6	1.7	0	2.2	3.3
mean	9.2%	8.9%	3.7%	1.0%	0.5%	0.8%	6.0%	4.9%	0.7%	1.4%	1.5%

Day 120

	% Bent			% Forked			% Dented			% Twisted	
	B1	B2	B3	F1	F2	F3	D1	D2	D3	T1	T2
Kuroda	9.4	11.1	1.1	0.0	1.1	0.0	3.3	3.9	3.3	0.0	1.1
	2.8	6.1	2.2	0.6	2.2	0.0	0.6	2.2	1.7	0.0	2.8
	3.3	8.9	3.3	0.6	2.8	2.2	0.0	0.0	1.7	0.0	0.6
	9.4	10.0	0.6	0.6	0.6	0.0	0.6	3.3	1.7	0.6	1.7
	12.2	2.8	0.6	0.0	1.7	0.0	0.6	1.7	1.7	0.0	1.7
mean	7.4%	7.8%	1.6%	0.3%	1.7%	0.4%	1.0%	2.2%	2.0%	0.1%	1.6%

Table 1. *Carrot shape development in 6 kuroda crops*

Results on size variability and shape development in the 13 crops examined have been summarised above. Soil characterisation at the sites was conducted and correlations between size and shape characteristics and soil conditions were examined. The field sites, each of which was a krasnozem soil, represented a range of soil conditions (organic matter, bulk density, pH). The soil characteristics were consistent with the findings of previous

studies of krasnozems, and expected relationships such as that between organic matter and bulk density were observed (Figure 23).

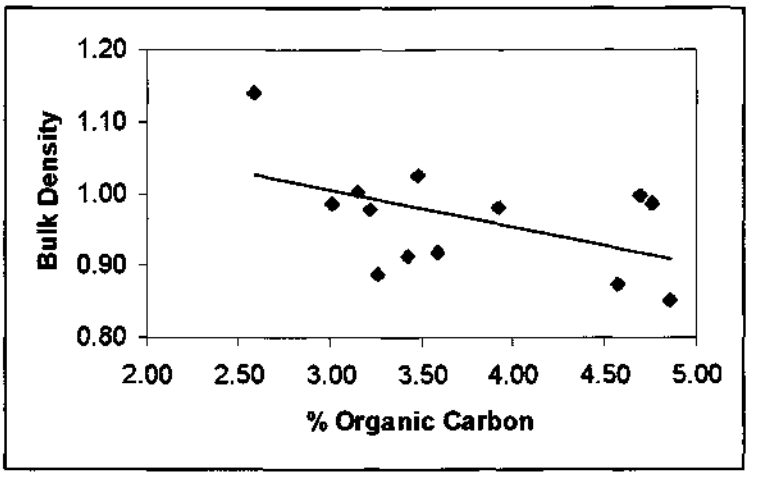

Figure 23. *Relationship between soil organic matter and bulk density at the 13 field sites*

Analysis of relationships between soil characteristics and carrot size and shape characteristics revealed a number of weak correlations. The most significant correlation was between carrot root length and soil bulk density at 10-20cm depth. Increasing bulk density was linked to decreased carrot root length. The correlations between soil bulk density at 0-10cm (Figure 24), 10-20cm (Figure 25) and 20-30cm (Figure 26) and root length are shown graphically below.

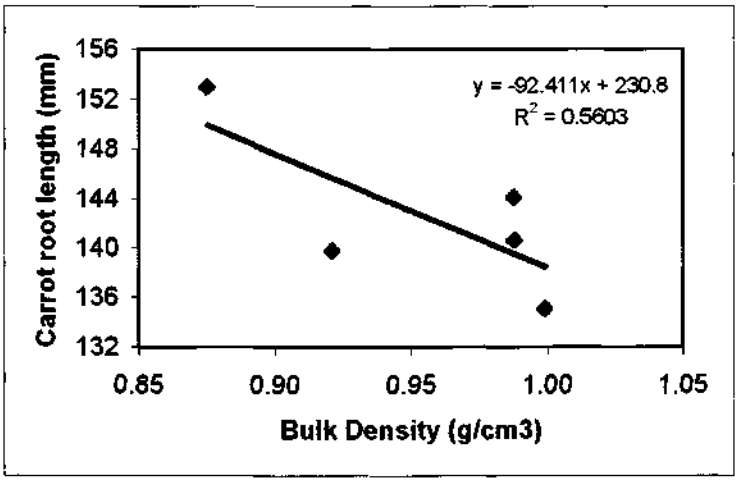

Figure 24. *Relationship between mean root length and soil bulk density in the top 10cm of the soil profile*

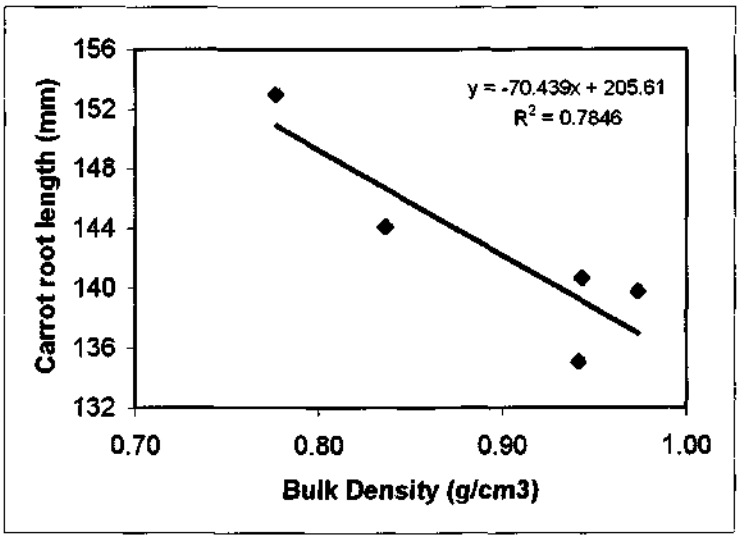

Figure 25. Relationship between mean root length and soil bulk density in the soil profile at 10-20cm depth

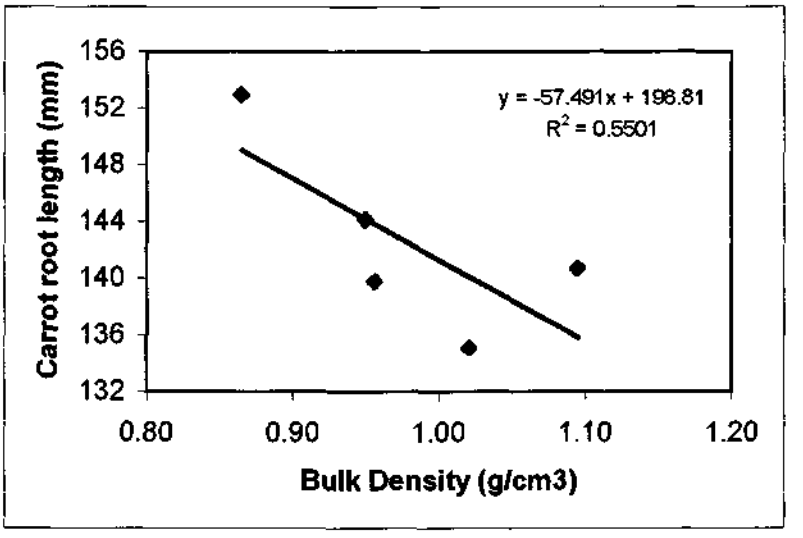

Figure 26. Relationship between mean root length and soil bulk density in the soil profile at 20-30cm depth

The correlation is strongest at 10-20cm soil depth, which is consistent with the average carrot root length of 14.5cm. The data suggest that increasing soil bulk density may impede root development during the critical early stages of development, resulting on shorter carrot during the filling out phase. The percentage of misshapen carrots in the crops was also correlated with soil bulk density, suggesting that variability in soil strength (linked to bulk density, organic matter content and soil moisture) may influence the path that the carrot root follows during the early development phase, ultimately leading to a misshapen carrot at maturity. This link between soil bulk density and carrot shape development requires further research as it may be possible to reduce the effects of high soil bulk density by appropriate management of paddock preparation and more importantly management of irrigation (timing and frequency) to reduce increases in soil strength in soils with high bulk density. Observations during the field trial also suggest that forking in carrots may, in some sites, be linked to soil strength/bulk density conditions, particularly where shallow plough pans occur.

(2) 1998/99 Patterns of carrot root filling

Glasshouse trials were conducted to examine development of shape characteristics in both kuroda and nantes carrot types. Carrots were planted in 25 litre potting bags containing potting media and raised under glasshouse conditions. Plants were sampled at 14 day intervals, beginning 28 days after planting, with five replicates of each variety sampled at each date. The diameter of each carrot was measured at 10cm intervals along its length, and sections were taken at each point for determination of cell number and cell size.

The change in carrot root diameter during plant development for hipak and kuroda varieties is shown in Figures 27 and 28 respectively.

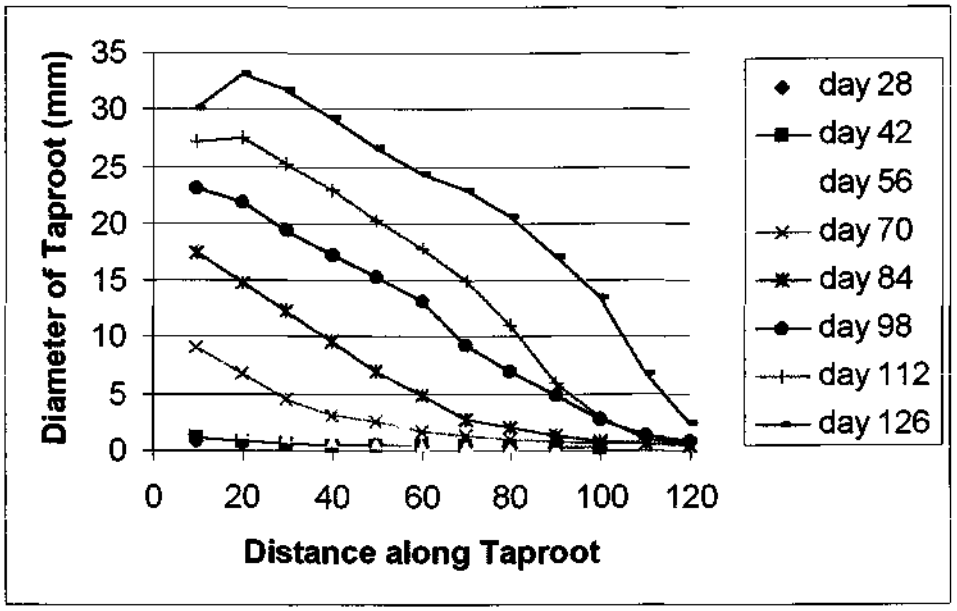

Figure 27. Pattern of root expansion in nantes type carrot

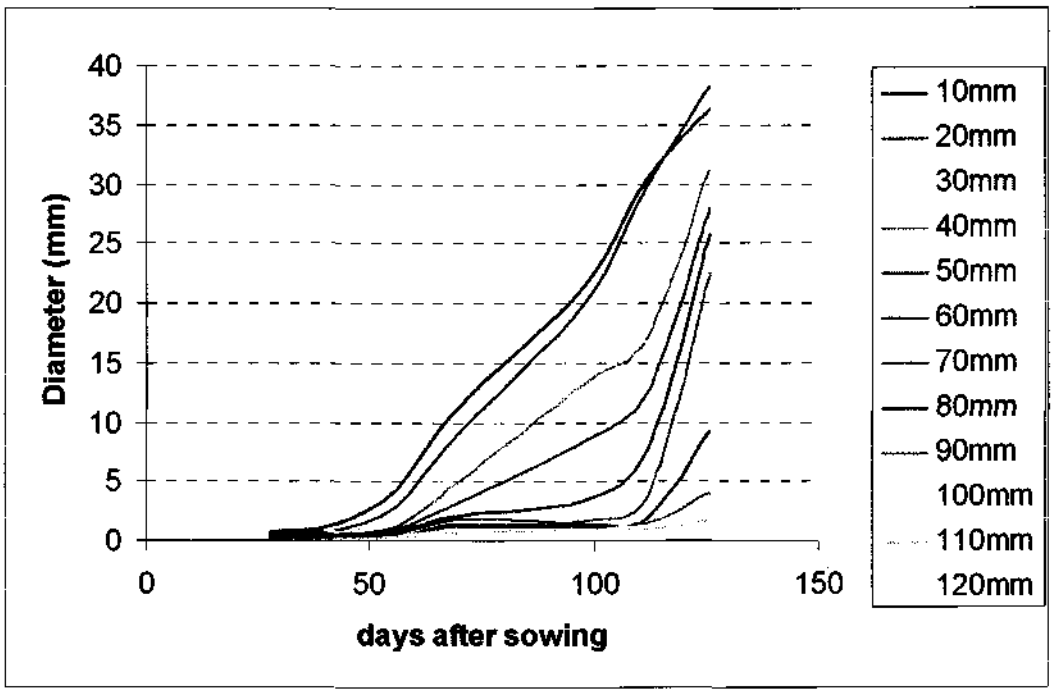

Figure 28. Pattern of root expansion in kuroda type carrot

The characteristic pattern of growth for both varieties consisted of rapid expansion in root diameter at the top of the root between days 56 and 98, followed by a phase of rapid expansion in root diameter in the lower section of the root in the later stages of development. This pattern of growth is best illustrated by examining the rate of change in root diameter between sample dates, as shown in Figure 29 for nantes type.

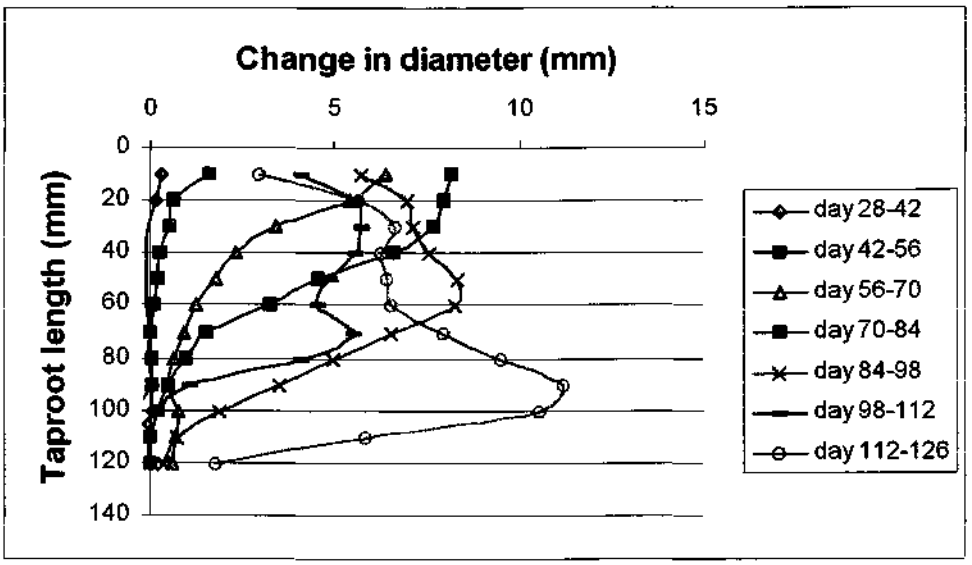

Figure 29. *Rate of change in carrot root diameter*

Root expansion appears to follow a gradient in deposition of storage materials, with the top of the root forming the major point of storage and therefore expansion early in development and gradual shifting of the major site of expansion lower down the carrot root later in development. Some of the variability in expansion rate trend lines may be the result of the low number of replicates (five) used in the study. An interesting observation from both the kuroda and hipak data is that the expansion occurring in the lower regions in the root occurs quite late in the development cycle and occurs at a rapid rate, suggesting a two phase root expansion process. This has some support in the literature from the work of McGarry (1995) who showed two phases of change in carrot tissue strength during root expansion. The understanding of carrot growth from this study should thus be useful in examining the process of splitting. The pattern of expansion in the lower sections of the root also explains the observed 'rounding off' of the root tip late in crop development. Change in root tip shape is a useful indicator of harvest maturity as it signals the end of the phase of rapid expansion in carrot root diameter.

The changes in root diameter can be explained by changes in cell number and cell size within the storage tissue. Changes in cell number in kuroda root during development are shown in Figure 30.

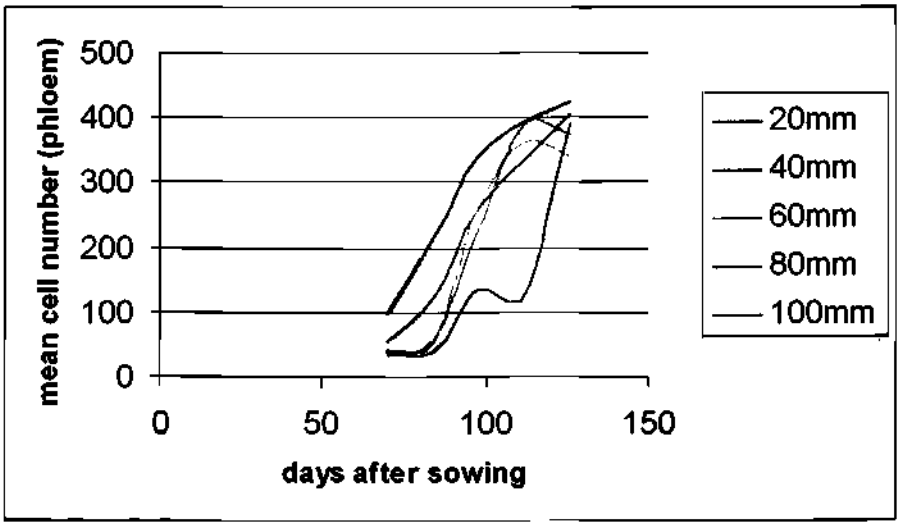

Figure 30. *Average cell number in carrot storage tissue*

Cell number increases in all sections of the carrot root during root expansion. The rate of increase in cell number is greater than the rate of root expansion earlier in development, but cell division continues to occur throughout the period of root expansion. There appears to be a phase of rapid cell division (relative to root expansion) near the top of the root up to around day 84, while the major phase of cell division lower in the carrot occurs after this date.

Phases of rapid cell division precede root expansion by 2 to 4 weeks, and occur over the duration of root growth. Cell division and root expansion began at the top of the carrot root and extended down the length of the root over the growing season. The maximum final carrot length appears to be established early in root development, and appears to be linked to root length and position of secondary thickening (as determined by observation of vascular cambium anatomy) within the root. Secondary thickening (cell division within the vascular cambium resulting in phloem parenchyma cells that form the storage tissue) in the root occurs from 28 days after planting and the rate of cell division is greatest at the top of the root. The rate of cell expansion in the top section of the carrot increases after this initial phase (so that the rate of cell expansion is greater than the rate of cell division) until maximum cell size is reached. Some root expansion continues past this time through continued cell division and expansion, but at a much reduced rate. As the tissue near the top of the carrot reached maximum storage capacity (as determined by cell size), the site of maximum rate of cell division and cell expansion shifts lower down the carrot root. Late in development, when cell expansion near the bottom of the carrot was restricted by the absence of cambial structure to facilitate secondary thickening, the rate of cell expansion at the base of the carrot increases dramatically. The carrot may continue to increase in size after this time through continued cell division within the secondary phloem tissue, but the rate of expansion is slower and storage cell size is at its maximum. This phase of growth, when storage capacity is close to maximum, is likely to correspond to the stage when carrot tissue reaches harvest maturity and also maximum susceptibility to splitting.

(3) 1999/2000 Effects of plant arrangement and density

While the field trial undertaken in 1999/2000 was aimed at examining root size uniformity, observations of carrot root shape in all treatments were also recorded. Plant density and spacing had significant effects on the percentage of carrots with shape defects (Figure 31).

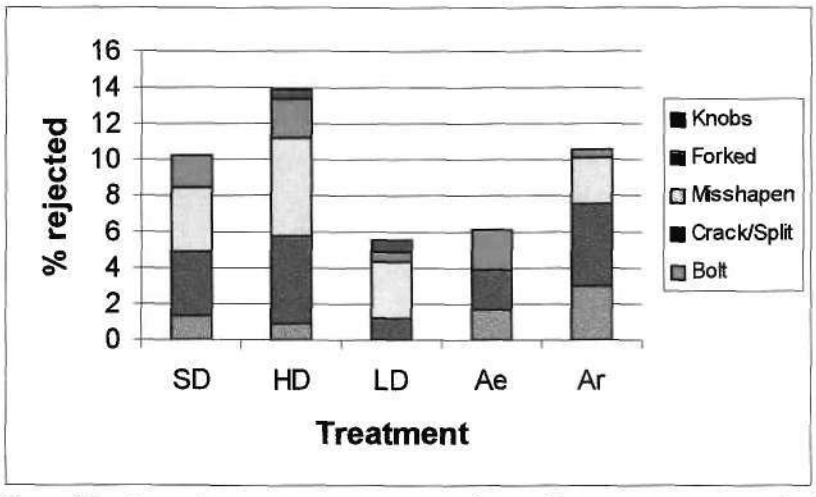

Figure 31. *Effect of density and arrangement on carrot shape. Treatments were standard density (SD), high density (HD), low density (LD), even arrangement at SD (Ae), and random arrangement at SD (Ar).*

Increasing plant density resulted in significantly higher percentage rejection of carrots based on shape characteristics. The higher rejection rate was mostly due to higher percentages of cracked/split and misshapen (bent, twisted) roots, although the number of forked carrots also increased. Increased uniformity in plant placement also lead to reduced rejection rates, with no misshapen carrots recorded in the even arrangement treatment and a lower percentage of cracked/split carrots. It is interesting to note that the percentage of forked carrots varied significantly between treatments, suggesting that non-biotic factors may contribute to the development of this disorder. The relationship between density/arrangement and the shape disorders (cracked/split, bent, twisted) suggests that competition between carrots may contribute to the regulation of carrot root development. The mechanism for this regulation is not known, but the influence of one carrot root on soil moisture content in its vicinity and hence soil strength properties and also water and nutrient availability for neighbouring carrots would be interesting areas of research.

DISCUSSION

Carrot root shape at harvest is principally determined during the crop establishment phase. Factors that influence the rate of growth and direction of growth of the taproot during early plant development determine the length and shape of the root at maturity. The taproot displays primary root anatomy during early growth, with secondary growth or thickening of the root occurring later following development of a cambial ring around a central xylem core. The mature carrot root consists of the xylem tissue core, a cambial ring, phloem tissue (the root storage tissue) and a periderm layer at the surface of the root. The initiation of secondary growth occurs during crop establishment and precedes the period of rapid expansion or filling of the carrot root. The final length of the carrot appears to be determined during the early growth phase, with conditions promoting rapid taproot growth and initiation of secondary growth down the length of the root resulting in greater potential root length. In addition, conditions that delay the onset of expansion growth or root filling lead to an extended duration of initiation of secondary growth and hence increased length potential. Further research is required to identify the factors triggering initiation of secondary growth and commencement of the rapid expansion phase. Soil conditions were identified in this study as one determinant of root length potential, with increased soil strength resulting in shorter root length at harvest presumably through slower root growth at establishment. Soil strength is linked to soil bulk density and soil water content, so maintenance of soil moisture is important in soils with high bulk density if the risk of development of short roots is to be avoided.

The direction of root growth through the soil following germination determines the shape of the root at harvest. Soil strength and/or soil water potential are likely to influence the direction of root growth, with roots growing around regions of high soil strength (eg. clods) or low water availability. Variability in soil strength and/or soil water potential within a soil profile will therefore increase the likelihood of development of bent or twisted roots. Expansion of the carrot root through secondary thickening can reduce the severity of bends and twists in the root resulting in a lower proportion of rejectable shape characteristics later in crop development. In heavy soils with low organic matter content, avoidance of high soil water deficits in the first 40 days after sowing is required in order to reduce the risk of development of poor shape characteristics in the crop. In addition, shape defects can be reduced by more even spacing of plants and by reduced planting densities.

IV. Carrot Splitting

LITERATURE REVIEW

Numerous observation of treatment effects on carrot splitting and cracking have appeared in the literature, but in was not until the early 1990's that a basic explanation of splitting susceptibility was proposed by researchers at Horticulture Research International in the UK (McGarry, 1993, 1994). While differences between cultivars were explained, and some irrigation and harvest maturity effects examined, the physiological basis of other treatments known to influence splitting and cracking were not examined. The commonly used strategies to minimize losses due to cracking and splitting are to harvest before carrots become over mature (defining maturity is a key point for this strategy), to maintain even crop growth over the season, and to avoid excess irrigation close to harvest.

Splitting in carrots occurs when the pressure within roots exceeds the tensile strength of the tissues. This may occur while the carrot is growing in the field, during harvest or handling/packing. Carrots split when the cell wall raptures, forming radial longitudinal fracture in the phloem parenchyma. Susceptibility to splitting varies between genotypes (McGarry, 1993), irrigation practices (McGarry, 1994) and timing of harvest.

There are two main aspects to carrot splitting; one is the internal turgor pressure and the second is the tissue strength (resistance to breakage). Conditions that lead to high water potential and turgor pressure are know to increase the susceptibility of the carrots to splitting (McGarry, 1993). Hence carrots irrigated heavily just prior to harvesting as well as carrots that are harvested early on cold mornings are more prone to splitting.

Tissue strength is also important, developing a resistance to splitting. McGarry (1995) showed that the tensile strength of carrot roots changes over time. Cultural factors that influence the tissue compositions and arrangement, and hence the strength of the tissues will be important in minimising susceptible cultivars to splitting. Nitrogen applications, spacing and timing of irrigation applications have shown to influence carrot splitting (Bienz, 1964; McGarry, 1994). The relationships between these treatments and carrot tissue properties are not known, and more research is required on the physiological basis of splitting in order to develop new strategies to reduce packout losses due to this disorder.

RESEARCH TRIALS

Splitting in carrots occurs when the pressure within roots exceeds the tensile strength of the tissues. This may occur while the carrot is growing in the field (referred to as cracking or growth cracks), or more commonly during harvest or handling/packing. Research in this project has concentrated on the physiological mechanisms of splitting/cracking, rather than assessing treatments to reduce the problem. Previous research in Australia has examined irrigation, nutrition and harvest maturity effects on splitting but has failed to deliver repeatable results. An understanding of the physiology of splitting is required in order to explain the effects of different field treatments and to develop effective strategies to reduce packout losses due to splitting.

Field and glasshouse trials were used to examine changes in carrot physiology and splitting susceptibility over 24 hour cycles. Anecdotal evidence suggested that carrots were more susceptible to splitting early in the morning than later in the day under Tasmanian conditions. The diurnal fluctuations in splitting susceptibility provide a useful model for examining the physiological basis of splitting. Research trials were conducted to firstly document diurnal (daily) changes in splitting susceptibility in kuroda type carrots, and secondly describe some of the physiological and structural changes that may be related to splitting susceptibility. Finally, treatments designed to reduce splitting were imposed in order to test the theories developed in the earlier trials.

(1) Diurnal Changes in Susceptibility to Splitting

Anecdotal evidence suggested that carrots are more susceptible to splitting early in the morning than later in the day. Harvesting commonly starts at first light, but may be earlier or later depending on harvesting schedule and factory throughput. In addition, carrots are much more susceptible to splitting on cold mornings than mild mornings. In order to document fluctuations in carrot root susceptibility to splitting, trials were conducted in four commercial kuroda paddocks between February and April. Carrots were harvested before sunrise and at regular intervals over the day, and splitting susceptibility tested using a modified force gauge. The trend in splitting susceptibility over the day was consistent in all paddocks, and the data shown here is from one site but is representative of all paddocks.

A 3m length of bed containing 6 rows of mature carrot roots from a commercial crop was used to measure diurnal changes in carrot susceptibility to splitting. Thirty carrots of even size were randomly selected and hand harvested at pre-dawn (7am) and every three hours until 4pm from within this area. The susceptibility of each carrot to splitting was assessed using a hand held penetrometer with a modified tip. The tip was 1cm long by 1mm wide, with a 30 degree face slope leading to the tip.

The tip of the penetrometer was gently pressed against the taproot approximately 2cm below the shoulder. The pressure at which the taproot began to fracture by inducing a split of at least 1cm length was recorded. Carrots that required more than 11kg to induce a fracture were recorded as not splitting. Both the proportion of carrots splitting and the mean force of those that did split were calculated.

The susceptibility of carrots to splitting decreased significantly from 7am to 10am and again from 10am to 1pm (Figure 32). A decrease in the percentage of carrots splitting

(>11kg) and an increase in the force required for those that did split (<11kg) was observed. An increase in the percentage splitting from 40% to 60% was observed from 1pm to 4pm.

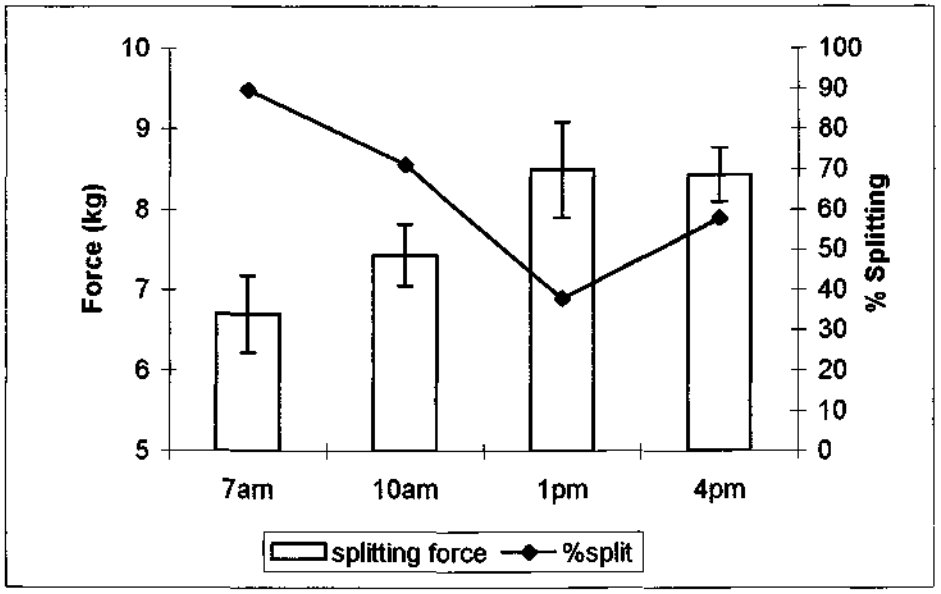

Figure 32. *Changes in susceptibility to splitting over a day(Kuroda).*

Over the day the percentage of carrot splitting decreased from 7am until 1pm and had increased again at 4pm. While these figures cannot be directly converted to likely splitting losses during harvesting operations, it does suggest that splitting losses could be reduced by delaying the start of harvesting in susceptible crops. Low night temperature is one factor that has been associated with increased susceptibility in crops, and observations over the four crops examined in this trial supported this hypothesis. Splitting susceptibility increased with decreasing night temperature.

(2) Temperature and splitting susceptibility

Evidence from the previous trial suggests that on cold mornings carrots are more susceptible to splitting than on warmer mornings. This observation has also been supported by industry experience that losses due to splitting are generally higher on frosty mornings. In the literature, lower temperatures and increased turgidity have been proposed to increase the susceptibility of harvested carrots to physical damage (Dickson 1966; Kokkoras 1998). An experiment was designed to assess the effects of temperature and its influence on carrots splitting.

A mature Kuroda crop was used to assess the effect of temperature on carrot splitting susceptibility. A 2 x 4 factorial experimental design consisting of 2 times of the day, pre-dawn (7am) and midday (12pm), and 4 temperatures ranging from 5°C to 25°C. At pre-dawn (7am) and midday (12pm) 10 carrots were assessed for splitting susceptibility. A further 44 carrots of even size were harvested and placed immediately into large bins half filled with water maintained at approximately 5, 12, 18 and 25°C. 11 carrots with leaves attached were placed in each of the containers so that the taproot was submerged. A lid was fastened, keeping the carrots in the dark. After 75 minutes carrots were removed and the water temperature and tissue temperature was recorded to confirm that the tissue had reached equilibrium with the water temperature. For 10 carrots splitting susceptibility was

tested using the modified penetrometer. Results were recorded as %splitting based on a maximum applied force of 11kg and the mean force required to split the root.

Ambient air temperature and carrot tissue temperature was also monitored. Air temperature was recorded hourly by placing a thermometer in a shaded area. Carrot tissue temperature was recorded using a carrot that had just been freshly hand harvested. A probe thermometer was inserted into three regions of the carrot tap root; 2cm below the shoulder, the centre of the carrot and 2 cm above the tip of the carrot root. The distance in the soil was thus (2cm below soil surface, 7cm below soil surface and 12cm below soil surface.

The pattern of change in splitting susceptibility and percentage splitting (Figure 33) was the same as described in the previous section.

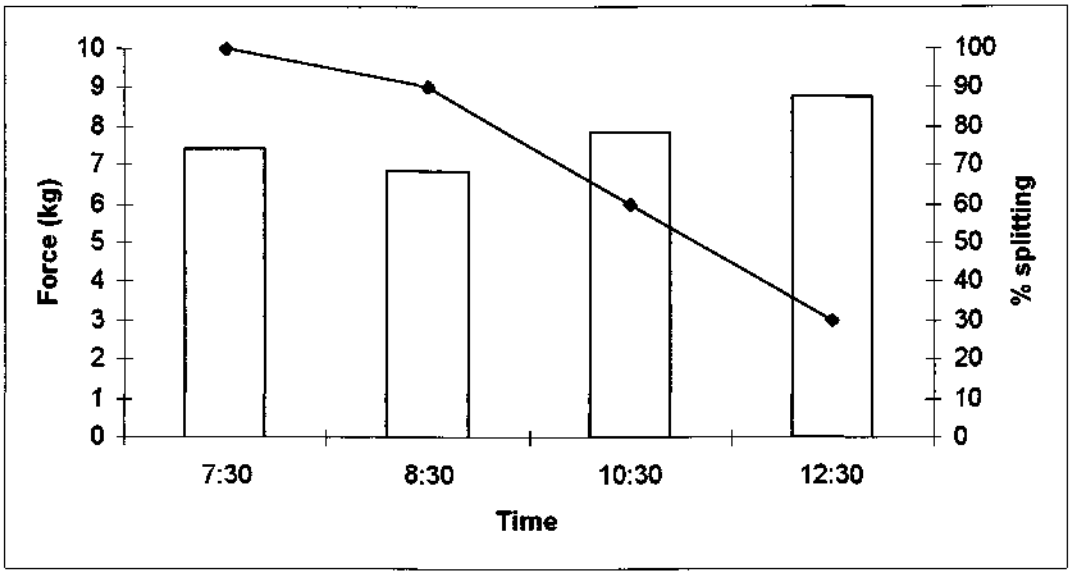

Figure 33. *Changes in percentage splitting (line) and force required to split carrot roots (bars).*

The percentage of carrots that split when an external force of 11kg or less was applied decreased from 100% pre dawn to 30% at 12:30. The temperature of the carrot roots increased over the same time period, from approximately 14°C to between 15°C and 16°C depending on position in the carrot (Figure 34).

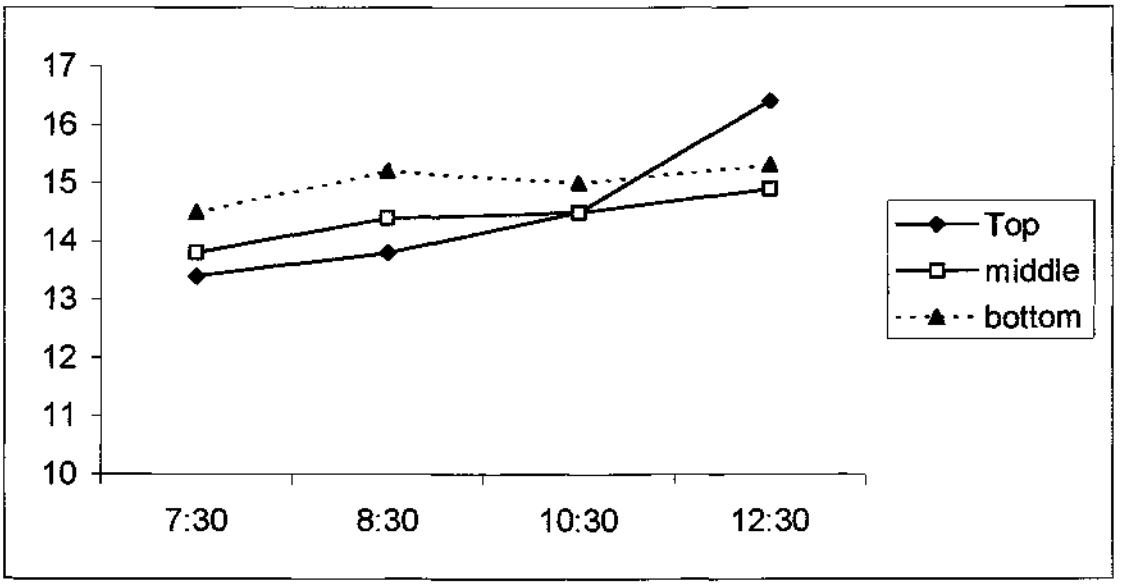

Figure 34. *Changes in carrot root temperature during the day*

While the change in temperature was small, it did follow an inverse trend splitting percentage suggesting that a relationship may exist. This trend could be used to account for the increased incidence of packout losses noted on cold morning. However, when carrots were removed from the ground predawn, equilibrated to a target temperature in water, and then assessed for splitting susceptibility, there was no increase in splitting percentage with lower temperatures (Figure 35).

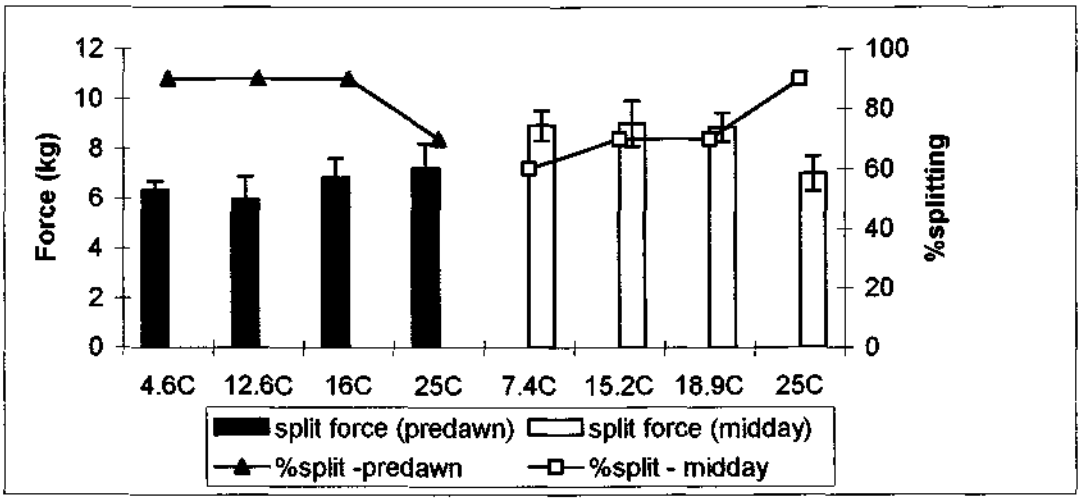

Figure 35. *Effect of carrot root temperature on splitting susceptibility and splitting pressure*

Splitting percentage and force required to split the carrots did not vary significantly between the 4.6°C, 12.6°C and 16°C treatments on predawn harvested carrots. The percentage splitting was lower and splitting pressure higher at the highest temperature, 25°C. Conversely, the high temperature treatment on carrots harvested at midday resulted in the highest percentage splitting and lowest splitting pressure. These results were not consistent with the theory of low tissue temperature in the morning producing higher susceptibility to splitting through a direct effect on tissue properties. It must thus be concluded that temperature during the night affects aspects of carrot root functioning that subsequently result in changes to splitting susceptibility.

(3) Effect of root size and position on splitting susceptibility

Cracking has been shown strongly linked to growth period/maturity of a crop (Fritz & Habben , 1975 McGarry 1995) it is likely that susceptibility may also be. However, it is unknown if the relationship between maturity and cracking is a direct influence of the size (diameter and length) of the carrot or to physiological development.

It is also unknown if the susceptibility to splitting is influenced by the spacing and arrangement of carrots within a bed system. Over the growing period of a carrot crop there are commonly differences in growth rates between carrots in the 'outer' and 'inner' rows of a bed. Carrots in inner rows are usually of a greater size/weight early in the life of the crop, but their growth tends to be slower over the final stages due to increased competition. This difference in growth pattern may influence the susceptibility of carrots to splitting.

The mature carrot crop used to assess diurnal changes in susceptibility to splitting (section 1 above) was also used in this experiment to assess the relationship between size of carrots and their susceptibility of splitting and between position of carrots within a bed system and their susceptibility to splitting.

A length of bed approximately 1.5m log was selected. At predawn (approx. 7am) 30 carrots were hand harvested from the outer row and the adjacent inner row (Figure 36). The length and shoulder diameter of each carrot was recorded prior to measuring their susceptibility to splitting.

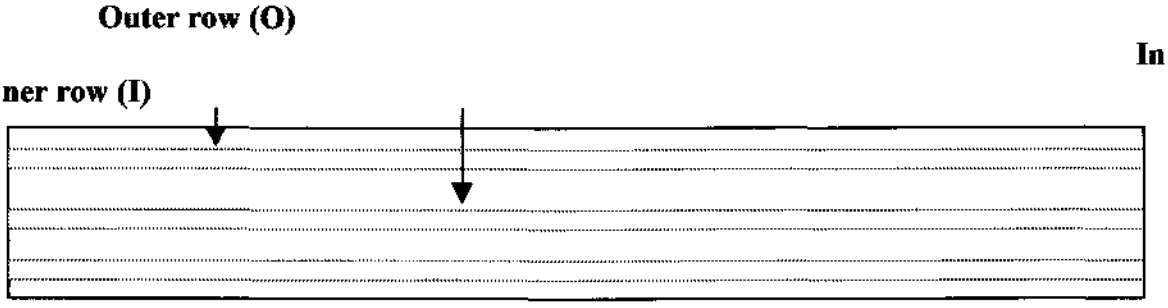

Figure 36. *Diagrammatic representation of bed and row placement. Susceptibility of carrots to splitting in the Outer row (O) and Inner row (I) were assessed.*

No relationship between length or diameter of carrots and the susceptibility to splitting from the outer row was observed. However, a weak relationship was found between both carrot root length and diameter and the force required to induce splitting for the inner row carrots (Figure 37).

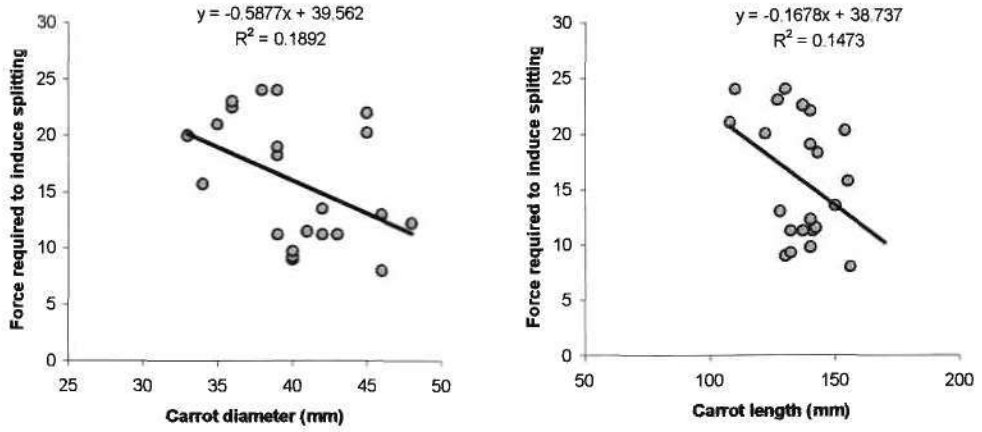

Figure 37. *Relationship between the Diameter (a) and Length (b) of carrots and force required to induce splitting. Carrots from Inner row (I). Significance, P<0.05 (a) and P<0.10 (b).*

Carrots from the inner rows had a greater mean diameter and mean length than carrots from the outer rows (Figure 38).

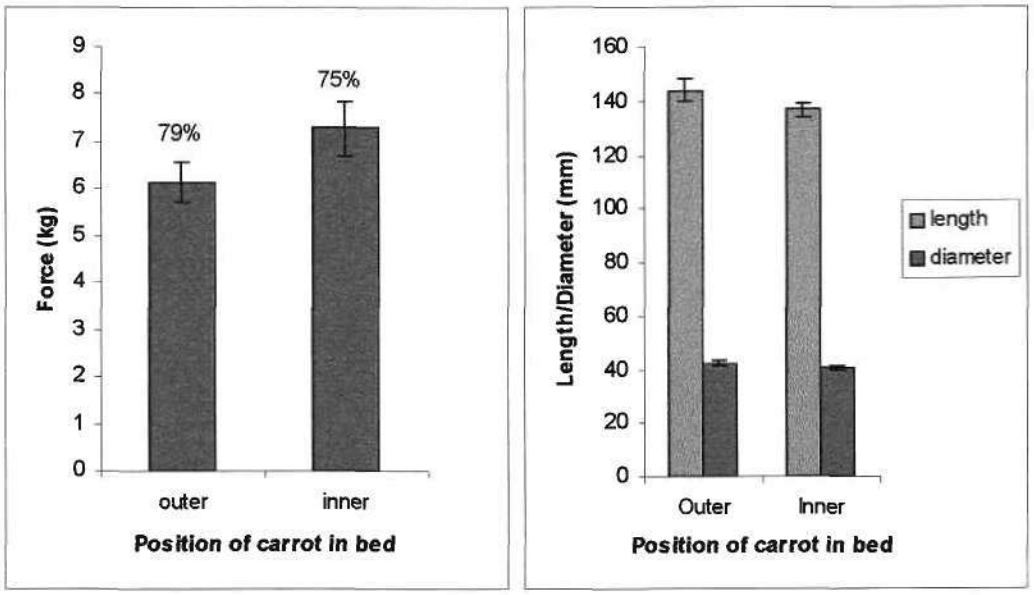

Figure 38. *Force required to induce carrots to split from the outer or inner rows (a). Percentage of carrot splitting from each position located above bars. Length and diameter of carrots from position (b) with labels showing mean values.*

There was only a small difference in the percentage splitting in carrots sampled from the outer (79%) and inner (75%) rows, and no significant difference in splitting pressure. Overall, the results suggest that row position in the bed, and size characteristics of carrots within a crop at harvest, have little effect on splitting susceptibility.

(4) Physiology of splitting

Since turgor pressure is known to influence the tissue stress and strain characteristics of carrots (Kokkoras, 1995) changes in susceptibility to splitting over a day may be largely a result of changes in water relations. Experiments were therefore conducted to investigate changes in water relations in carrot leaf and root tissue in both field grown and glasshouse grown plants. All measurements were repeated using 10 replicates or greater.

Leaf water potential was recorded in a commercial kuroda crop at harvest maturity every 2 hours over a day beginning predawn (6:30am) until 4:30pm. A scholander type pressure bomb was used for water potential reading and undamaged, recently fully matured leaves were used.

Root water potential and osmotic potential readings were taken using a psychrometer. Core samples 1.5cm in diameter and approximately 1-2cm in length containing phloem tissue were taken from approximately 2 cm below the shoulder of the carrot taproot. Fresh sections were used immediately for water potential assessment. Duplicate cores were placed in sealed vials and then immediately into liquid nitrogen. Osmotic potential of these cores was recorded following thawing of the sections.

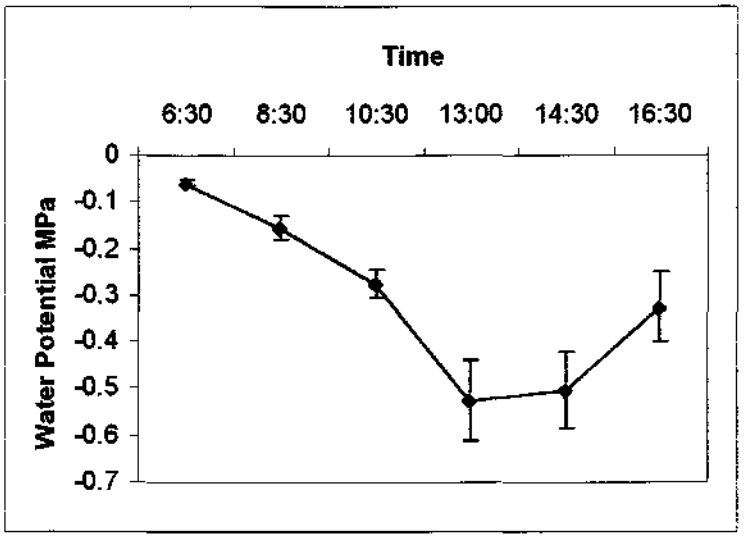

Figure 39. Changes in leaf water potential

Leaf water potential changed over the duration of the day (Figure 39). Water potential declined between 6:30am and 1pm and increased again until 4:30pm. This response is common to many crops, and indicates stomatal closure at approx 1pm to reduce water loss. Stomatal closure results in an increase in water potential. This pattern is similar to that of percentage splitting in carrot crops, and suggested the reduced splitting during the day could be a response to declining water potential and hance tissue turgor. However, results for the root storage tissue indicated a slight increase in water potential over the day (Figure 40).

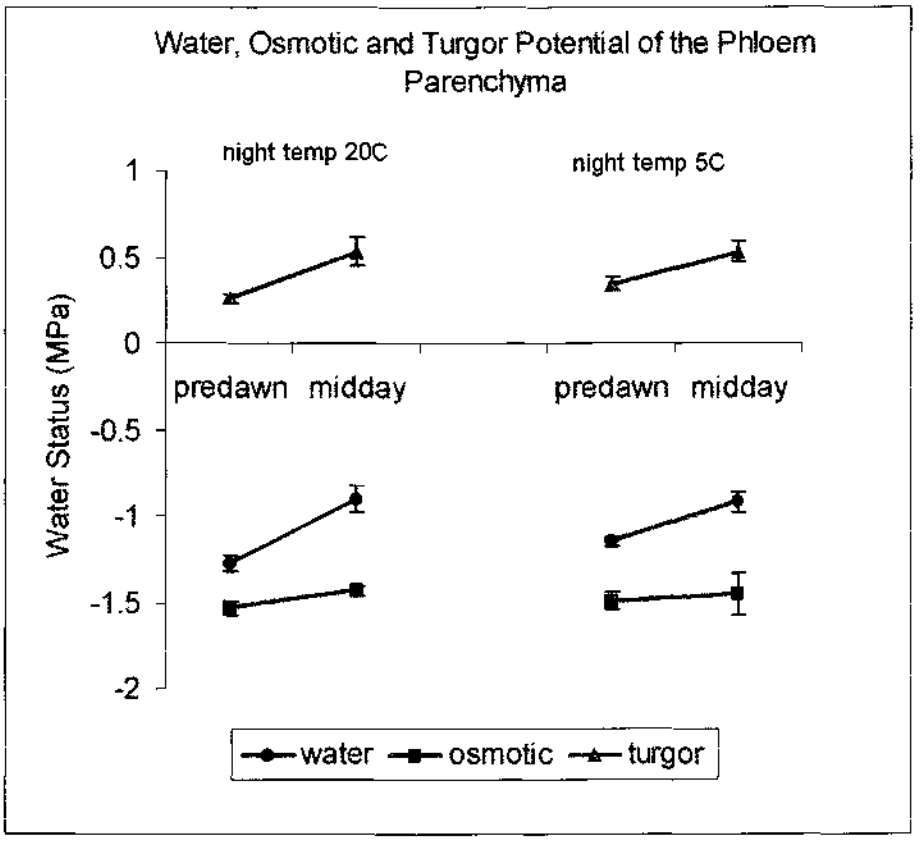

Figure 40. *Water relations in storage root tissue after cool and warm night conditions*

The water, osmotic and turgor potentials of phloem parenchyma show similar trends after cool (5°C) and warm (20°C) night time temperatures. As the water potential in the root does not display a similar trend as leaf water potential over the day, there must be a significant resistance to water movement from the storage tissue in the root to the leaves.

An alternative hypothesis to explain changes in root tissue properties and hence susceptibility to splitting over the day. One possibility is that susceptibility to splitting coincides with periods of carrot root expansion. Measurement of changes in carrot root diameter, using a sensitive LVDT system, indicated that root expansion takes place at night and early in the morning, and coincides with periods of susceptibility to splitting (Figure 41).

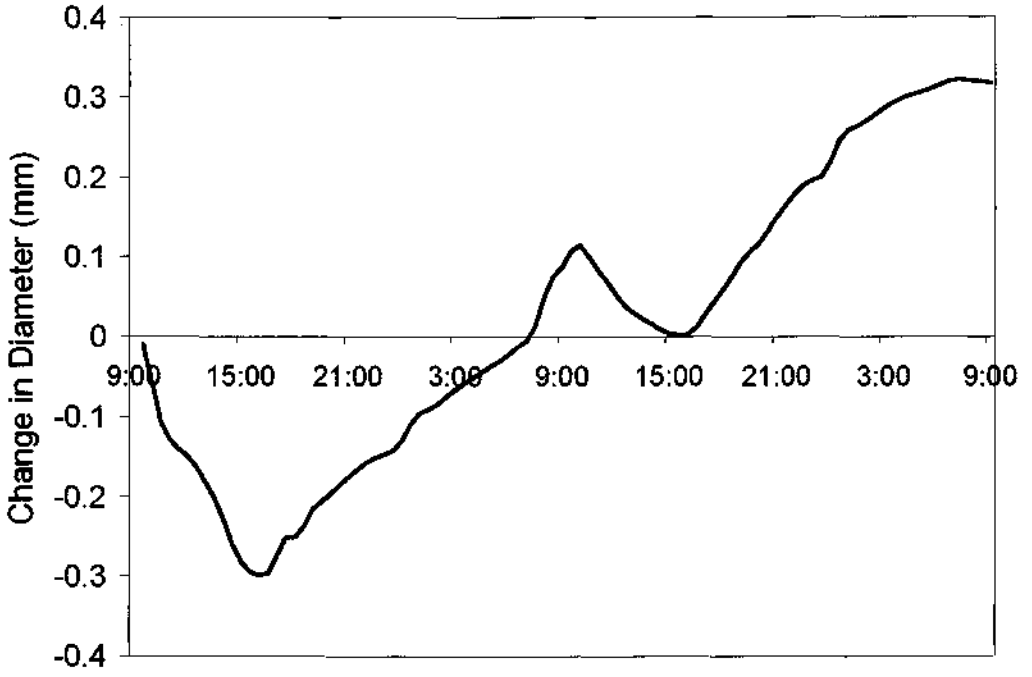

Figure 41. *Diurnal changes in carrot root diameter(commencing 9am, completed 48 hours later)*

Changes in root tissue properties in order to accommodate expansion may predispose the carrot root to splitting. Further research is required to link changes in susceptibility to splitting to root expansion growth.

(5) Treatments to reduce susceptibility to splitting

The results reported are consistent with carrot root expansion occurring during the night and early morning, and the tissue being more susceptible to splitting during this period. Expansion requires water uptake from the roots, and subsequent movement of water and photosynthate from leaves to the storage tissue in the roots. Water from the soil moves via the xylem or core of the root into the shoot system, before moving with the carbohydrates in the phloem or outer section of the root to the storage cells. Temperature may influence either the rate of movement of carbohydrates or the rate at which the tissue can expand, and therefore directly influence susceptibility to splitting. Removing the source of carbohydrates may reduce any turgor increase (pressure build-up) within the taproot during expansion and thus reduce splitting susceptibility. A trial was undertaken to examine the effect of leaf removal on the day before harvest to test this hypothesis. The treatments applied were lifting roots (Root Lifted), removing all leaves (Leaves Removed), removing oldest leaves (Leaves Trimmed) and an untreated control (Control).

A mature Kuroda crop was used to assess the splitting susceptibility of carrots after applying treatments. The experimental layout was a randomised complete block, as shown below. Each treatment was replicated three times. Each block consisted of 2.4 length of bed. Each bed contained 6 rows. The treatments applied were lifting roots (Root Lifted), removing leaves (Leaves Removed), removing oldest leaves (Leaves Trimmed) and an untreated control (Control). In each case 30 cm bed was treated, leaving a 30cm buffer, before applying the next treatment.

Block 1	Block 2	Block 3
Leaves Removed	**Leaves Trimmed**	**Roots Lifted**
30cm buffer		
Control	**Roots Lifted**	**Leaves Trimmed**
30cm buffer		
Roots Lifted	**Leaves Removed**	**Control**
30cm buffer		
Leaves Trimmed	**Control**	**Leaves Removed**

Lifting Roots involved lifting carrot roots slightly (approximately 5cm) then allowing them to relax back into the soil.
Removing Leaves – Removing all leaves with secateurs to be level with the shoulder height of the taproot.
Leaves Trimmed – Removing outer ¾ leaves leaving 3-4 youngest fully developed leaves.
Control – untreated carrots

Treatments were applied 1-2pm the day prior to assessing. The susceptibility of the carrots to splitting was assessed between 7am and 9am, starting with block 1.

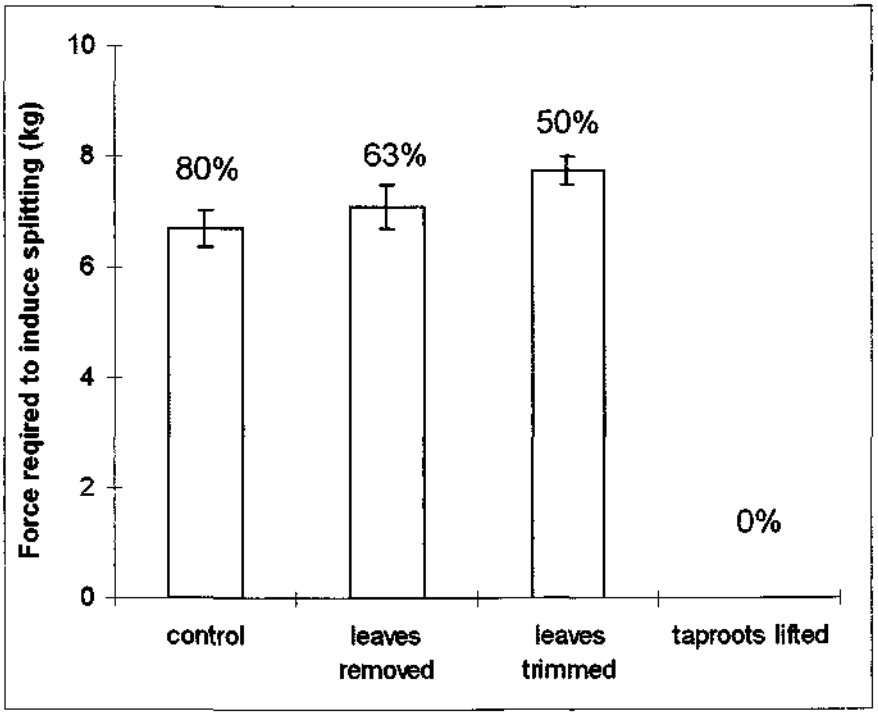

Figure 42. *Effects of preharvest treatments on splitting susceptibility*

Splitting percentage was reduced from 80% to 50% by trimming leaves while force required to split the carrots was significantly increased. Lifting carrots had the greatest effect, but may not be a commercially feasible treatment as mechanical harvesting following lifting may be impaired. The results indicate that the theory developed to explain splitting may be correct, and also suggest a direction for further research to develop commercially effective methods to reduce splitting losses in carrot crops.

DISCUSSION

Carrot splitting during growth (growth cracking) and harvesting (harvest splitting) occurs sporadically in carrot crops and can result in very significant packout losses. Splitting results from the imposition of mechanical stresses on the carrot root tissue where the tissue is too weak to withstand the stress. Mechanical stress accumulates within the carrot tissue during the root expansion period. The level of intrinsic stress may be sufficient to overcome tissue strength during growth or an additional external stress applied during harvesting may be required to induce tissue failure. The susceptibility of carrot roots to splitting is thus dependent on the internal stresses and the tissue properties (flexibility and strength).

Carrot susceptibility to splitting varies diurnally with significantly higher susceptibility early in the morning and late in the afternoon. Periods of higher susceptibility to splitting correspond to periods of carrot root expansion. The expansion process in plant tissue involves loosening of cell wall, movement of water to provide the driving force for expansion, and regulation of the osmotic potential within the expanding cells. Night temperature influences the susceptibility to splitting, with increased susceptibility occurring following cold nights. Carrot temperature when harvested does not have a significant effect on susceptibility, suggesting that temperature at night must be influencing either regulation of cell elasticity or water relations. Carrot harvesting following cold nights should be avoided until late morning (10:00am or later based on observations in this project) to reduce the risk of splitting. Susceptibility to splitting also increases following maturity, so harvesting at or soon after rounding of the root is recommended along with delays in harvesting until later in the morning for over mature crops. Removal of outer leaves or undercutting of carrots the day before harvesting also reduces susceptibility to splitting, and the mechanism is likely to be associated with storage tissue water relations and partitioning of photosynthate to the storage tissue.

Significant advances in understanding the physiological basis of splitting have been developed in this project. Further work on splitting physiology is currently being completed in a PhD project being undertaken at the University of Tasmania by Alistair Gracie. Opportunities exist for the application of these findings to the development of crop management strategies to reduce losses due to splitting. The use of a handheld penetrometer to assess susceptibility to splitting prior to harvest has been demonstrated but needs to be calibrated against actual damage levels during harvesting. The effects of crop management practices, particularly irrigation management and nitrogen nutrition, on the physiological processes shown to influence susceptibility to splitting should be characterised in order to determine effective management strategies to reduce splitting susceptibility.

V. Discussion

The regulation of size and shape in carrot roots is complex but development of the crop during the establishment phase has been shown to be critical to the final characteristics of the harvested carrots in a crop. Much of the variability existing in carrot crops during the first 80 days of growth is due to variability in embryo size within then seedlots used, while competition between carrots accounts for changes in variability during the later stages of crop development. A certain amount of variability within a crop is inevitable due to the interaction between individual plants at the planting densities required in commercial production. Selection of cultivars with increased capacity to perform under competitive (high density) conditions will reduce variability but is not always possible given the range of desirable characteristics required for particular markets.

Seed grading was not effective in increasing to a commercially significant level the size uniformity within crops, and thus the variability in embryo size within seedlots did not explain variability in root weight at harvest for the kuroda and nantes type carrots examined in this project. While seedling weight was strongly correlated to embryo size, other factors such as competition between plants, genetic variability, and differences in timing of maturity must have impacted on size variability. It appears that carrot growth rate decreases close to maturity, resulting in decreased size variability in crops approaching harvest as larger, more mature carrot growth slow while smaller, less mature carrots continue to grow rapidly. Factors influencing the variability in growth stage within a crop, as well as factors influencing the size potential of individual plants, would therefore affect the size variability in the crop at the harvest date. Field factors such as soil type and ground preparation, along with management of irrigation and seed sowing, have been shown to influence emergence time and would therefore be expected to contribute to variability in maturity. These factors, along with genetic variability, are also likely to determine the size potential of the plants. Treatments that reduce variability in emergence, and subsequent stage of growth as the crop develops, as well as limiting genetic variability will reduce variability in root size at harvest. Management of crops to ensure even emergence is likely to be a critical determinant of size variability in carrot crops, but even under optimum conditions variability due to genetic and competition factors will be present.

Management of plant spacing and density was shown to influence root size distribution within the crop. Improvements in planting precision to ensure even distances between plants, and selection of appropriate plant density can be used to maximise the proportion of carrots in target size ranges. These treatments may also reduce packout losses due to poor shape characteristics. Carrot root shape at harvest is principally determined during the crop establishment phase. Factors that influence the rate of growth and direction of growth of the taproot during early plant development determine the length and shape of the root at maturity. The final length of the carrot appears to be determined during the early growth phase, with conditions promoting rapid taproot growth and initiation of secondary growth down the length of the root resulting in greater potential root length. In addition, conditions that delay the onset of expansion growth or root filling lead to an extended duration of initiation of secondary growth and hence increased length potential. Soil conditions were identified in this study as one determinant of root length potential, with increased soil strength resulting in shorter root length at harvest presumably through slower root growth at establishment. Soil strength is linked to soil bulk density and soil

water content, so maintenance of soil moisture is important in soils with high bulk density if the risk of development of short roots is to be avoided.

The direction of root growth through the soil following germination determines the shape of the root at harvest. Soil strength and/or soil water potential are likely to influence the direction of root growth, with roots growing around regions of high soil strength (eg. clods) or low water availability. Variability in soil strength and/or soil water potential within a soil profile will therefore increase the likelihood of development of bent or twisted roots. Expansion of the carrot root through secondary thickening can reduce the severity of bends and twists in the root resulting in a lower proportion of rejectable shape characteristics later in crop development. In heavy soils with low organic matter content, avoidance of high soil water deficits in the first 40 days after sowing is required in order to reduce the risk of development of poor shape characteristics in the crop. In addition, shape defects can be reduced by more even spacing of plants and by reduced planting densities.

Carrot susceptibility to splitting increases with crop maturity, changes in a predictable cycle during the day and night, and increases significantly following cold night conditions. The physiological mechanisms underlying these changes have been examined in the project and will permit the development of strategies to control splitting. Carrot harvesting following cold nights should be avoided until late morning (10:00am or later based on observations in this project) to reduce the risk of splitting. Susceptibility to splitting increases following maturity, so harvesting at or soon after rounding of the root is recommended along with delays in harvesting until later in the morning for over mature crops. Removal of outer leaves or undercutting of carrots the day before harvesting also reduces susceptibility to splitting, and the mechanism is likely to be associated with storage tissue water relations and partitioning of photosynthate to the storage tissue.

VI Conclusions

Management of crop establishment is critical to the uniformity of the crop at harvest and the size and shape characteristics of the harvested roots. The major seed and soil factors influencing carrot size and shape have been identified and some strategies for managing crops to maximise packout in target size ranges are proposed. Extension of crop modelling packages developed in the UK to incorporate size variability data collected in this project is possible and would result in programs to optimise plant spacings and densities to achieve target yields and size grades. There is scope for further application of the project results through the development of critical soil strength values and target soil water tensions for soils of different bulk densities, allowing prediction of conditions where risk of misshapen carrots is high. Improved irrigation management to ameliorate high risk conditions would then be possible. In addition, conditions that delay the onset of expansion growth or root filling lead to an extended duration of initiation of secondary growth and hence increased length potential. Further research is required to identify the factors triggering initiation of secondary growth and commencement of the rapid expansion phase.

Significant advances in understanding the physiological basis of splitting have been developed in the project. Opportunities exist for the application of these findings to the development of crop management strategies to reduce losses due to splitting. The use of a handheld penetrometer to assess susceptibility to splitting prior to harvest has been demonstrated but needs to be calibrated against actual damage levels during harvesting. The effects of crop management practices, particularly irrigation management and nitrogen nutrition, on the physiological processes shown to influence susceptibility to splitting should be characterised in order to determine effective management strategies to reduce splitting susceptibility.

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Appendix 1

CARROT ASSESSMENT SURVEY

Grower Name:..... Location:.....

Paddock ID No. or Contract No:..... Company:.....

PADDOCK INFORMATION

Soil type: *(please circle)* Krasnozem Cressy soils Black Cracking Clays

Duplex soils Deep Sands other.....

Aspect: (eg NorthWest facing).....

Slope: *(please circle)* flat(0-3°) slight(3-10°) medium(10-30°) steep(>30°) undulating

Row orientation: (eg North-South)..... # Nematode count No./m^2:.....

Years since carrots were grown on the same paddock:.....

Previous two crops grown on the paddock: 1996..... 1995.....

SEED INFORMATION

Cultivar:..... # Seedlot ID:.....

Size grading:..... # Seed treatment:.....

Germination %:.....

SOWING

Planter:..... # Operator:.....

Date:..... # Sowing rate (kg/ha):.....

Target spacing: between seeds (cm):..... between rows (cm):..... depth (cm):.....

SEEDBED PREPARATION

Seedbed prepared: *(please circle)* flat ridge bed

Date of seedbed preparation:.....

Depth of tillage (cm):.....

IRRIGATION

Water status at sowing: *(please circle)* 2 3 4 5 6 7 8
dry ideal wet

Rainfall/irrigation for first 14 days after sowing: *(please circle)* 2 3 4 5 6 7 8
dry ideal wet

Date of first watering or rainfall following sowing:.....

Type of irrigation system used:.....

Soil crusting *(please circle)* yes no

EMERGENCE DATA

Date recorded:..... # Target population /m^2:..... # Actual population /m^2:.....

Health and vigour of seedlings approx. 3 weeks after sowing: 2 3 4 5 6 7 8
poor average excellent

FERTILISER APPLICATIONS

Preplanting soil nutrient assessment undertaken: (please circle) yes no

Preplanting pH:.....

Fertiliser applications:

DATE	FERTILISER USED	RATE	APPLICATION METHOD

WEED CONTROL

Herbicides applied:

DATE	HERBICIDE USED	RATE	FINAL WEED STATUS